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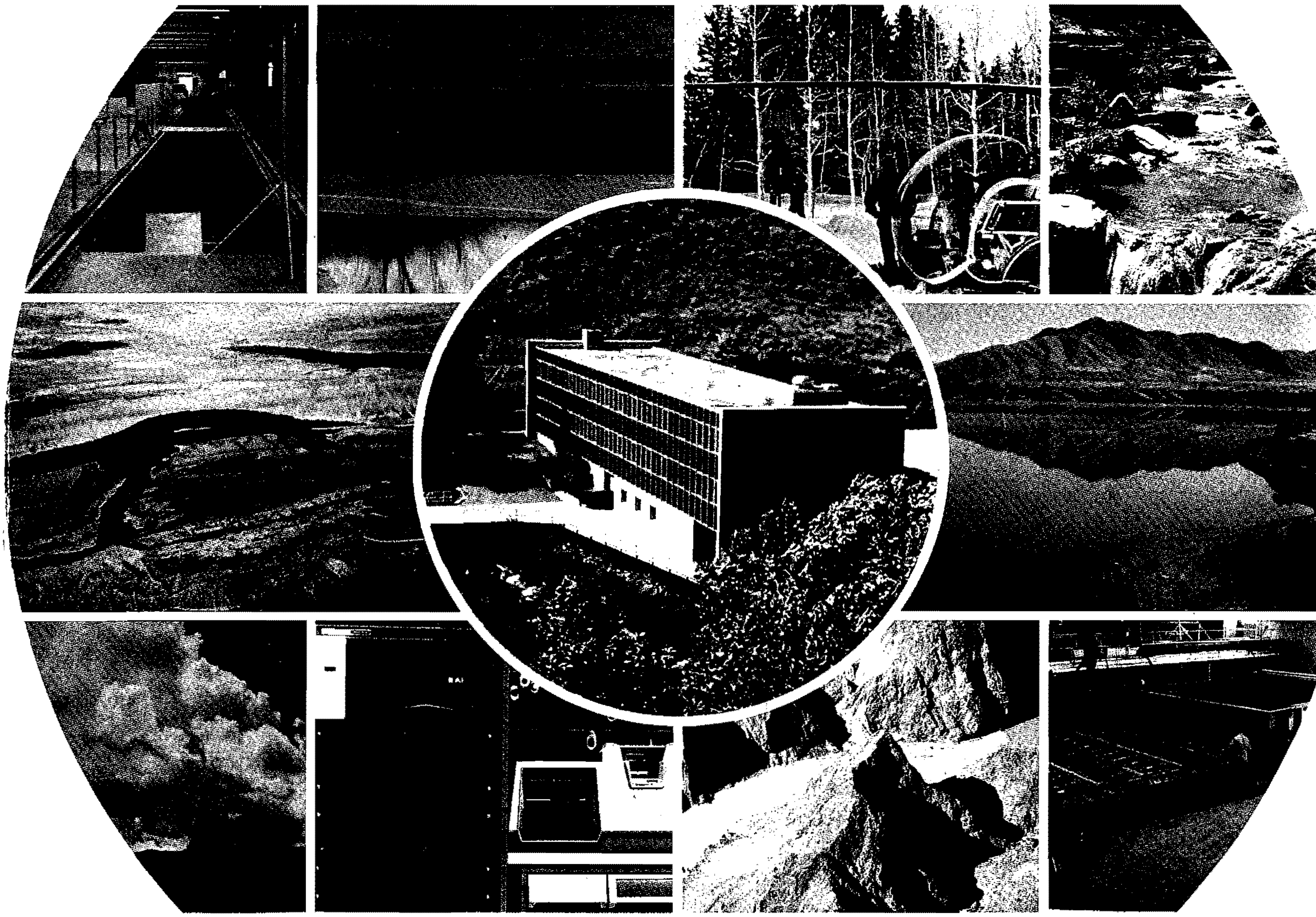

Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

November 1979

WATER QUALITY SERIES
UWRL/Q-79/03

# MODELING THE PERFORMANCE OF THE INTERMITTENT SAND FILTER

by

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# ABSTRACT

Several models were developed to predict the efficiency of the intermittent sand filter (ISF) in removing algae from wastewater stabilization pond effluent; volatile suspended solids (VSS) was the analytical technique used to identify algal concentrations. The first (ISF model) and second (modified ISF model) models consisted of two distinct portions: a surface algal layer (SAL) component and a sand phase component. In the ISF model, the sand phase component was described in terms of 20 empirical sand filter efficiency terms (20 $\lambda$ coefficients); in the modified ISF model, a functional relationship between $\lambda$ and filter depth was developed. The modified ISF model was less accurate than the ISF model in predicting filter effluent quality.

The third model (simplified ISF model) consisted of a single component (the sand phase). The mass of algae which was deposited to the SAL component in the first two models was, instead, forced into the top (2 inch) layer of sand. The functional relationship between the sand phase filter term and filter depth was recalculated and utilized to describe the decrease in the concentration of algae during the filtration process. The simplified ISF model was comparable to the ISF model in predicting filter effluent quality.

The simplified model predicted 85 percent VSS removal for 0.17 mm effective sand size ($\varepsilon'$) filters and 44 percent VSS removal for 0.40 and 0.68 mm $\varepsilon'$ filters. The application of the simplified ISF model is subject to limitations of maximum hydraulic loading rates of 0.7 million gallons per acre per day and maximum mass loadings of 49 grams of SS per $m^2$ per day for 0.17 mm effective size sand.

Design curves, in which period of filter operation was described as a function of mass loading, were developed for ISF systems containing 0.17, 0.40, and 0.68 mm $\varepsilon'$ media. Wastewater stabilization pond effluents having calcium carbonate precipitation problems were included as a special case in this analysis.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

## LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

## SECTION 1

## INTRODUCTION

### Nature of Problem

Excessive algal growths in wastewater lagoon systems must be removed from the wastewater prior to discharge into receiving streams. Intermittent sand filters (ISF) are utilized as a polishing step on wastewater stabilization pond effluents to remove these suspended solids. ISF processes have been studied extensively at Utah State University (Marshall and Middlebrooks 1974, Hill et al. 1976, Harris 1977, Tupyi 1977). Field scale filter operations at Mount Shasta, California, Moriarty, New Mexico, and Ailey, Georgia, also were studied to determine the effectiveness of ISF as lagoon effluent polishing devices (Russell et al. 1979). Models to predict the performance of the ISF when treating wastewater stabilization lagoon effluents have not been developed. The laboratory, pilot, and field scale performance studies referenced above contain adequate data to evaluate models.

### Objectives

The general objective of this research was to model the performance of the ISF and develop engineering design equations for the ISF process using data collected in the laboratory and field.

Specific objectives of the research were to:

1. Review current literature to obtain information on existing sand filter models.

2. Formulate model variables to adequately describe the ISF system.

3. Define appropriate measurements to quantify the effects of model variables.

4. Operate laboratory scale ISF units to examine the removal of influent algae from the wastewater with depth.

5. Study the development of the surface algal layer (SAL) to ascertain its importance in the ISF process.

6. Develop and refine ISF regression models.

7. Employ numerical methods to solve the differential equations used in the models.

8. Validate the models using field data.

9. Present practical design equations based upon the ISF models.

## SECTION II

## MATERIALS AND METHODS

### General

Design of the laboratory procedures were based on the empirical relationships developed by Ives (1960) and preliminary data from three field sites (Russell et al. 1979). The modifications to be made in developing the ISF model must account for the biological activity of the ISF and the fact that the filter system under study is intermittently loaded.

The study consisted of two phases that were operated concurrently. The laboratory phase involved extensive testing of model variables and subsequent development of the ISF model. The field phase consisted of the collection of solids and carbon data with depth at three operating ISF facilities around the United States; the purpose of this phase was to provide actual field operational data to be utilized in model validation.

As a prelude to the laboratory experimentation, an algae culture was grown for application onto the filters. A steady state population of algae was cultured and maintained throughout the laboratory phase.

### Laboratory Phase

Six filter experiments were performed in the laboratory phase of the study. The first two experiments were conducted to gather data in the sand phase of the ISF. The suspended solids (SS), volatile suspended solids (VSS), total organic carbon (TOC) and soluble organic carbon (SOC) analyses (Appendix G) were performed on the filter influent, effluent, and on treated wastewater collected at 1, 2, 3, 6, and 9 inch depths within the filter. All analyses were conducted according to Standard Methods (APHA 1971) or U.S. Environmental Protection Agency analytical procedures (EPA 1974). Particulate organic carbon (POC) was calculated as the difference between TOC and SOC. The filters used in the first two runs were operated until plugging occurred, at which time volatile solids data were collected on the surface algal layer (SAL). In runs three through six, five columns at the same daily mass loading (DML) level were operated for different periods of time for each experiment. From the influent solids concentration (Css) and flow rate (Q) values, the expected run time was estimated (based upon runs one and two). The SAL ash weight measurements were then performed at time increments throughout each run to obtain SAL values during the period of operation. After the SAL was removed from the ISF, the column was taken out of service and prepared for the next experiment using different influent suspended solids concentrations and/or hydraulic loading rates.

Nine experimental filtration columns were constructed in order to describe a 3 x 3 variable matrix. The filter columns (Figure 1) were housed in the chlorination building at the Logan wastewater stabilization ponds. This site was selected primarily because of availability of space (large enough to house filter columns) and because of its location next to a supply of fresh secondary wastewater stabilization pond effluent. The existing pipeline between the lagoon effluent site and the chlorination building was utilized to deliver daily supplies of secondary effluent needed for the maintenance of the steady state algal culture. The nine columns were constructed using two sections 3 feet in length of 6 inch diameter (5.5 inch inner diameter) cylindrical plexiglass tubing bolted together at the middle to form columns 6 feet in length (Marshall and Middlebrooks 1974). The laboratory column is shown in Figure 1.

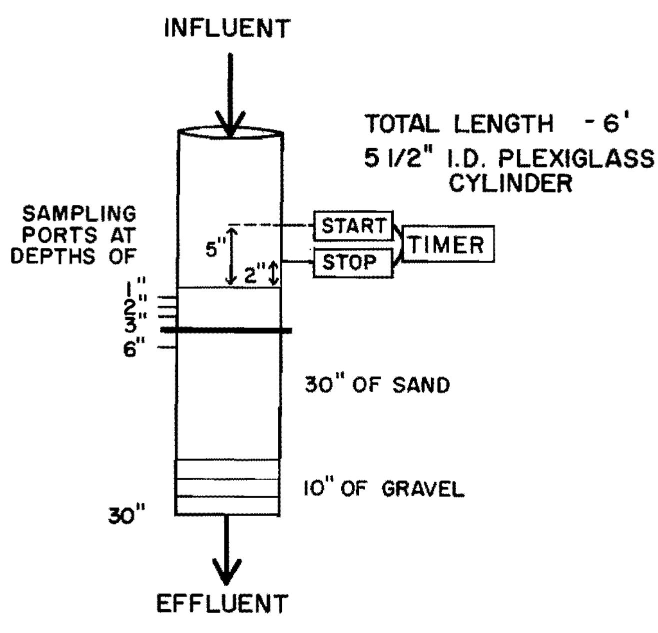



Figure 1. Laboratory ISF column.

The columns were filled with sand and gravel taken from the 4 x 4 x 6 feet tall filter boxes used by Hill et al. (1976) while studying series ISF operation. The gravel was removed from the filter box, separated, dried, and then graded into appropriate sizes using a shaker.[1] The sand was taken from the middle of the 0.17 mm effective sand size ($\varepsilon'$) box, mixed, dried in the sun, and placed in the columns to the 3 feet level. The columns were bolted together, and distilled water was added to the columns to compact the sand. After each compaction, sand was added to bring the depth back to the 3 feet level. Oven dried 0.17 mm $\varepsilon'$ sand (103°C) was weighed and loaded on the compacted sand up to the level which yielded a 30 inch sand column (Figure 1). No noticeable compaction resulted from further wetting of the column with distilled water.

The sand was analyzed by the Soils Laboratory, Department of Civil and Environmental Engineering, to confirm that it was indeed 0.17 mm $\varepsilon'$ sand. The results are summarized below:

$$D_{10}\ (\varepsilon') = 0.17 \text{ mm}$$

$$D_{60} = 1.0 \text{ mm}$$

$$C_u = \frac{D_{60}}{\varepsilon'} = 5.9$$

$$\rho_s = 2.65 \text{ g/cc}$$

$$\gamma_s = 165.44 \text{ lbs/ft}^3$$

where $D_{10}$ = the sieve size that 10 percent of the sand passed, and the effective sand size, $\varepsilon'$; $D_{60}$ = the sieve size that 60 percent of the sand passed; $C_u$ = uniformity coefficient; $\rho_s$ = density of sand; and $\gamma_s$ = specific weight of sand.

The initial or clean filter porosity, $f_o$, was calculated from the weight of dry sand loaded into the columns and the specific weight of the sand (Table 1).

The initial porosity of the 0.17 mm sand was taken as the average of these nine values, $f_o = 0.344$. The standard deviation (S) was 0.025 and the standard error of the mean ($S/\sqrt{n}$, where n is the number of values) was 0.008.

Sampling ports were located on the filter columns at 1, 2, 3, 6, and 9 inch depths below the sand surface (Figure 1). The sampling ports were constructed of 1/4 inch diameter plexiglass tubing and were positioned flush with the inner wall of the cylinder. The openings into the filter were covered with screen having 0.338 mm square holes. This screen was selected such that the holes in the screen were larger than the pores of the clean sand filter. Because the screen had larger holes than the effective size of the sand (0.17 mm), some fines entered the ports. The ports were thoroughly rinsed with distilled water prior to the start of the experiment. Because suspended solids (SS) was the primary variable in the first run, special care was taken to insure that these sample ports remained free of fines. This was accomplished through constant observation and periodic cleaning of the ports with a 1/4 inch diameter test tube

[1]Gilson Screen Company, Malina, Ohio, located in the Soils Laboratory, Department of Civil and Environmental Engineering, College of Engineering, at Utah State University.

Table 1. Clean filter porosity determination data for laboratory scale filtration units.

| | Dry Sand Loaded into Columns | | | | |
|---|---|---|---|---|---|
| ISF Column # | Height of Sand (inches) | Total Volume ft$^3$ | Weight of Sand lbs. | Volume of Solids ft$^3$ | $f_o$ |
| 1 | $4^{15/16}$ | 0.06789 | 7.105 | 0.04295 | 0.367 |
| 2 | 5 | 0.06875 | 7.430 | 0.04491 | 0.347 |
| 3 | $4^{3/4}$ | 0.06531 | 7.108 | 0.04296 | 0.342 |
| 4 | $5^{1/8}$ | 0.07046 | 7.099 | 0.04291 | 0.391 |
| 5 | $5^{1/8}$ | 0.07046 | 7.917 | 0.04785 | 0.321 |
| 6 | $4^{3/4}$ | 0.06531 | 7.152 | 0.04323 | 0.338 |
| 7 | $5^{1/4}$ | 0.07218 | 8.296 | 0.05014 | 0.305 |
| 8 | $4^{3/8}$ | 0.06015 | 6.614 | 0.03998 | 0.335 |
| 9 | $4^{1/2}$ | 0.06187 | 6.614 | 0.03998 | 0.354 |

$$\text{Volume of solids} = \frac{\text{Weight of sand in column}}{\text{Weight of sand/ft}^3}$$

$$f_o = \frac{\text{volume of voids}}{\text{total volume}} = \frac{\text{total volume - volume of solids}}{\text{total volume}} = 0.344$$

brush on the day prior to sampling. Approach velocities (W) of ISF influents were measured directly utilizing timers which were designed to start when the surface of the influent was 5 inches above the sand and to stop when the surface of the influent was 2 inches above the sand (Figure 1).

Rose (1951) found that a ratio of effective size to column diameter of 1:50 or less for a filter system would minimize wall effects. In this study ($\varepsilon'$ = 0.17 mm, column inner diameter = 139.7 mm) the $\varepsilon'$ to column diameter ratio was 1:822, which is far less than 1:50.

The three suspended solids concentrations (SS) applied to the laboratory scale filters were 75, 50, and 25 mg/ℓ. Suspended solids concentrations in the algal growth chamber were adjusted daily so that the filters received the exact concentration (Css) required. The three hydraulic loading rates used were 0.7, 0.5, and 0.3 million gallons per acre per day (mgad). The experimental design for experiments one and two are shown in Table 2.

It was observed in experiment one that the low mass loadings applied to the filters receiving effluent containing 25 mg/ℓ of SS yielded run times greater than 93 days for the 0.5 and 0.3 mgad hydraulic loading rates. Because of time constraints in the laboratory phase, it was decided to eliminate the 25 mg/ℓ influent SS concentration from subsequent experiments. Therefore, in experiment two and in the SAL quantitative experiments (three through six) only SS concentrations of 75 and 50 mg/ℓ were utilized.

Prime importance was placed upon the daily determination of the algal culture SS concentrations because inaccurate measurements would lead to incorrect solids loadings onto the filter. Direct SS measurement of the culture in the tank prior to loading the filters lacked the necessary accuracy because after the determination of tank SS (a minimum of 1 1/2 - 2 hours analysis time) the tank SS had changed. Therefore, instantaneous SS concentrations were measured daily by determining the optical density (OD) of the culture at a wave length of 750 mμ (a 1 cm pathlength) using a Bausch and Lomb Spectronic 20. Algal culture tank SS concentrations were found to be linearly related to optical density measured at 750 mμ. This linear relationship, which was updated weekly, was used to obtain SS levels in the tank immediately prior to filter loading. Measurements of OD were also made on the 75, 50, and 25 mg/ℓ SS samples prior to loading as a check on the accuracy of the dilution process. An example of the OD versus SS relationship is presented in Figure 2.

The data in Figure 2 represent the OD versus SS values for 2 - 50 mg/ℓ, 2 - 75 mg/ℓ, and six tank measurements between September 29 and October 2, 1977. Distilled water (0 mg/ℓ SS) yielded OD values of zero, and this coordinate point was also utilized in calculating the linear regression equation relating OD and SS. The relationship was assumed to be linear between 0 and 50 mg/ℓ SS.

Intermittent loadings were made once daily with subsequent analyses performed on the influent, depth ports, and effluent samples twice per week until the filter plugged. Plugging was defined as failure to pass all of the wastewater applied during a loading within 24 hours. Loadings were applied to the appropriate columns according to the schedule shown in Table 3.

The influent suspended solids consisted of algae grown in a fiberglass culture tank (6 x 2 x 1.5 feet) with an approximate volume of 18 $ft^3$ (163 gallons). A bank of 6 fluorescent lights (4 feet long) suspended approximately 1.5 feet above the water surface generated a surface illumination

Table 2. Experimental design showing the suspended solids concentrations and hydraulic loading rates used in laboratory experiments 1 and 2.

| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Run 1<br>SS, mg/ℓ | 75 | 50 | 25 | 75 | 50 | 25 | 75 | 50 | 25 |
| Hydraulic Loading Rate, mgad | ← 0.7 → | | | ← 0.5 → | | | ← 0.3 → | | |
| Run 2<br>SS, mg/ℓ | 75 | 75 | 50 | 50 | 75 | 50 | 50 | 75 | 50 |
| Hydraulic Loading Rate, mgad | ← 0.7 → | | | | ← 0.5 → | | | ← 0.3 → | |

of 675 foot candles (f.c.) (Figure 3). Aluminum foil was added to the lighting banks and to both sides of the tank above the water surface in order to increase the reflection of light into the culture tank.

Mixing was continuous using two propeller type mixers[1] at sufficient speeds to totally mix the tank. In addition, the tank walls and bottom were scraped daily prior to all tank SS determinations (prior to any filter loadings).

Since the filters were loaded intermittently (once daily), the algal culturing tank was also loaded once daily with secondary wastewater stabilization pond effluent. This semicontinuous loading schedule obviated the operational problems inherent in a continuously loaded system by allowing the operator to manually load the culturing tank. The Logan lagoon secondary effluent at times contained zooplankters (Harris 1977), and to avoid contaminating the culture with zooplankton, the wastewater was filtered through 0.52 mm ε' sand filter columns prior to being placed in the culturing tank (Figure 3). This sand prefilter removed all zooplankters and some algae (Tupyi 1977). By using prefiltration, the algal stock culture could be maintained at the high concentrations required with the minimum risk of periodic grazing by zooplankters. Complete mixing of the algal culture tank also inhibited zooplankton growth.

It was necessary that the algal culture SS concentration be maintained in excess of 75 mg/ℓ in order to obtain the highest SS loading. To offer a margin of operational safety, the culture was maintained at SS concentrations of 90 to 110 mg/ℓ. Based upon the volumes and concentrations of algal culture needed, the volume of daily flow of secondary lagoon effluent added to the culture tank was found to be 13 gallons.

Continuous flow-continuously stirred process kinetics were utilized to describe the algal culturing system (McGauhey et al. 1968). The maximum or steady-state concentration of organisms is a function of the aqueous phase nutrient concentration as shown in Figure 4. The mass balance equations for these processes are:

Change = input - output + growth - decay . . (1)

$$\frac{dX_1}{dt} V = QX_o - QX_1 + \mu X_1 V - k_d X_1 V$$

$$\frac{dX_1}{dt} = \frac{Q}{V}(X_o - X_1) + \mu X_1 - k_d X_1$$

At steady state, $\frac{dX_1}{dt} = 0$, and $X_o = 0$; therefore,

$$\mu - k_d = \frac{1}{\theta} \quad . . . . . . . . . (2)$$

$\theta$ = hydraulic residence time, $V/Q$, t
$\mu$ = specific growth rate, $t^{-1}$
$k_d$ = decay coefficient, $t^{-1}$

[1]Mixing Equipment Co., Inc., Rochester, New York.

Table 3. Daily column loading schedule.

| Loading: | | 0.7 | 0.5 | 0.3 |
|---|---|---|---|---|
| DHL | cm of algal culture applied | 65.50 | 46.78 | 28.05 |
| DLOAD | ℓ applied | 10.04 | 7.17 | 4.30 |

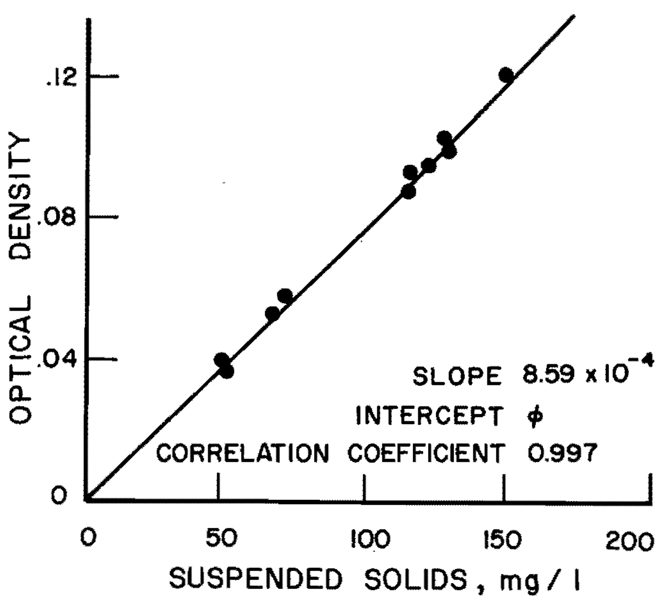



Figure 2. Algal culture tank OD versus SS relationship for 9/29 - 10/2/77.

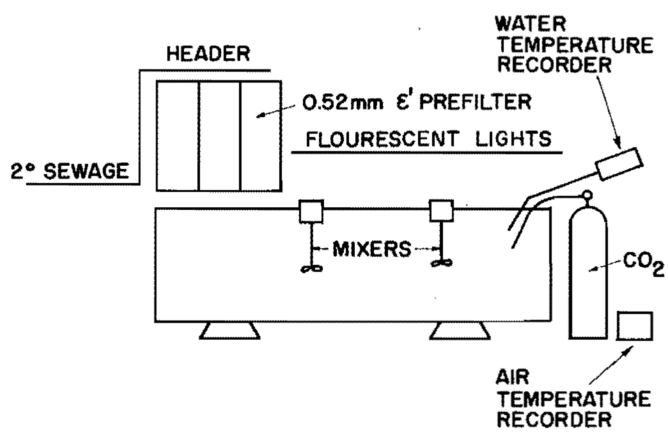



Figure 3. Influent algal suspension culturing tank.

There exists an inverse relationship between specific growth rate, $\mu$, and hydraulic residence time, $\theta$. In order to describe the relationship between algal concentration (X) and $\theta$, Michaelis-Menten growth kinetics are applied:

$$\mu = \hat{\mu}\left[\frac{S_1}{K_s + S_1}\right] \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

in which

$\hat{\mu}$ = maximum specific growth rate, $t^{-1}$
$K_s$ = saturation constant, $ML^{-3}$

Combining Equation 3 with the mass balance expression (Equation 2):

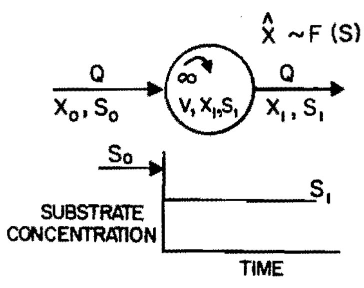
$$\mu = \hat{\mu}\left[\frac{S_1}{K_s + S_1}\right] = k_d + \frac{1}{\theta} \quad . \; . \; . \quad (4)$$

Solving for $S_1$ (the substrate concentration) gives:

$$S_1 = \frac{K_s\left(k_d + \frac{1}{\theta}\right)}{\hat{\mu} - \left(k_d + \frac{1}{\theta}\right)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

For a steady state system, $S_1$ is an inverse function of $\theta$. It is important to maintain a constant hydraulic residence time, therefore, maintaining constant $S_1$ concentrations in the culturing tank. This results in the required $X_1$ (algal concentration) since $X \sim F(S)$.

Since $\theta = V/Q$ = 163 gallons/13 gallons/day, $\theta$ was set at 12.5 days for this system when 13 gallons per day were withdrawn from and added to the tank.




$\hat{X}$ = maximum conc. of algae, $ML^{-3}$
S = substrate concentration, $ML^{-3}$

$X_oS_o$ = Input; $X_1S_1$ = Tank, Output } Algae and Substrate Levels

Q = Flow Rate, $L^3t^{-1}$
$V$ = Tank Volume, $L^3$

Figure 4. CSTR model (McGauhey et al. 1968).

Insufficient populations of algae entered the tank through the prefilter: therefore, it was necessary to seed the tank by taking 30 gallons of algal suspension directly from the lagoon system, filter it through a #10 Wisconsin plankton net, and place it in the tank. The suspension did not grow and it was concluded that prefiltration of Logan lagoon secondary effluent resulted in insufficient nutrient(s) in the stock culture tank. Therefore, nutrients were added at levels of three times those present in the algal assay medium, AAM (EPA 1971) for nitrogen, phosphorus, and trace elements (including chelated iron, Table 4).

Nutrients were added to the culture tank daily along with the input of freshly filtered secondary wastewater stabilization pond effluent. Carbon addition and pH regulation were provided by bubbling $CO_2$ into the culture at rates adequate to maintain the pH value between 7.0 and 8.0 for a given existing flow and mixing conditions.

Temperature, an important factor in experiments involving biological activity, was monitored continuously on strip chart recorders (Figure 3). Air temperature in the chlorination building housing the laboratory filter units and water temperature in the algal culturing tank were measured. Temperature dependence of biological reaction rates have been quantified by Clark and Ungersma (1972) as follows:

$$K_T = K_{20} * \psi^{(T-20)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

in which

$K_T$, $K_{20}$ = reaction rates at T°C, 20°C
$*$ = multiplication sign
$\psi$ = temperature activity coefficient
T = temperature, °C

When the ISF model was validated on field data, this relationship (Equation 6) was utilized to correct biological reaction rate terms when field temperatures differed from standard laboratory temperatures.

The maintenance of a steady state algal (suspended solids) concentration was a function of temperature, mixing schemes, light, nutrient input levels ($S_o$) and

Table 4. Nutrient spikes to algal culture tank influent.

| | |
|---|---|
| A. $NaNO_3$ | 12.6 mg N/l Influent |
| B. $K_2HPO_4$ | 0.6 mg P/l Influent |
| C. Micronutrients | 3 * AAM[a] µg/l Influent |
| D. Iron + EDTA | 3 * AAM[a] µg/l Influent |
| $CO_2$ Bubbled Into Tank To Maintain A Tank pH Range of 7-8 | |

[a]AAM, Algal Assay Medium (EPA, 1971).

hydraulic residence times ($\theta$ = 12.5 days). The system, as described, was able to maintain $X_1$ between 90-110 mg/ℓ SS.

The daily quantity of 13 gallons of algal culture was pumped into a 15 gallon polyethylene carboy used as a mixing tank. This mixing tank was connected to another pump which was in series with a 10-foot length of 3/4-inch diameter hose with a ball valve located in the length of hose. With the pump operating and the end of the discharge hose placed in the mixing tank, the suspension was allowed to mix. A grab sample was taken for immediate OD determination. Mixing tank SS levels were then calculated from the current relationship between OD and SS mg/ℓ (an example of which is shown in Figure 2), and appropriate dilutions were made to attain appropriate SS concentrations (75, 50, and 25 mg/ℓ). Laboratory determinations of SS and VSS levels were performed daily on mixing tank and 75, 50, and 25 mg/ℓ filter influents to verify the OD measurements.

Dilutions of the algal stock suspension were made with distilled water (DW) during the first run of the experiment. This DW dilution allowed maintenance of the different SS feed levels (75, 50, and 25 mg/ℓ) but introduced the variable of differing ionic strength of the filter influent. Because the sand phase of the ISF model was developed utilizing run 1 data, it was assumed that varying ionic strengths of the input lagoon effluent did not affect the ISF system.

To quantify the model parameter Css and the rate of change of Css with depth ($\partial$Css/$\partial$z), samples were analyzed at various depths within the filter for SS, VSS, and POC. These parameters were regulated such that they were variable among the columns (model variable) but were constant to individual columns. The tank SS was utilized to set dilution schedules to obtain appropriate levels of SS, VSS, and POC for the respective columns. Because the algal population could change in composition throughout the experiments, the algal culture was sampled weekly to identify and count algae.

Hydraulic characteristics of groundwater seepage flows are dependent upon the degree of saturation of soils through which such flows occur. In systems exhibiting partially saturated conditions, flows will occur in one direction only (with gravity in the z direction) and horizontal flow (into the sampling ports) cannot occur. Thus, it was difficult to sample the system.

Heavy deposition and/or biological activity resulted in a decrease in the porosity of the upper layers of the filter system and subsequently caused irregularities (unsaturated conditions) to exist below the layer of restricted porosity (Jeppson and Nelson 1970). The problem of unsaturated flow was compounded by the existence of an algal layer (SAL) on the surface of the ISF. Although this problem, which is extreme in finer soils, becomes diminished in coarser soils and sands where the particle sizes and porosities are larger, unsaturated flow was observed to have occurred in the ISF.

When conditions in the laboratory filtration units were such that flow did not occur on a sampling day, a vacuum was applied to the sampling port to withdraw a sample. Even though minimum amounts of vacuum were applied (lowering of port pressure 2 or 3 psi), the samples collected were obviously biased, causing increased amounts of algae to be deposited in the sample. This was evident from observation of the SS on the GF/C glass fiber filters. Normally, these filters would exhibit a very orderly decrease in algae with depth; whereas, when vacuum was applied the SS were more concentrated with algae.

The utilization of a vacuum to draw samples in the laboratory columns was discontinued. If a sampling port did not yield a sample (indicative of unsaturated conditions), the sample was omitted.

Development of Surface Algal Layer

The analytical procedure implemented to quantify the development of the SAL with time was ash weight determination. Ash weight measurements were made for each column in each of the six laboratory scale experimental filter runs. The ash weight analysis quantified the mass of volatile solids present in the SAL at the time of sampling. The entire SAL was removed from the surface of the ISF column and weighed (wet weight). A portion was then removed for chlorophyll determinations and the remainder of the SAL was dried at 103°C (dry weight). This latter portion was then ashed at 550°C (ash weight) and the difference between the dry and ash weights (corrected for the amount removed for chlorophyll) represented the entire mass of SAL present on the column at the time of analysis. The parameter utilized in the model to describe SAL was the value of the SAL per square centimeter of surface area (SALC):

$$\text{SALC} = \text{SAL Mass/Surface Area, mg/cm}^2$$

The selection of this method of quantification of the SAL is discussed in the section dealing with the mass balance equation for the SAL.

All six experimental filter runs were utilized to describe the buildup of SAL with time at different hydraulic loading rates and Css concentrations. In the first two runs, the SAL was scraped and analyzed for ash weight when each column plugged. In runs three through six, the experiments were designed specifically to describe the SAL at times prior to plugging; ash weight measurements were taken at times during the experimental filter run. Because removal of the SAL or a portion of the SAL during an experiment either completely or partially changed the characteristics of the system, when an ash weight measurement was made on a filter, the filter was taken out of service. Experiments three through six were performed on five columns receiving the same SS concentrations and hydraulic loading rates (Table 5).

## Field Phase

Field data collected at three sites (Mount Shasta, California; Ailey, Georgia; and Moriarty, New Mexico) were used in an attempt to validate the ISF model. Data consisted of SS, VSS, TOC, and SOC concentrations at depths within an operating ISF. Influent and effluent values were obtained from samples collected by Russell et al. (1979) in the concurrent ISF field evaluation study.

At the first site visited by the field research team (Mount Shasta, California), samples were taken at depths of 3, 6, and 9 inches (replicated) within the filter bed. This was done to duplicate three of the five port depths studied in the laboratory experiments. Sample depths were altered throughout the field phase on the basis of previous site experience. Development of depth samplers capable of sampling from the surface of the ISF was necessary because the operational scale ISFs were encased in concrete thus negating the possibility of utilizing sampling ports from the sides of the filter units.

The sampler consisted of a 1 1/4 inch diameter PVC pipe capped at the lower end with a permanent point (to allow for easier placement of the sampler into the filter) and a two holed rubber stopper in the upper end to contain an air duct for pressure build-up and release and a vacuum line (Figure 5).

A hole was augered out of the filter sand to the appropriate depth, and the sampler was placed in the hole and any space near the sampler was filled with loose sand. At a distance of 13 inches from the tip was situated a circular recessed strip, 3/8 of an inch wide with 1/4 inch holes bored around the circumference of the sampler (within the strip). The strip was covered with fine mesh screen (0.338 mm holes) to prevent sand from entering the sampler. This screen had a larger mesh than the porosity of the filter so that the screen had no effect upon the quality of the filtrate at that level. Prior to collecting samples with depth, the filter bed was loaded several times to allow the sampler to settle.

Table 5. Influent SS and hydraulic loading rates for laboratory experiments 3-6.

| Experimental Run | Influent SS mg/l | Hydraulic Loading mgad |
|---|---|---|
| 3 | 50 | 0.7 |
| 4 | 75 | 0.7 |
| 5 | 50 | 0.5 |
| 6 | 75 | 0.5 |

In preliminary field studies at Mount Shasta, California, it was observed that only the first wave of filtrate would enter the sampling holes. This occurred such that smaller volumes of samples were collected at the 6 and 9 inch depths (Russell, personal communication, 1977). When the lagoon effluent was applied to the ISF, the direction of flow was one dimensional. A front moved down through the filter and conditions of saturation existed in the area of the frontal wave. As effluent appeared in the collection system of the filter, it was hypothesized that a counter wave of unsaturation moved upward from the bottom and reached an elevation in the filter which was dependent upon the porosity of the filter bed and especially upon the porosity of the SAL and upper layers. As the filter was utilized and deposition increased, problems of unsaturated flow existed. It was the balance between good drainage characteristics (larger porosities) of sand favoring saturated flows and deposition favoring unsaturated flows which determined whether or not samples were collected.

Failure of the samplers to fill resulted in utilization of vacuum equipment to lower the pressure in the sampler 2 or 3 psi to allow filtrate to flow into the sampler. This was accomplished by drawing a vacuum with the pressure valve closed; when the sampler was loaded, the valve was opened and the sample was drawn into the collection flask (Figure 5). Based upon the bias of laboratory data utilizing vacuum techniques, this technique was discontinued in the field study.

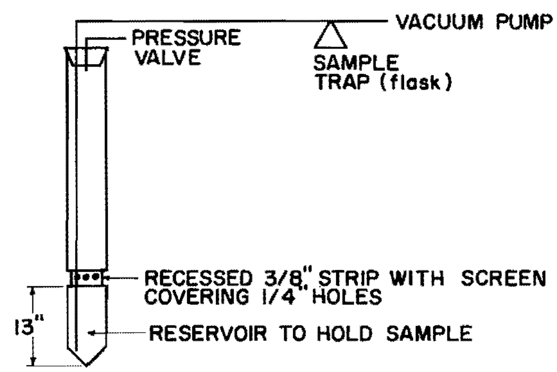



Figure 5. Field sampler for operational ISF.

In order to obtain field data, an attempt was made to slow the flow from the filter with the objective of creating pressure conditions in the filter to allow sample to enter the sampler. This technique produced no positive results and was not utilized. Therefore, as in the laboratory, when unsaturated conditions existed at depths within the field units, samples were not taken.

Because most deposition occurred at the surface, the Mount Shasta sampling was only moderately successful at the lower depths of 6 and 9 inches. Due to the partially saturated and saturated flows which occur in seepage flows (Figure 6) subsequent depth sampling was done only at the upper layers of the filter, i.e., 1.5, 3, and 6 inches.

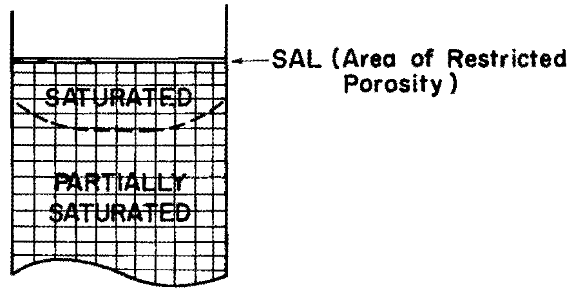



Figure 6. Hypothetical flownet, ISF.

## SECTION III

## MODEL DEVELOPMENT

A detailed literature review of intermittent sand filtration of wastewater is presented by Hill et al. (1977). In the following model development only pertinent literature are referenced. Detailed information on earlier work can be obtained by referring to Hill et al. (1977).

Filtration theory was initially developed when Iwasaki (1937) assumed that the removal of suspended matter (Css) from the filtered fluid was a function of the concentration of the suspended matter.

$$-\frac{\partial Css}{\partial z} = \lambda Css \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which

Css = concentration of measured parameter in fluid being filtered, $ML^{-3}$ or $L^3L^{-3}$ or dimensionless
z = depth, L
$\lambda$ = filter parameter, $L^{-1}$
M = mass
L = length

The filter parameter ($\lambda$) is a measure of filter efficiency (Ives and Sholji 1965) and is variable throughout a filter run. This variability is due to changes in the internal pore geometry of the porous medium (Ives, 1960) and reflects changes in bed porosity, f. In terms of the hydraulics of the system, $\lambda$ is a function of the interstitial or seepage velocity ($\bar{\omega}$) of the filtrate.

Utilization of the basic Iwasaki model yielded the principal assumption of sand filtration theory: the removal of influent suspended solids (Css) from the filtered wastewater results in accumulation of deposits in the pores of the sand filter. It was the development of $\lambda$, to include $\lambda_i$, the clean filter coefficient, and the subsequent modification of $\lambda$ throughout the operation of the filter as a result of the volume of deposited solids per unit volume of filter (specific deposit, $\sigma$) which allowed this model to describe the filtration process.

$$\lambda = \lambda_i + F(\sigma) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

in which

$\lambda_i$ = clean filter coefficient (at $\sigma = 0$), $L^{-1}$
F = function of
$\sigma$ = specific deposit, $L^3L^{-3}$ or dimensionless

The value of $\lambda_i$ depends upon the initial filter bed conditions ($\varepsilon'$, $C_u$, and $f_o$), the system's hydraulics ($\bar{\omega}$), and the influent water quality (Css, T), in which

$\varepsilon'$ = effective sand size; $D_{10}$, the diameter of sieve opening through which 10 percent of the sand passes, L
$C_u$ = uniformity coefficients; $D_{60}/D_{10}$ (the diameter of sieve through which 60 percent of the sand passes)/$\varepsilon'$, dimensionless
$f_o$ = clean filter porosity, dimensionless
$\bar{\omega}$ = interstitial or seepage velocity, $Lt^{-1}$
T = temperature

When $\lambda$ is plotted versus time of filtration, initially $\lambda$ increases linearly with $\sigma$ (Iwasaki 1937, Stein 1940):

$$\lambda = \lambda_i + c\sigma \qquad c = \text{filter coefficient} \quad . \quad (9)$$

In the later stages of filter operation, when increased accumulated deposits exist in the sand filter, $\lambda$ will begin to decrease with increased $\sigma$ (Ives 1960):

$$\lambda = \lambda_i + c\sigma - \frac{\phi\sigma^2}{f_o - \sigma}, \quad \phi = \text{filter coefficient} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The clean filter porosity, $f_o$, was measured directly at the start of the filter run. The constants ($\lambda$, c, and $\phi$) were empirically determined from laboratory data. The filter parameter, $\lambda$, as defined in Equation 10, is a function of specific deposit.

The Ives (1960) model is combination of Equations 7 and 10):

$$-\frac{\partial Css}{\partial z} = \lambda Css = \left(\lambda_i + c\sigma - \frac{\phi\sigma^2}{f_o - \sigma}\right) Css \quad . \quad (11)$$

and was developed in the laboratory under ideal conditions consisting of the following:

1. Influent SS constant and uniform with time
2. Uniform size influent particles
3. Uniform filter medium, nonstratified
4. Constant temperature
5. Constant flow

It was the rigorous maintenance of these ideal conditions which allowed Ives to develop the empirical relationships used in his rapid sand filtration model.

Computations involving the above differential equation (Equation 11) in combination with the continuity equation (Equations 12, 13, 14) for the system resulted in completion of the model. The continuity equation describes the equality between the change in concentration of fluid being filtered and the accumulation of deposit (Ives 1960):

$$-\partial Css\ Q\ \partial t = \partial\sigma\ A\ \partial z \quad . . . . . . (12)$$

in which

$Q$ = flow rate, $L^3t^{-1}$
$t$ = time, t
$A$ = surface area, $L^2$

Rearranging

$$\frac{\partial\sigma}{\partial t} = -\frac{Q}{A}\frac{\partial Css}{\partial z} \quad ; \quad \text{setting } \vec{V} = Q/A \quad . (13)$$

$$\frac{\partial\sigma}{\partial t} = -\vec{V}\frac{\partial Css}{\partial z} \qquad \vec{V} = \text{velocity vector} \quad . (14)$$

The velocity vector represents the daily hydraulic load to the filter, and the units are $Lt^{-1}$. The basic Ives model, as written, is a steady state model which does not include a biological activity term. The steady state assumption is that the concentration of material within the pores of the sand filter does not change with time; or, $(\partial Css/\partial t)$ is zero.

$$\frac{\partial\sigma}{\partial t} = -\vec{V}\frac{\partial Css}{\partial z} + (f-\sigma)\cancelto{0}{\frac{\partial Css}{\partial t}} \quad . . . . (15)$$

The ISF differs from a rapid sand filter in that lagoon effluents are intermittently loaded to the system, and there are periods each day when lagoon effluents are not present on the filter surface. Also, the water is not forced through the filters by increasingly larger heads as the filter run proceeds. As a result, a definite surface algal layer (SAL) develops on the ISF. This layer essentially divides the ISF into two basic areas of activity: SAL and sand. The SAL and those processes which occur within the SAL will be used to formulate the first portion of the ISF model. The sand phase of the model will be described in terms of the Ives model with an added biological activity term.

In the Ives rapid sand filtration system (and in the sand phase of the ISF), as the operation of the filter proceeds, specific deposits ($\sigma$) occurred at different rates within the different layers of sand. Classically, the $\sigma$ versus depth relationship is shown graphically in Figure 7 (Ives 1961). Most of the deposit occurred near the surface of the sand. The sand filter, which is initially homogeneous in character, develops layers of different permeability during filter operation. Because laminar flow conditions exist in the filter system and because of the surface tension of water, the filtered wastewater will proceed through the filter at the same rate at all depths at any time, t. This rate is described by the velocity term, $\vec{V}$.

The continuity equation (Equation 14) can be integrated directly to obtain $\sigma_2$, the specific deposit at any time $t_2$, when $\sigma_1$, the specific deposit at the previous time step, $t_1$ is known.

$$\frac{\partial\sigma}{\partial t} = -\vec{V}\frac{\partial Css}{\partial z} \quad . . . . . . . . . (16)$$

$$\sigma_2 = \sigma_1 - \vec{V}\int_{t_1}^{t_2} (\Delta Css/\Delta z)\,dt \quad . . . . (17)$$

Therefore, $\sigma$ can be calculated for each time and depth. Utilizing the data thus obtained for $\sigma$, the empirical determination of the filter parameter $\lambda$(in terms of its coefficients $\lambda_i$, c, and $\phi$) is accomplished by

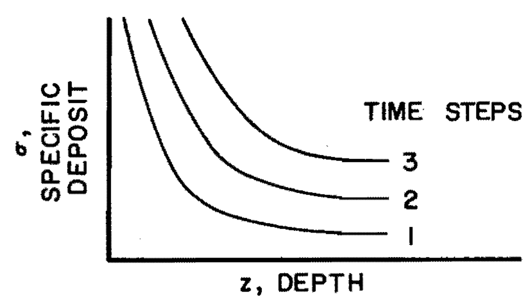



Figure 7. Specific deposit as a function of depth within the sand filter system.

combining the basic model (Equation 7) and the continuity equation (Equation 14):

$$-\frac{\partial Css}{\partial z} = \lambda Css \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$\frac{\partial \sigma}{\partial t} = -\vec{V}\frac{\partial Css}{\partial z} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

therefore

$$\frac{\partial \sigma}{\partial t} = \vec{V}\lambda\ Css \text{ or } \lambda = \frac{1}{\vec{V}Css}\frac{\partial \sigma}{\partial t} \quad . \quad . \quad . \quad (18)$$

To solve for the filter parameter $\lambda$, Ives (1960) plotted $\sigma$ versus time for each layer of sand in order to determine $\partial\sigma/\partial t$ for each time and depth. Given $\sigma$ and time coordinates throughout the filter run, the slope at any time can be calculated utilizing numerical techniques. The hydraulic loading rate ($\vec{V}$, centimeters of lagoon effluent applied/day) and Css (the concentration of solids entering any sand layer) are known. Css for the surface layer of sand is the Css of the influent sewage. The Css values from each subsequent sand layer are measured and $\lambda$ is calculated directly from Equation 18.

To evaluate the filter coefficients ($\lambda_i$, c, and $\phi$), $\lambda$ is plotted versus $\sigma$ for each level (Figure 8). The clean filter efficiency coefficient, $\lambda_i$, is the $\lambda$ value at $t = 0$ (determined by extrapolation of the relationship back to $\sigma = 0$). The coefficient c is defined as $\partial\lambda/\partial\sigma$ at $t = 0$. With $\lambda_i$, $f_o$, c, $\sigma$, and $\lambda$ known, $\phi$ is calculated directly from Equation 19:

$$\phi = \frac{(\lambda_i + c\sigma - \lambda)(f_o - \sigma)}{\sigma^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

The coefficients which describe $\lambda$ are known and the Ives model, which describes the decrease in Css with depth as a function of influent Css, is now complete:

$$-\frac{\partial Css}{\partial z} = \lambda Css = \left(\lambda_i + c\sigma - \frac{\phi\sigma^2}{f_o - \sigma}\right) Css \cdot \quad . \quad (11)$$

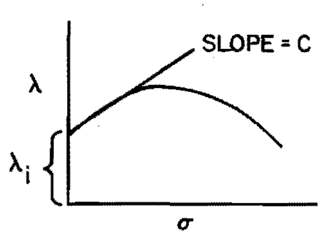



Figure 8. Ives' filter efficiency term as a function of specific deposit.

Once the SAL has been described, the concentration of solids, Css, going onto the sand portion of the ISF can be determined. The Ives rapid sand filtration model will be modified to include the biologically active elements present in the sand portion of the ISF. Having quantified the biological activity term, the sand phase filter efficiency term can be determined and its value plotted versus time in operation for each layer.

## Porosity

The approach velocity (W, discharge velocity) defined as the rate at which fluid approaches the surface of the sand, is a parameter that is easily measured in filtration systems. A functional relationship between porosity (f) and approach velocity (W) can be developed, and this relationship can be used to describe the porosity at any time during the filtration run in terms of measured approach velocity.

Harr (1962) defines W as the quantity of fluid which percolates through a unit area of porous medium per unit time. The approach velocity is the product of the porosity of the medium and the seepage velocity ($\bar{\omega}$, interstitial velocity):

$$W = f * \bar{\omega} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Groundwater seepage principles were used to develop a solution for the seepage velocity. The seepage velocity ($\bar{\omega}$) is difficult to measure during a filter run without destroying part of the filter bed, but the approach velocity (W) is easily measured. By using the relationship (Equation 20) between seepage velocity and the porosity at any time, t, it is possible to express $\bar{\omega}$ in terms of W.

ISF determinations assume one dimensional flow (in the vertical, z, direction). The approach velocity at any time, t, is a function of the porosity and the permeability of the medium (Harr 1962). The relationship is expressed in Equation 21:

$$\frac{dW}{dt} = -\frac{gf}{K}W \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

in which

g = gravitational constant, Lt-2
K = coefficient of permeability, Lt-1

The coefficient of permeability, K, is a function of temperature because of fluid viscosity considerations (Equation 22):

$$K = k_o \frac{\gamma_w}{\mu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

in which

$k_o$ = physical permeability, $L^2$
$\gamma_w$ = specific weight of water, $\mathcal{F}L^{-3}$
$\mu$ = dynamic viscosity, $\mathcal{F}tL^{-2}$, $Mt^{-1}L^{-1}$
$\mathcal{F}$ = force

$k_o$ depends upon the structural characteristics of the sand. Any temperature changes noted required that corrections for K be made.

Integration of Equation 21 results in the determination of f/K at any time, t (Equation 23):

$$\int_{W_o}^{W_t} \frac{dW}{W} = -g\int_{t=0}^{t} \frac{f}{K}\, dt$$

$$\ln \frac{W_t}{W_o} = -\frac{gf}{K}(t)$$

$$f/K = \ln \frac{W_o}{W_t} / gt \quad . . . . . . (23)$$

In order to obtain porosity in terms of approach velocity, Darcy's Law (Equation 24) is implemented:

$$W = Ki = -K\frac{\partial h}{\partial z} \quad . . . . . . . . (24)$$

in which:

i = hydraulic gradient, $-\partial h/\partial z$

Rearranging Equation 24 and substituting it into Equation 21 yields an expression for the change in approach velocity in terms of the variables porosity and hydraulic gradient (Equation 25)

$$\frac{\partial W}{\partial t} = gf\frac{\partial h}{\partial z} \quad . . . . . . . . . . (25)$$

The hydraulic gradient in these formulations is constant. To define the hydraulic properties of the system, the Carman-Kozeny equation (Rich 1961) was utilized (Equation 26):

$$\frac{dh}{dz} = r^{3/4}\,\frac{(1-f)}{f^3}\,\frac{W^2}{g\varepsilon'\phi} \quad . . . . . . (26)$$

in which

$\varepsilon'$ = effective particle size
$\phi$ = shape factor
r = friction factor

Collecting all the constants and equating them for a new constant $\alpha$:

$$\frac{dh}{dz} = \alpha\,\frac{(1-f)}{f^3}\,W^2 \quad . . . . . . . . (27)$$

At t = 0, the porosity is the clean filter porosity $f_o$ and the approach velocity is $W_o$. At any time t, the porosity is $f_t$ and the approach velocity is $W_t$; the quotient of the two gradients is unity (at t = 0 and t = t):

$$\frac{\dfrac{dh}{dz} = \alpha\dfrac{(1-f_o)}{f_o^{\,3}}W_o^{\,2}}{\dfrac{dh}{dz} = \alpha\dfrac{(1-f_t)}{f_t^{\,3}}W_t^{\,2}} = 1 \quad . . . . . . (28)$$

Therefore,

$$\left(\frac{W_t}{W_o}\right)^2 = \left[(1-f_o)/f_o^{\,3}\right]\left[f_t^{\,3}/(1-f_t)\right] \quad . . . (29)$$

$W_o$ and $f_o$ are constants for a given ISF system (determined prior to filter operation). The porosity at any time t is obtained by using the Newton-Raphson iterative technique to solve Equation 29 (Carnahan et al. 1969):

$$CON = \text{Constant} = (1-f_o)/f_o^{\,3}$$

$$CQ = (W_o/W_t)^2 * CON = \text{constant for each time step}$$

$$1 = CQ\,\frac{f_t^{\,3}}{1-f_t}\ \therefore\ 1 - f_t = CQ\,f_t^{\,3}\ \therefore\ CQ\,f_t^{\,3} + f_t - 1 = 0 \quad . . . . . . . (30)$$

Set function G = CQ $f_t^3$ + $f_t$-1. Differentiating G with respect to porosity at any time t, and $f_t$

$$DERIV = \frac{dG}{df_t} = 3\,CQ\,f_t^{\,2} + 1 \quad . . . . . (31)$$

Iterating until consecutive determinations of porosity differ by less than some error function (i.e., < 10-6), porosity at any time t is determined:

$$f_{t_{i+1}} = f_{t_i} - \frac{G}{DERIV} \quad . \; . \; . \; . \; . \; . \; (32)$$

$$ERROR = ABSOLUTE\ VALUE\ (f_{t_{i+1}} - f_{t_i})$$

where the subscript i indicates the iteration number. This procedure allows calculation of porosity at any time t utilizing the known hydraulic parameter of approach velocity.

## Porosity Definitions

1. Porosity (f) is defined as the volume of voids ($\forall_v$) divided by the total volume ($\forall_t$) where $\forall_t$ equals $\forall_v$ plus the volume of solids ($\forall_s$):

$$a. \quad f = \frac{\forall_v}{\forall_t} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (33)$$

$$b. \quad \forall_v + \forall_s = \forall_t \quad . \; . \; . \; . \; . \; . \; . \; . \; (34)$$

$$c. \quad \frac{\forall_v}{\forall_t} + \frac{\forall_s}{\forall_t} = 1 \quad . \; . \; . \; . \; . \; . \; . \; . \; (35)$$

2. Packing Factor (P.F.) is defined as the decimal percent of $\forall_t$ which is taken up by solids:

$$d. \quad P.F. = \frac{\forall_s}{\forall_t} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (36)$$

Therefore, substituting a and b into c gives

$$f + P.F. = 1 \quad \text{or} \quad P.F. = (1-f) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (37)$$

## Model Variables

In order to completely describe the variation of algal biomass applied to the filter, hydraulic loading rates as well as SS concentration levels were considered; therefore, the second variable in the study was hydraulic loading. In recent studies involving the upgrading of lagoon effluents utilizing the ISF system, Clark (1977) concluded that it was the mass loading and not the hydraulic loading which affected filter effluent quality. The product of VSS and Q terms yields a single process variable of daily mass loaded (DML). If the ISF were to function uniformly for a range of DML values, coefficient(s) could be developed which would describe performance of the ISF system in any given mass loading range. This mass loading concept would greatly simplify the development of the model and would allow prediction of performance of any ISF system within the ranges so defined.

## Basis for Model

The ISF model was formulated in two stages because the ISF system consists of two distinct regions: the surface algal layer (SAL) and the sand. The SAL portion of the model was described utilizing data gathered in the six experimental (laboratory scale) filter runs completed in this research. The sand portion of the model was described utilizing Ives rapid sand filter model as a template. Data gathered in the laboratory were used to develop the biological activity term completing the description of the sand phase of the ISF system.

## Surface Algal Layer Model

The functional relationship which described the buildup of SAL with time of filter operation was developed as a function of accumulated mass loaded (AML). The individual experimental units were loaded at a constant rate (mg/ℓ VSS and mgad hydraulic loading rate) for each experiment; therefore, the variable time is the same as AML for the laboratory units (differing only by a conversion factor: time * daily mass loaded = accumulated mass loaded). In order to describe any ISF system (not just those systems which had the same daily mass loadings as the laboratory scale units), it was necessary to choose AML as the independent variable. Daily mass loaded (DML) values were calculated by averaging the input VSS concentration in mg/ℓ ($C_{IN}$) to each column over each experimental filter run:

$DML = C_{IN}*DLOAD$, where DLOAD represents the daily hydraulic loading in liters (ℓ)

. . . . . . . . . (38)

Pertinent SAL data for each column operated in the laboratory phase of the research are listed in Table 6.

When SALC was plotted versus AML and the data were grouped according to ranges of daily mass loaded (DML), a functional relationship of the same form as a saturation function (Equation 39) was obtained.

$$SALC = (SK1 * AML)/(SK2 + AML) \quad . \; . \; . \; . \; (39)$$

in which

| | | |
|---|---|---|
| SALC | = | surface algal layer, mg/cm2 |
| SK1 | = | accumulation function, mg/cm2 |
| SK2 | = | accumulated mass loaded at one-half the maximum SALC, mg |
| AML | = | accumulated mass loaded, mg |
| * | = | multiplication symbol |

The ranges of DML finally selected were based upon the appearance of a functional relationship between SALC and AML (Table 7).

Because Ranges II and III gave approximately the same relationship, these data were grouped together yielding Range II-III consisting of laboratory DML values of 279-687 mg/column/day (Figure 9). At the lower mass loadings (Range I), the data were scattered, but because Range II-III data (19 out of 29 data points) resulted in the saturation type function, the same functional form was utilized for Range I data (Figure 10). Grouping all data (29 data points plus the origin) and applying the saturation type function yielded the single relationship which could be used to describe SALC as a function of AML (Figure 11). Therefore, a single set of coefficients (SK1 and SK2) described SALC in terms of AML for all ISF loadings between 9 and 45 grams/m$^2$/day. The coefficients were developed utilizing an algorithm designed to approximate coefficients for systems of nonlinear equations (Beltrami 1970).

The coefficients (SK1 and SK2) quantifying the saturation type function (Equation 39) are listed in Table 8. On the flat portion of the curve (Figures 9-11), where dSALC/dAML approaches 0, biological processes (i.e., decay) balance any deposition of solids to the SAL such that the net change in SALC is zero. It must be emphasized that this phenomenon (mass deposited = mass decayed) will never occur because the filter will plug prior to this condition.

The laboratory data summarized in Table 6 and shown in Figures 9 - 11 represent all the experimental SAL ash weight data except for experiment 1, column 9. This column was loaded at 99 mg/day and developed only 4.5 mg/cm$^2$ SALC after 93 days of filter operation. It was hypothesized at the completion

Table 6. Surface algal layer (SAL) mass data.

| Filter Run | Column No. | Daily Mass Loaded mg | Parameters at Time of SAL Measurement: Time days | Accumulated Mass Loaded, mg | SALC mg/cm$^2$ |
|---|---|---|---|---|---|
| 1 | 1 | 687 | 23 | 15790 | 28.0 |
| | 2 | 499 | 36 | 17960 | 22.3 |
| | 3 | 251 | 60 | 15060 | 33.5 |
| | 4 | 468 | 50 | 23400 | 26.5 |
| | 5 | 335 | 51 | 17060 | 23.1 |
| | 6* | 165 | 93 | 15390 | 14.9 |
| | 7 | 286 | 50 | 14300 | 21.0 |
| | 8 | 201 | 55 | 11040 | 31.2 |
| | 9* | 99 | 93 | 9230 | 4.5 |
| 2 | 1 | 551 | 15 | 8265 | 11.8 |
| | 2 | 551 | 21 | 11571 | 17.5 |
| | 3 | 355 | 16 | 5680 | 9.4 |
| | 4 | 366 | 21 | 7686 | 12.5 |
| | 5 | 394 | 31 | 12214 | 19.5 |
| | 6 | 272 | 66 | 17952 | 32.3 |
| | 7 | 272 | 73 | 19856 | 32.7 |
| | 8 | 250 | 46 | 11500 | 13.2 |
| | 9* | 163 | 55 | 8965 | 10.3 |
| 3 | 1 | 423 | 5 | 2115 | 3.8 |
| | 2,3 | 423 | 8 | 3384 | 6.9 |
| | 4,5 | 423 | 9 | 3807 | 9.6 |
| 4 | 4 | 455 | 3 | 1365 | 6.6 |
| | 2,8 | 455 | 6 | 2730 | 9.4 |
| | 3 | 455 | 8 | 3640 | 10.6 |
| | 1 | 455 | 11 | 5005 | 16.8 |
| 5 | 3 | 263 | 7 | 1841 | 8.4 |
| | 5 | 263 | 10 | 2630 | 13.1 |
| | 8,9 | 263 | 20 | 5260 | 18.9 |
| 6 | 4 | 391 | 4 | 1564 | 8.8 |
| | 1,2,3 | 391 | 7 | 2737 | 9.0 |

*Due to time constraints in the labortory phase, columns 6 and 9 (Run 1) and column 9 (Run 2) were terminated prior to plugging.

of experimental filter run 1 that the lower DML units would perform for periods of time exceeding the time constraints for the research; therefore, it was decided to eliminate the lower DML from further study. Differentiating the saturation function (Equation 39) with respect to AML, an exact solution for the rate of change of SALC as a function of AML was obtained (Equation 40):

$$\frac{dSALC}{dAML} = (SK1 * SK2)/(SK2 + AML)^2 \quad . \quad . \quad . \quad . \quad . \quad (40)$$

Since,

$$AML = t * DML = t * (C_{IN} * DLOAD) \quad . \quad . \quad (41)$$

then,

$$dAML = dt * (C_{IN} * DLOAD) \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

therefore,

$$d\,\frac{SALC}{dt} = d\,\frac{SALC}{dAML} * C_{IN} * DLOAD \quad . \quad . \quad . \quad . \quad . \quad (43)$$

$$d\,\frac{SALC}{dt} = \frac{(SK1 * SK2)}{(SK2 + AML)^2} * C_{IN} * DLOAD \quad . \quad . \quad . \quad (44)$$

## Mass Balance Equation--Surface Algal Layer

The rate of change of SAL mass with time was equated to the difference between the mass flux in the lagoon effluent flow as it passed through the SAL and the rate at which

Table 7. Data groupings for saturation function (SALC as a function of AML).

| Range of DML | | | Experimental Filter Run - Column | No. of Columns in Group |
|---|---|---|---|---|
| No. | Laboratory Scale mg/column/day | Field Scale $g/m^2$/day | | |
| I | 131-279 | 9-18 | 1-3, 1-6, 1-8, 2-6, 2-7, 2-8, 2-9 Run 5, omitted 1-9 | 10 |
| II | 279-408 | 18-27 | 1-5, 1-7, 2-3, 2-4, 2-5 Run 6 | 7 |
| III | 408-687 | 27-45 | 1-1, 1-2, 1-4, 2-1, 2-2 Runs 3 and 4 | 12 |

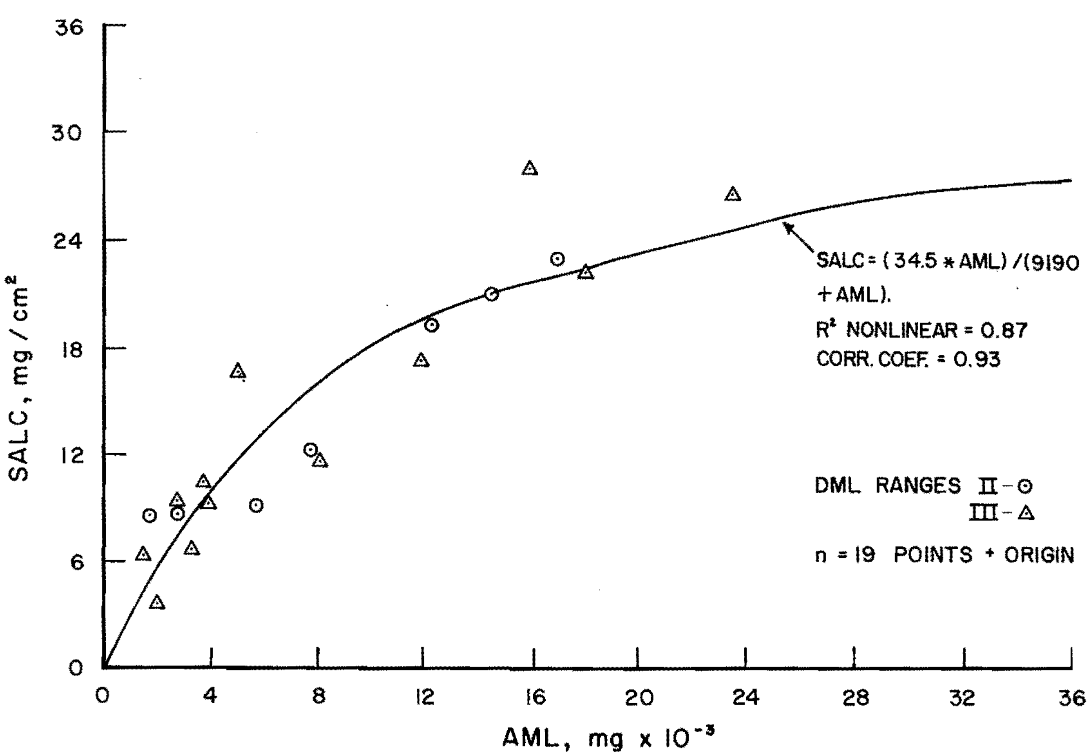



Figure 9. SALC as a function of AML.

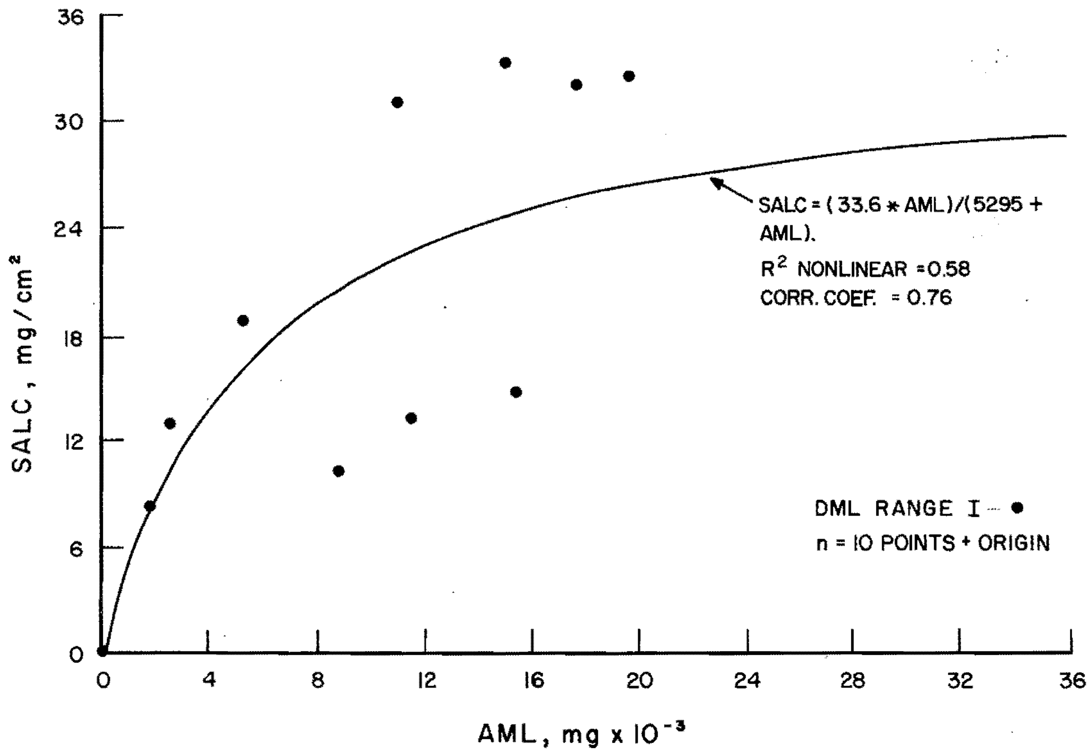



Figure 10. SALC as a function of AML.

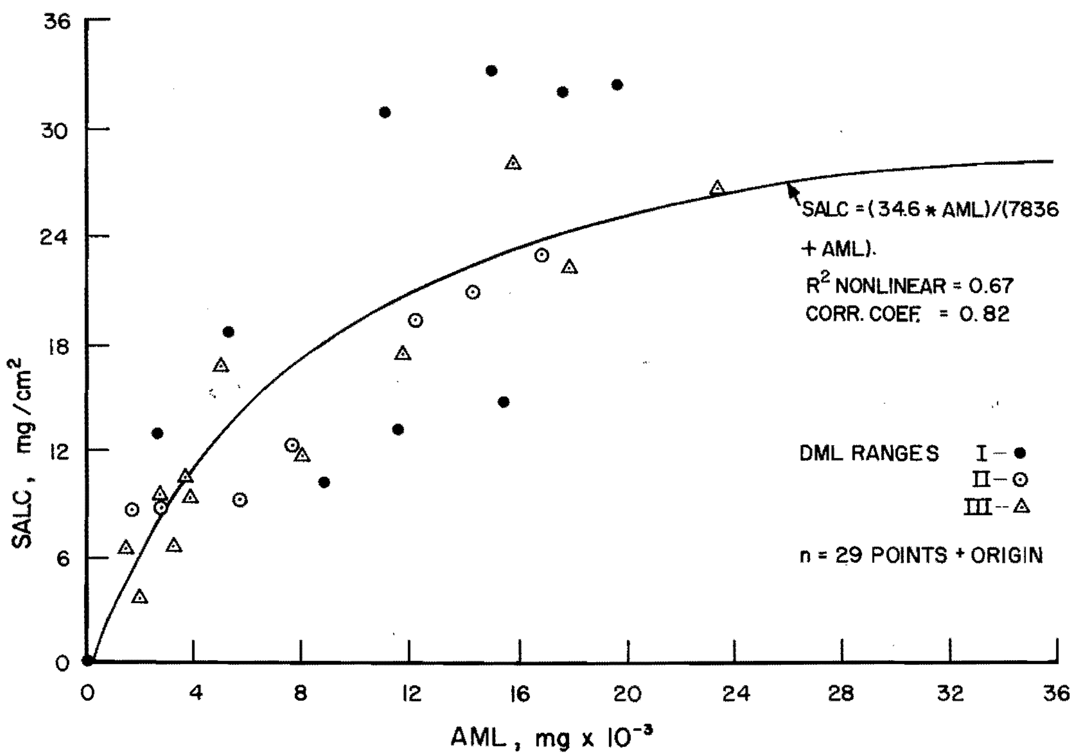



Figure 11. SALC as a function of AML.

Table 8. Saturation function (SALC as a function of AML).

| DML Range No. | DML Range Mass Loaded mg loaded/ column/day | No. of Data Points | SK1 mg/cm$^2$ | SK2 mg loaded | $R^2$ Nonlinear |
|---|---|---|---|---|---|
| II,III | 279-687 | 19 + origin | 34.5 | 9190 | 0.87 |
| I | 131-279 | 10 + origin | 33.6 | 5295 | 0.58 |
| I,II,III | 131-687 | 29 + origin | 34.6 | 7836 | 0.67 |

the mass of SAL was biologically decayed (Equation 45). This is shown schematically in Figure 12.

$$d\,\frac{C*\forall}{dt} = Q*(C_{IN} - C_{OUTF})*10^{-3} - cd*C*\forall \quad \text{(mg/day)} \qquad (45)$$

in which

Q = rate of flow of lagoon effluent through the SAL, cm$^3$/day
C = concentration of SAL, mg/cm$^3$
$\forall$ = volume of SAL, cm$^3$
$C_{IN}$,$C_{OUTF}$ = SAL influent and effluent [VSS], mg/ℓ
cd = decay coefficient, day$^{-1}$
$10^{-3}$ = ℓ/cm$^3$
ΔxΔy = surface area of SAL, cm$^2$
Δz = depth of SAL, cm

It was assumed in this simplified mass balance expression that net biological growth does not occur in the SAL. Net biological growth herein is defined as an overall increase in the mass of the SAL due to biological mechanisms. Because of the alternating wet and dry conditions in the SAL, it is reasonable to assume that growth within the SAL will be balanced by the losses during the drying cycle. SAL is biologically described in terms of only algal and bacterial activity. Algal growth is only possible at the surface of the SAL due to light limitations within the SAL. Light is limiting to the surface algae when the dense algal suspension is above the ISF during loading. Between loadings when there is no lagoon effluent on the filter, lack of adequate moisture on the surface layer prevents any algal growth. Bacterial activity, although not quantified, definitely occurs within the SAL. However, such activity results in a decrease in SAL mass since substrates utilized by the bacteria consist partly of the algae present within the SAL. It was assumed that the

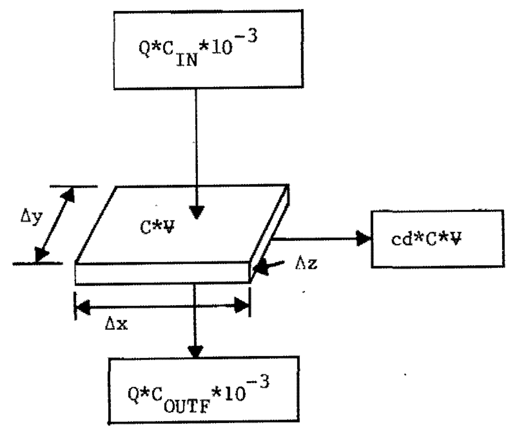



Figure 12. Schematic of SAL mass balance equation.

bacterial population increase due to uptake of soluble organic carbon from the lagoon effluent was negligible.

Model development includes certain definitions and simplifying assumptions:

$$d\,\frac{C*\forall}{dt} = Q * (C_{IN} - C_{OUTF}) * 10^{-3} - cd * C*\forall$$

$\forall = \Delta x \Delta y \Delta z$

$\Delta x \cdot \Delta y$ = Area, constant with respect to (w.r.t.) time

$\Delta z = \delta$, thickness SAL

$\Delta z'$ = depth of sewage lagoon effluent applied

$$d\,\frac{C*\forall}{dt} = Q*(C_{IN} - C_{OUTF})*10^{-3} - cd*C*\forall$$

$$d\,\frac{\Delta x\Delta y\Delta z \cdot C}{dt} = \frac{\Delta x\Delta y \cdot \Delta z'}{day}\,(C_{IN} - C_{OUTF})*10^{-3} - cd*\Delta x\Delta y\Delta z \cdot C$$

$$d\,\frac{\delta \cdot C}{dt} = \frac{\Delta z'}{day} * (C_{IN} - C_{OUTF}) * 10^{-3} - cd*\delta*C \qquad (46)$$

Del ($\delta$), the thickness of the SAL is variable with time. An expansion of the left hand side of the mass balance equation (Equation 46) would be:

$$\frac{\delta dC}{dt} + \frac{Cd\delta}{dt}$$

To avoid this additional term in the equation, the definition of SALC in terms of $mg/cm^2$ is introduced:

$$SALC,\ mg/cm^2 = \delta * C \quad . \ . \ . \ . \ . \ . \ . \ (47)$$

The daily hydraulic load (DHL) in cm of lagoon effluent applied per day is described by $\Delta z'$/day; therefore, the mass balance expression becomes Equation 48. This is shown schematically in Figure 13.

$$d\ \frac{SALC}{dt} = DHL * (C_{IN} - C_{OUTF}) * 10^{-3} - cd * SALC$$

$$(mg/cm^2/day) \quad . \ . \ . \ . \ . \ . \ . \ (48)$$

$C_{OUTF}$, the final concentration of sewage VSS out of the SAL is the only unknown in this formulation, since dSALC/dt and SALC are known at any time t (from SALC versus AML saturation function, Equation 39). Solving Equation 48 for $C_{OUTF}$ yields:

$$C_{OUTF} = C_{IN} - \left[\frac{dSALC}{dt} + cd*SALC\right] \frac{10^3}{DHL}$$

$$. \ . \ . \ . \ . \ . \ (49)$$

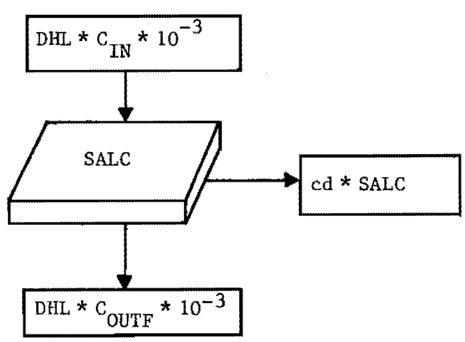



Figure 13. Schematic of SAL mass balance equation in terms of $C_{OUTF}$.

Expressed in terms of the variable AML:

$$C_{OUTF} = C_{IN} - \left(\frac{dSALC}{dAML} * C_{IN} * DLOAD + cd * SALC\right) * \frac{10^3}{DHL}$$

$$. \ . \ . \ . \ . \ . \ (50)$$

in which dt = dAML/($C_{IN}$*DLOAD); therefore,

$$C_{OUTF} = C_{IN} - C_{IN} * \frac{dSALC}{dAML} * DHL * AREA * 10^{-3} * \frac{10^3}{DHL}$$

$$- \frac{cd * SALC * 10^3}{DHL} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ (51)$$

in which DLOAD = DHL*AREA*10-3

$$C_{OUTF} = C_{IN} * \left[1 - \left(\frac{dSALC}{dAML}\right) * AREA\right] - \frac{cd * SALC * 10^3}{DHL}$$

SAL MODEL. . . . . . . . . . . (52)

Equations 49 and 52 deal with the SAL as a "black box," in other words, no attempt is made to determine what processes are actually occurring within the SAL. Two methods were developed which estimated the value of cd to be utilized as an initial guess for this coefficient in model calibration. The first method elaborated upon the physical and biological mechanisms inherent in the SAL. Two additional terms were included in Equation 48: a physical removal term and a sloughing term. The second method involved a simplified empirical definition of the final VSS concentration out of the SAL. The second method utilized to estimate cd is described in Appendix A. Once the decay coefficient, cd, was defined, it was utilized in the SAL model (Equation 52) to predict $C_{OUTF}$.

## Sand Phase

The sand portion of the model was developed utilizing Ives rapid sand filter model as a template and adding a biological activity component.

$$\frac{d\sigma}{dt} = DHL * (- DCSS/DZ) + \beta ETA * \sigma$$

Basic Model (Sand Phase) . . . . . . . (53)

in which

$\sigma$ = specific deposit in the pore space of the sand,

$\frac{\text{volume of deposit}}{\text{volume of filter}}$ (v/v)

DHL = daily hydraulic load (cm of effluent applied/day)

$-DCSS/DZ$ = the decrease in VSS concentration with depth of filter,

$\frac{\text{volume of algae}}{\text{volume of filtrate}} / \text{cm of layer thickness}$

βETA = biological activity coefficient of sand column, $day^{-1}$

DZ = depth or thickness of sand layer, cm

The basic model (Equation 53) describes the increase in specific deposit with time (or with AML) as the sum of the mass flux term (DHL*[-DCSS/DZ]) and the reaction term (βETA* σ). The model was written such that the reaction term indicates growth if βETA were positive and decay if βETA were negative.

The sand phase filter term (λ, in units of $cm^{-1}$) is defined as the sand phase filtering efficiency normalized by influent VSS concentration in volume/volume to the sand layer:

$$\lambda = -\frac{DCSS/DZ}{CSS_{IN}} \quad \ldots\ldots\ldots (54)$$

or

$$-DCSS/DZ = \lambda CSS_{IN} \quad \ldots\ldots (55)$$

in which

-DCSS = VSS concentration change across sand layer,

$CSS_{IN}$ = VSS concentration into sand layer, volume of algae/volume of filtrate

The solution of the sand phase model involved definition of the biological term βETA and solving directly the basic model (Equation 53) for specific deposit, σ, at each time step. The sand phase filter term (λ, Equation 55) substituted into Equation 53 for a portion of the mass flux term (-DCSS/DZ) yields:

$$\frac{d\sigma}{dt} = DHL * (\lambda * CSS_{IN}) + \beta ETA * \sigma \quad \ldots (56)$$

$$\lambda = (d\sigma/dt - \beta ETA * \sigma)/(DHL * CSS_{IN}) \quad . (57)$$

This λ value was calculated for each filter, each layer, and each time step.

Because of the large number of data points (i.e., columns 6 and 9 ran for 93 days in experiment 1), it was decided to utilize only data developed on sampling days (episodes). Calculations of βETA and subsequent determination of λ involved data generated on sampling days. Filters 1 and 2 had only four episodes, therefore, for these two filter columns, data were taken every other day from day 1 until the day of plugging.

The sand phase of the ISF model was developed utilizing VSS concentration as the parameter which quantifies the change in filtrate mass with time of filter operation. Samples were taken and analyzed for SS, VSS, TOC, and SOC concentrations at 1, 2, 3, and 6 inch depths within the filter in addition to filter influent and effluent. In subsequent analysis of SAL parameter $C_{OUTF}$ (final VSS concentration out of the SAL) it was concluded, since the 1 inch effluent VSS value was consistently greater than the $C_{OUTF}$ value necessary to generate the SALC values from the saturation type function, that the 1 inch effluent values would not be used in the ISF model. The 1 inch values were assumed to be inaccurate due to the fact that it is impossible to sample a laboratory ISF system so close to the surface without obtaining errors due to filtrate entering the 1 inch port directly along the ISF wall (wall effects at shallow depths). The final ISF model was developed using influent, 2 inch, 3 inch, 6 inch, and effluent VSS values. Sand layers were defined as 0-2 inches, 2-3 inches, 3-6 inches, and 6-30 inches (Table 9). The sand phase filter term, λ, was developed for each of the four layers described in Table 9.

Basic Sand Model

$$\frac{d\sigma}{dt} = DHL * (-DCSS/DZ) + \beta ETA * \sigma \quad \ldots (53)$$

$$\frac{d\sigma}{dt} = DHL * (CSS_{IN} - CSS_{OUT})/DZ + \beta ETA * \sigma \quad . (58)$$

Table 9. Sample ports and sand layers utilized in development of the sand phase of the ISF model.

| Port No. | | Depth in. | Depth cm | Sand Layer No. | Boundaries | Thickness in. | Thickness cm | Volume ℓ |
|---|---|---|---|---|---|---|---|---|
| 1 | Influent | 0 | 0 | 1 | 0-2 inches | 2 | 5.08 | 0.778 |
| 2 | | 2 | 5.08 | 2 | 2-3 inches | 1 | 2.54 | 0.389 |
| 3 | | 3 | 7.62 | 3 | 3-6 inches | 3 | 7.62 | 1.168 |
| 4 | | 6 | 15.24 | 4 | 6-30 inches | 24 | 60.96 | 9.344 |
| 5 | Effluent | 30 | 76.20 | | | | (DZ) | |

where $CSS_{IN}$, $CSS_{OUT}$ represent VSS concentrations into and out of the layer being analyzed. The $CSS_{OUT}$ value represents the influent VSS concentration to the layer below. The units of $CSS_{IN}$ and $CSS_{OUT}$ are volume of algae/volume of filtrate. Specific deposit, σ, was determined from a simple difference form of the basic sand model at each time step (Equation 60):

$$\sigma_y - \sigma_x = \frac{DHL * (CSS_{IN} - CSS_{OUT})}{DZ} * DELT + \beta ETA * \sigma_x * DELT \quad . . . . . . (59)$$

or

$$\sigma_y = \sigma_x + \frac{DHL * (CSS_{IN} - CSS_{OUT})}{DZ} * DELT + \beta ETA * \sigma_x * DELT \quad . . . . . . . (60)$$

in which

DELT = dt, the time step, 1 day
$\sigma_x$ = specific deposit at previous time step
$\sigma_y$ = specific deposit at present time step; y = x + DELT
$\sigma_o$ = 0 initial condition of zero specific deposit within pores of ISF at time zero

DHL is known and $CSS_{IN}$ and $CSS_{OUT}$ are measured; therefore, in order to calculate $\sigma_y$, βETA alone remains without quantification.

## βETA, Sand Phase Biological Activity Term

Net biological activity (BAY) of the sand phase of the ISF system is expressed in terms of specific deposit (σ, volume of deposit/volume of filter). Actual biological activity (AAY) is defined as the sum of the individual specific deposits for each layer of the sand phase in any given filter column.

$$AAY = \sum_{i=1}^{4} \sigma_i \quad . . . . . . . . . . . (61)$$

in which

$\sigma_i$ = the specific deposit in layer i
= $(CSSD_i - CSSD_{i+1})$*DHL*DELT/$DZ_i$
i = 1,2,3,4
$CSSD_i$ = influent [VSS] to layer i, volume of algae/volume of filtrate
$CSSD_{i+1}$ = effluent [VSS] from layer i, volume of algae/volume of filtrate
DHL = daily hydraulic load, cm/day
DELT = time step, day
$DZ_i$ = thickness of layer i, cm

Total biological activity (TAY) is defined as the specific deposit to the entire sand column calculated by using column influent ($CSS_{IN}$ to layer 1) and column effluent ($CSS_{OUT}$ of layer 4).

$$TAY = (CSSD_1 - CSSD_5) * DHL * DELT/DEP \quad . . . . . . . . . (62)$$

in which

$CSSD_1$ = sand phase influent [VSS], volume of algae/volume of filtrate
$CSSD_5$ = column effluent [VSS], volume of algae/volume of filtrate
DEP = the depth of the filter, cm

Net biological activity (BAY) is defined as the difference between AAY and TAY.

$$BAY = AAY - TAY \quad . . . . . (63)$$

When these activities were plotted versus time (or AML), all nine filter columns of laboratory experiment 1 yielded the same form (Figure 14).

βETA, the sand phase biological term (units of $day^{-1}$) is the coefficient which describes the rate of change of BAY normalized for AAY with time

$$\frac{dBAY_j}{dt} = \beta ETA * AAY_{j-1} \quad . . . . . . . . (64)$$

where the net activity is described for the present time step, $BAY_j$, and the actual activity is based upon the previous time step, $AAY_{j-1}$. The initial conditions are that the βETA for day 1 is zero.

$$\frac{dBAY_j}{AAY_{j-1}} = \beta ETA * dt \quad . . . . . . . . . (65)$$

Plotting $(BAY_j/AAY_{j-1})$ versus time yielded the slope, βETA. βETA values were calculated utilizing numerical techniques on [$(BAY_j/AAY_{j-1})$, time] data sets. These values for βETA represent column values; therefore, for a given column, the same βETA value will be utilized for all layers within that column in calculating $\sigma_y$ using Equation 60.

βETA values were calculated for each column on a daily basis. In order for βETA to be a coefficient (instead of a variable) it would have to be a constant. βETA values were calculated daily for each column of experimental laboratory filter experiment 1. These daily βETA values were plotted versus time and in all nine plots, βETA values were variable initially and constant thereafter (zero slopes); βETA was therefore assumed to be a coefficient. In order to determine the final value of βETA for each column, mean βETA values were calculated for the episode data (Table 10). These mean βETA values were

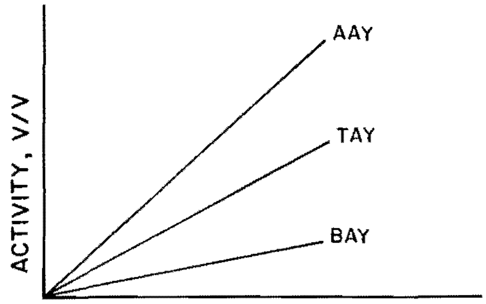



Figure 14. Activity as a function of time.

used in Equation 60 to calculate specific deposit at each time step for each sand layer. Because of the magnitude of these mean βETA values, the reaction term (mean βETA * σ) had a negligible effect upon the specific deposit within the pores of the ISF system. Therefore the reaction term was omitted from the sand phase model leaving the Ives model to describe the decrease in VSS concentration with depth in the ISF.

## Sand Filter Term, λ

Analysis of the impact of mean βETA values upon the sand phase model resulted in deletion of the sand biological activity term (βETA) from the sand phase model.

$$\frac{d\sigma}{dt} = DHL * (- DCSS/DZ) \quad . \ . \ . \ . \ . \ . \ (66)$$

$$\frac{d\sigma}{dt} = DHL * (CSS_{IN} - CSS_{OUT})/DZ \quad . \ . \ (67)$$

$$\sigma_y = \sigma_x + \frac{DHL * (CSS_{IN} - CSS_{OUT}) * DELT}{DZ} \quad . \ (68)$$

$$\frac{d\sigma}{dt} = DHL * (\lambda * CSS_{IN}) \quad . \ . \ . \ . \ . \ . \ (69)$$

$$\lambda = (d\sigma/dt)/(DHL * CSS_{IN}) \quad . \ . \ . \ . \ . \ (70)$$

To use AML in the ISF model, it was necessary to convert from time to AML:

$$dt = \frac{dAML}{DML} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (71)$$

in which

$$DML = \text{daily mass loaded} = C_{IN} * DLOAD = (mg/\ell) * (\ell/day) \quad . \ . \ . \ . \ . \ (38)$$

$$\frac{d\sigma}{dAML} = \frac{1}{DML} * [DHL * (- DCSS/DZ)] \quad . \ . \ . \ . \ (72)$$

$$\sigma_y = \sigma_x + \frac{1}{DML} * \left[\frac{DHL * (CSS_{IN} - CSS_{OUT})}{DZ}\right] * (AML_y - AML_x) \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (73)$$

in which

y is the present time step
x is the previous time step

For day 1:

$$\sigma_1 = \frac{1}{DML} * \left[\frac{DHL * (CSS_{IN} - CSS_{OUT})}{DZ}\right] * AML_1 \quad . \ (74)$$

Substituting $\lambda * CSS_{IN}$ (Equation 55) for a portion of the mass flux term in Equation 72:

$$\frac{d\sigma}{dAML} = \frac{1}{DML} * [DHL * \lambda * CSS_{IN}] \quad . \ . \ . \ . \ (75)$$

Table 10. Mean βETA values for laboratory experimental filter run 1 (initial variable daily βETA values omitted).

| Column | Period Day-Day | Mean βETA $day^{-1}$ | Standard Deviation | Data Points Used All Data | Comments ($BAY_j/AAY_{j-1}$) |
|---|---|---|---|---|---|
| 1 | 5-23 | -.01618 | .03134 | 10/12 | |
| 2 | 5-35 | -.00804 | .0266 | 16/18 | |
| 3 | 16-51 | -.00090 | .00735 | 6/10 | |
| 4 | 13-44 | -.00145 | .00397 | 7/9 | |
| 5 | 16-44 | -.00448 | .00680 | 7/10 | |
| 6 | 6-93 | +.00395 | .03220 | 15/19 | Omitted Days 13,16,20 |
| 7 | 9-44 | -.00125 | .00449 | 7/8 | |
| 8 | 9-44 | -.00433 | .01031 | 7/8 | |
| 9 | 6-93 | -.00409 | .01333 | 18/19 | |

$$\left[\frac{\sigma_y - \sigma_x}{AML_y - AML_x}\right] * \frac{DML}{DHL * CSS_{IN}} = \lambda \quad . \quad . \quad . \quad . \quad (76)$$

Given the definition of DML (Equation 38) and that $CSS_{IN} = C_{IN}/DEN$, the final expression for $\lambda$ in terms of AML becomes:

$$\lambda = \left[\frac{\sigma_y - \sigma_x}{AML_y - AML_x}\right] * \frac{DEN * DLOAD}{DHL} \quad . \quad . \quad . \quad (77)$$

For day 1:

$$\lambda = \left(\frac{\sigma_1}{AML_1}\right) * \frac{DEN * DLOAD}{DHL} \quad . \quad . \quad . \quad . \quad . \quad . \quad (78)$$

where DEN = density of influent algae = density of $\sigma$ = 7.137ε-05 mg dry weight/ℓ wet volume.

Utilizing Equation 68, specific deposit was calculated directly for each column, layer, and day. Plotting $\sigma_y$ versus AML for each column and layer throughout the operation of laboratory filter experiment 1 resulted in a linear increase of $\sigma_y$ in all cases except those summarized in Table 11.

All but three of the eight plots of specific deposit versus AML that did not give a good relationship occurred at sampling Layer 2 indicating that sampling was inaccurate at this point. Difficulty was experienced in obtaining samples from an unsaturated sand. The slopes ($d\sigma/dAML$) for each column and layer were calculated using linear regression analysis. For the exceptions to linearity, the best fit functional relationship was calculated using regression analysis on cubic and quadratic forms. The results of the regression analyses are listed in Table 12, and the plots of the data are represented in Figures 15-23.

Table 11. Summary of filter columns and sand layers not yielding a linear relationship between $\sigma_y$ and AML.

| Filter Column | Sand Layer | Comments |
|---|---|---|
| 2 | 2 | Zero slope, positive slope |
| 3 | 2 | Variable slopes |
| 3 | 3 | Variable slopes |
| 5 | 2 | Variable slopes |
| 6 | 2 | Negative slope |
| 7 | 2 | Negative slope |
| 9 | 3 | Variable slopes |
| 9 | 4 | Variable slopes |

The slopes determined from the regression analyses (Table 12) were substituted into the final expression for $\lambda$:

$$\lambda = \left(\frac{\sigma_y - \sigma_x}{AML_y - AML_x}\right) * \frac{DEN * DLOAD}{DHL} = \frac{SLOPE * DEN * DLOAD}{DHL} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (77)$$

Since DLOAD and DHL were constant loadings to each column of laboratory filter experiment 1, $\lambda$ was constant for each layer exhibiting linear buildup of $\sigma$ (Table 13). In order to obtain consistent units in this expression of $\lambda$, it was again noted that the surface area of the filter and the surface area of the sewage applied were equal.

Arranging the $\lambda$ data from Table 13 in terms of DML ranges, a single set of composite $\lambda$ coefficients could be utilized to describe any ISF system operating within those ranges (Table 14). This final set of $\lambda$ coefficients was determined directly as the mean $\lambda$ value of the individual $\lambda$ values (which exhibited linear increase in $\sigma$ with time of filter operation) within each DML range. The 3 sets of 4 $\lambda$ coefficients listed in Table 14 were utilized as initial estimates of $\lambda$ to predict the effluent values for each layer within the sand phase during model calibration. Filter effluent was predicted as [VSS] out of layer 4.

$$\lambda = \frac{(-DCSS/DZ)}{CSS_{IN}} = \frac{(CSS_{IN} - CSS_{OUT})}{DZ * CSS_{IN}} \quad . \quad . \quad (54)$$

Therefore

$$CSS_{OUT} = CSS_{IN} - \lambda * DZ * CSS_{IN} \quad . \quad . \quad . \quad (79)$$

or

$$CSS_{OUT} = CSS_{IN} * (1. - \lambda * DZ) \quad . \quad . \quad . \quad . \quad (80)$$

$CSS_{OUT}$ may also be expressed as a power function by directly integrating the equation defining $\lambda$:

$$-(DCSS/DZ) = \lambda * CSS_{IN} \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

$$\int_{CSS_{IN}}^{CSS_{OUT}} \frac{DCSS}{CSS_{IN}} = -\lambda * \int_{Z_0}^{Z_1} DZ$$

or

$$\ln \frac{CSS_{OUT}}{CSS_{IN}} = -\lambda * (Z_1 - Z_0)$$

Table 12. Specific deposit versus accumulated mass loaded.[a]

| DML Range | Column (# of Data Points)[b] | Layer | F Ratio | Table Value of $F^d$ at 1% Level | B(0) Constant | B(1) x Coefficient | B(3) $x^2$ Coefficient | B(4) $x^3$ Coefficient | dσ/dAML (SP-SX)/($AML_i$-$AML_{i-1}$) | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| III | 1[c] | 1 | 137. | 6.55 | -.1105ε-03 | .1634ε-06 | | | .1634ε-06 | 0.93 |
| | (13) | 2 | 879. | 6.55 | -.4200ε-04 | .8841ε-07 | | | .8841ε-07 | 0.99 |
| | | 3 | 3044. | 6.55 | .7965ε-05 | .8982ε-07 | | | .8982ε-07 | 1.00 |
| | | 4 | 1348. | 6.55 | -.6925ε-04 | .7520ε-07 | | | .7520ε-07 | 0.99 |
| III | 2[c] | 1 | 3151. | 5.98 | -.4046ε-03 | .4369ε-06 | | | .4369ε-06 | 0.99 |
| | (19) | 2 | B(3) 216. | 5.98 | -.1185ε-03 | | -.1841ε-10 | .1947ε-14 | -.3682ε-10x + .5841ε-14$x^2$ | 1.00 |
| | | | B(4) 639. | 5.98 | | | | | | |
| | | 3 | 1071. | 5.98 | -.6175ε-04 | .1756ε-06 | | | .1756ε-06 | 0.98 |
| | | 4 | 14354. | 5.98 | .7577ε-05 | .4001ε-07 | | | .4001ε-07 | 1.00 |
| III | 4 | 1 | 166. | 7.21 | -.6786ε-03 | .3745ε-06 | | | .3745ε-06 | 0.95 |
| | (10) | 2 | 213. | 7.21 | .2838ε-03 | .1769ε-06 | | | .1769ε-06 | 0.96 |
| | | 3 | 64. | 7.21 | -.2420ε-03 | .8093ε-07 | | | .8093ε-07 | 0.89 |
| | | 4 | 561. | 7.21 | -.4516ε-05 | .5736ε-07 | | | .5736ε-07 | 0.99 |
| II | 5 | 1 | 123. | 6.94 | -.7954ε-03 | .4070ε-06 | | | .4070ε-06 | 0.93 |
| | (11) | 2 | 17. | 6.94 | -.5380ε-03 | .1151ε-06 | | | .1151ε-06 | 0.66 |
| | | 3 | 247. | 6.94 | .3360ε-03 | .2283ε-06 | | | .2283ε-06 | 0.96 |
| | | 4 | 337. | 6.94 | -.3514ε-04 | .2763ε-07 | | | .2763ε-07 | 0.97 |
| II | 7 | 1 | 823. | 7.57 | -.1827ε-03 | .6268ε-06 | | | .6268ε-06 | 0.99 |
| | (9) | 2 | B(1) 67. | 7.57 | .4645ε-04 | -.4350ε-06 | .2618ε-10 | | -.4350ε-06 + .5236ε-10x | 0.94 |
| | | | B(3) 40. | 7.57 | | | | | | |
| | | 3 | 68. | 7.57 | -.6047ε-04 | .7260ε-07 | | | .7260ε-07 | 0.91 |
| | | 4 | 9969. | 7.57 | -.2506ε-05 | .3838ε-07 | | | .3838ε-07 | 1.00 |
| I | 3 | 1 | 112. | 6.94 | -.2912ε-03 | .2614ε-06 | | | .2614ε-06 | 0.93 |
| | (11) | 2 | 0.5 | 6.94 | -.2349ε-03 | | .1467ε-11 | | .2934ε-11x | 0.48 |
| | | 3 | 75. | 6.94 | -.2402ε-04 | | | .3442ε-15 | .1033ε-14$x^2$ | 0.89 |
| | | 4 | 28802. | 6.94 | -.8738ε-06 | .4771ε-07 | | | .4771ε-07 | 1.00 |
| I | 8 | 1 | 53. | 7.57 | -.1142ε-03 | .2765ε-06 | | | .2765ε-06 | 0.88 |
| | (9) | 2 | 203. | 7.57 | -.1027ε-03 | .1826ε-06 | | | .1826ε-06 | 0.97 |
| | | 3 | 1053. | 7.57 | -.6363ε-05 | .1565ε-06 | | | .1565ε-06 | 0.99 |
| | | 4 | 272. | 7.57 | -.1420ε-04 | .3646ε-07 | | | .3646ε-07 | 0.97 |
| | 6 | 1 | 1312. | 5.92 | -.2421ε-03 | .3081ε-06 | | | .3081ε-06 | 0.99 |
| | (20) | 2 | 41. | 5.92 | -.3292ε-03 | -.1691ε-06 | | | -.1691ε-06 | 0.69 |
| | | 3 | 2215. | 5.92 | .7236ε-04 | .2091ε-06 | | | .2091ε-06 | 0.99 |
| | | 4 | 331. | 5.92 | .3648ε-04 | .3989ε-07 | | | .3989ε-07 | 0.94 |
| | 9 | 1 | 8414. | 5.92 | -.1815ε-04 | .7901ε-06 | | | .7901ε-06 | 1.00 |
| | (20) | 2 | 214. | 5.92 | -.3605ε-03 | .3869ε-06 | | | .3869ε-06 | 0.92 |
| | | 3 | B(1) 117. | 5.92 | -.4051ε-04 | .1486ε-06 | | -.1226ε-14 | .1486ε-06 - .3678ε-14$x^2$ | 0.90 |
| | | | B(4) 60. | 5.92 | | | | | | |
| | | 4 | B(1) 663. | 5.92 | -.1437ε-04 | .3801ε-07 | | -.2745ε-15 | .3801ε-07 - .8235ε-15$x^2$ | 0.98 |
| | | | B(4) 259. | 5.92 | | | | | | |

[a]Data represent episode (sampling day) values for specific deposit and AML.

[b]# Data Points includes origin: Day 0, Specific Deposit = AML = 0.0.

[c]Columns 1 and 2 only had 4 episodes; therefore data, DAY = 1, TMAX, 2.

[d]Standard Mathematical Tables, 1972, S. M. Selby, editor, The Chemical Rubber Co. 705 p.

[e]Read as $-0.1105*10^{-3}$ and $0.1634*10^{-6}$.

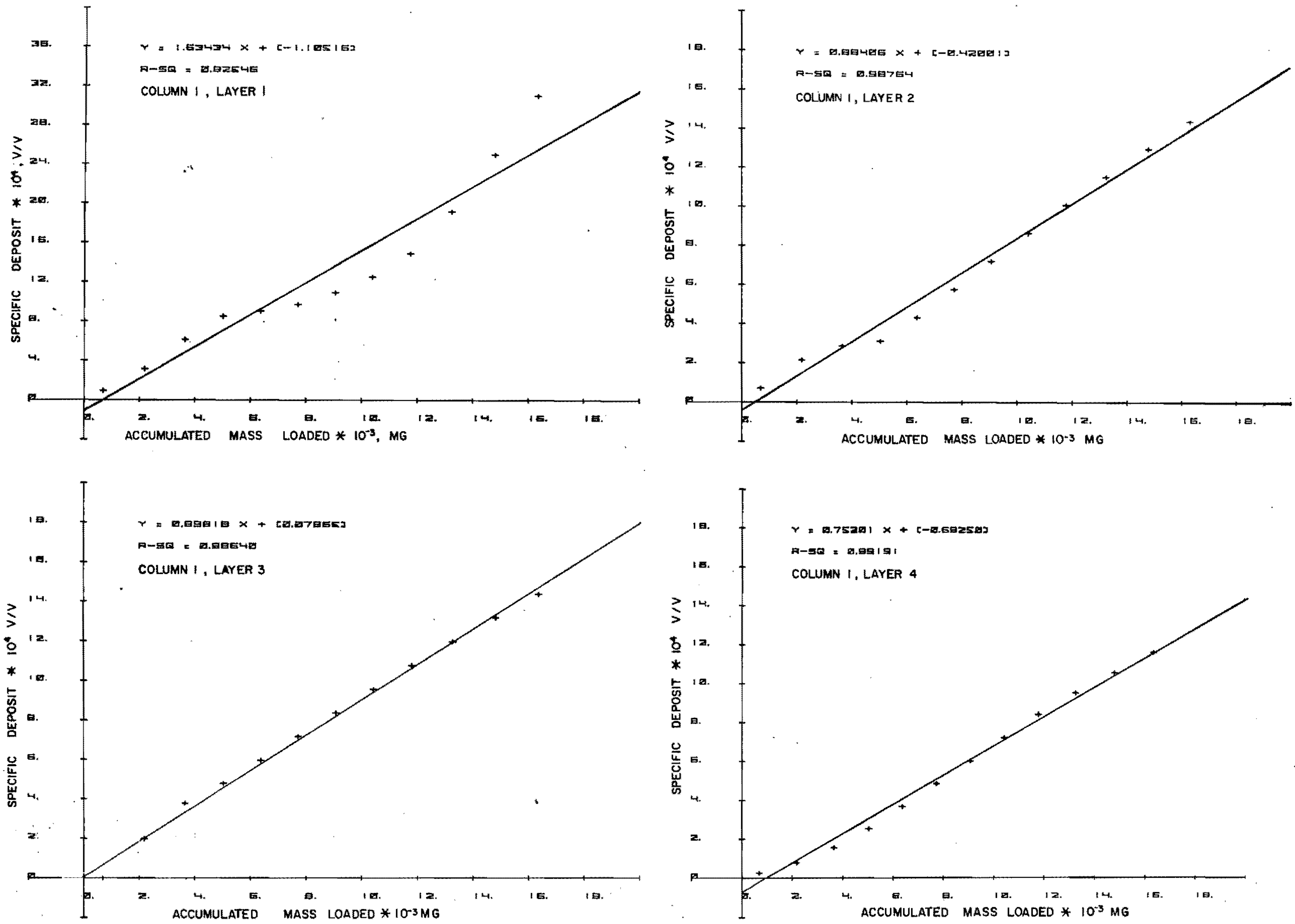



Figure 15. Individual layer specific deposits for column 1 as a function of AML.

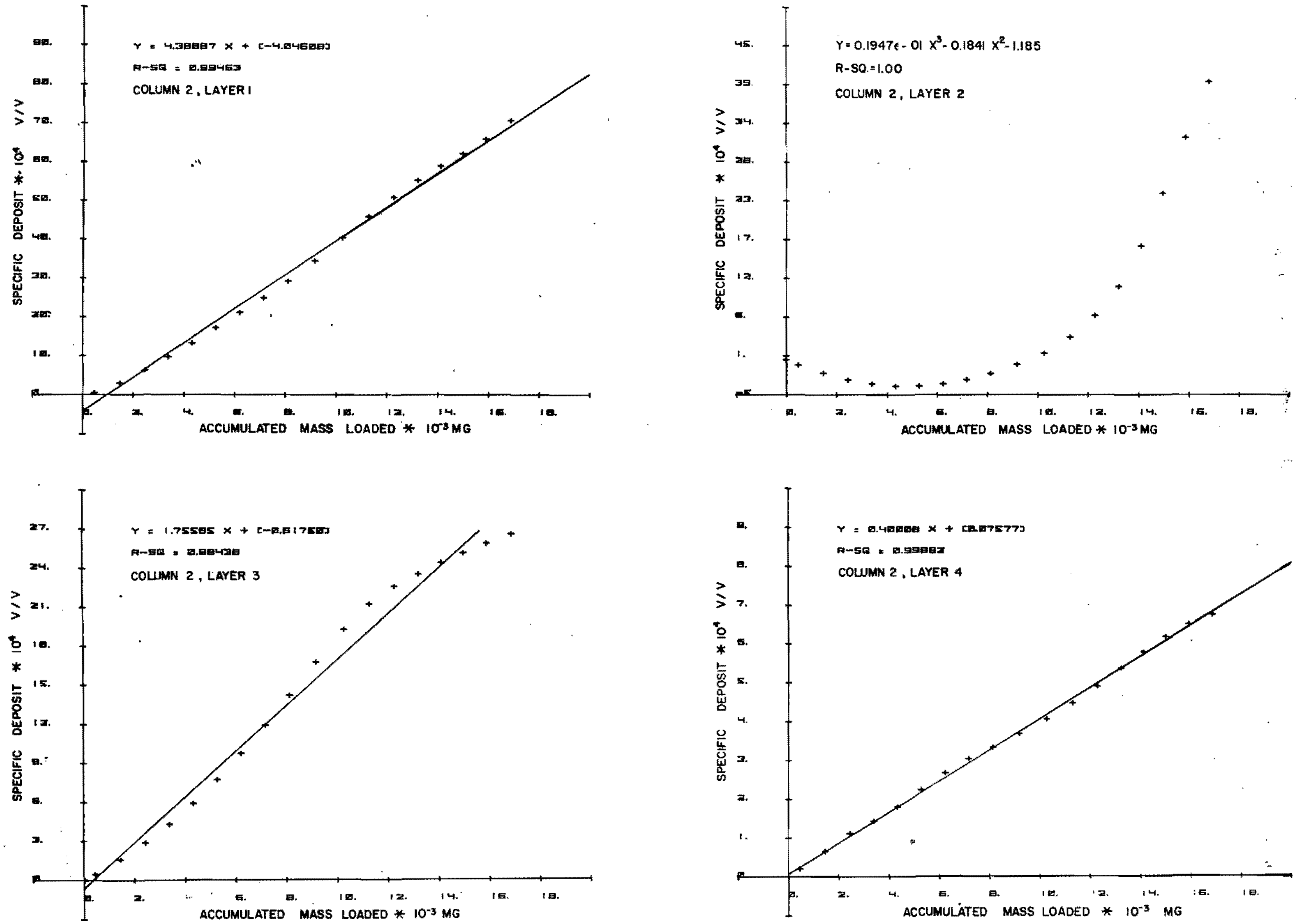



Figure 16. Individual layer specific deposits for column 2 as a function of AML.

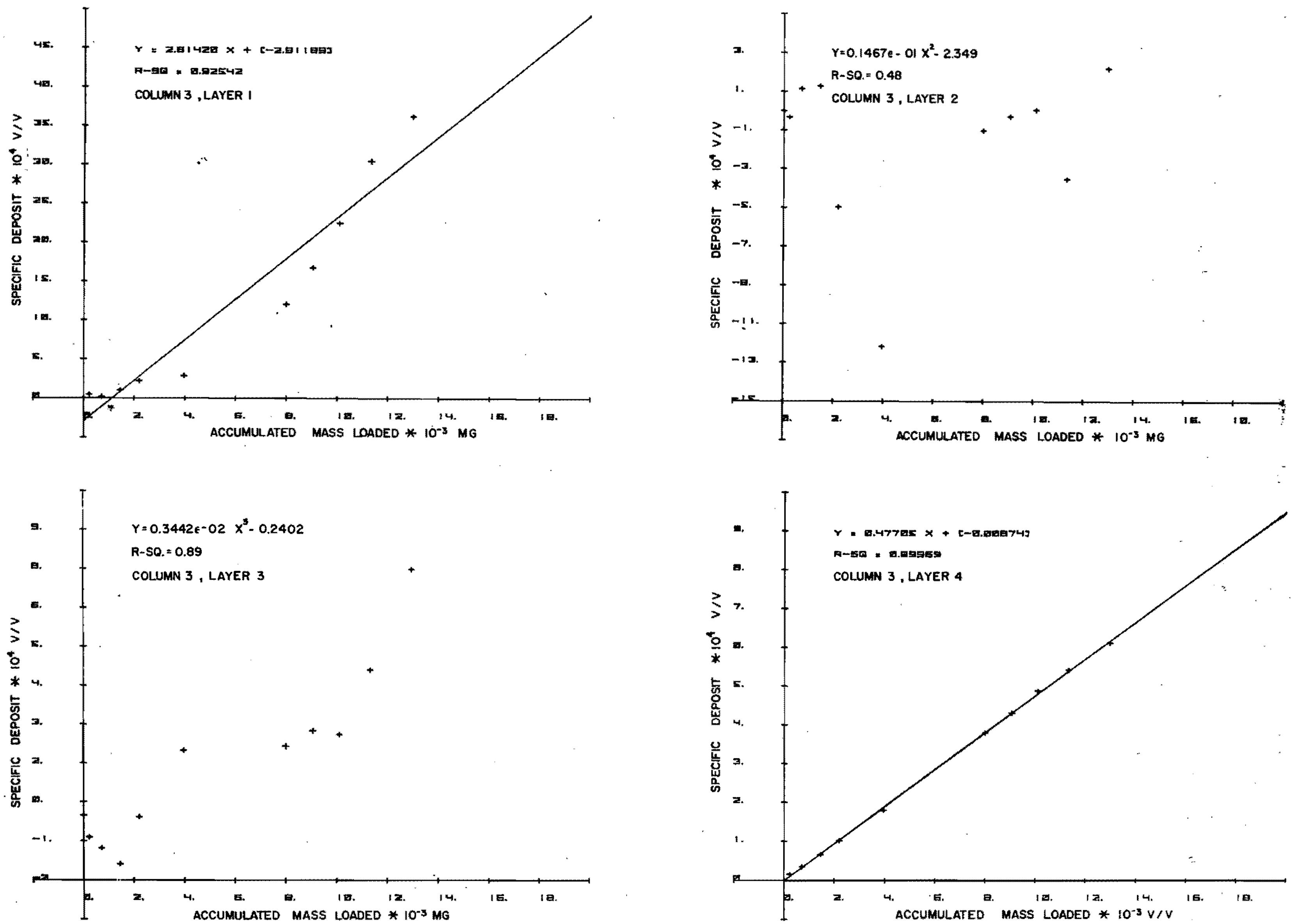



Figure 17. Individual layer specific deposits for column 3 as a function of AML.

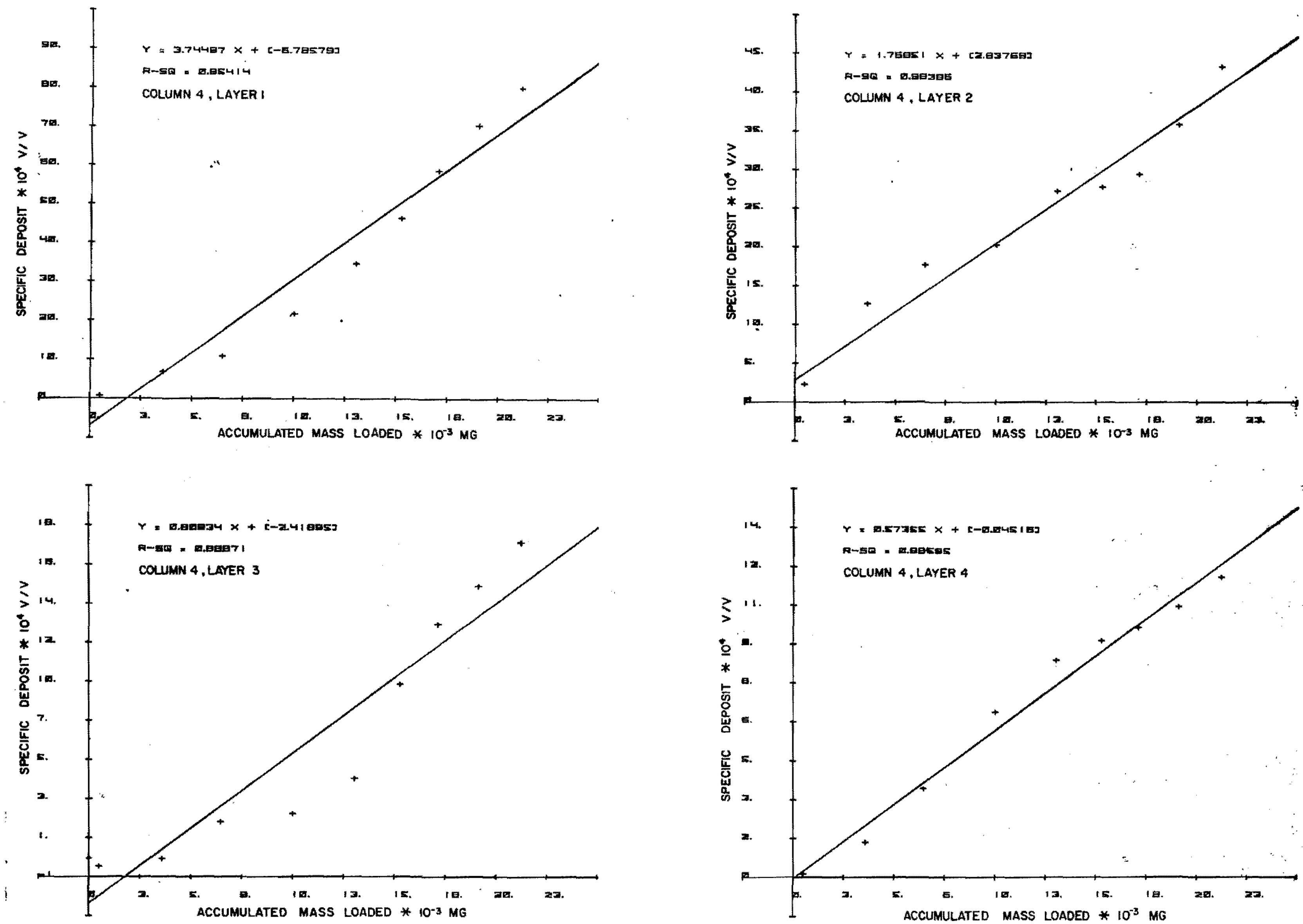



Figure 18. Individual layer specific deposits for column 4 as a function of AML.

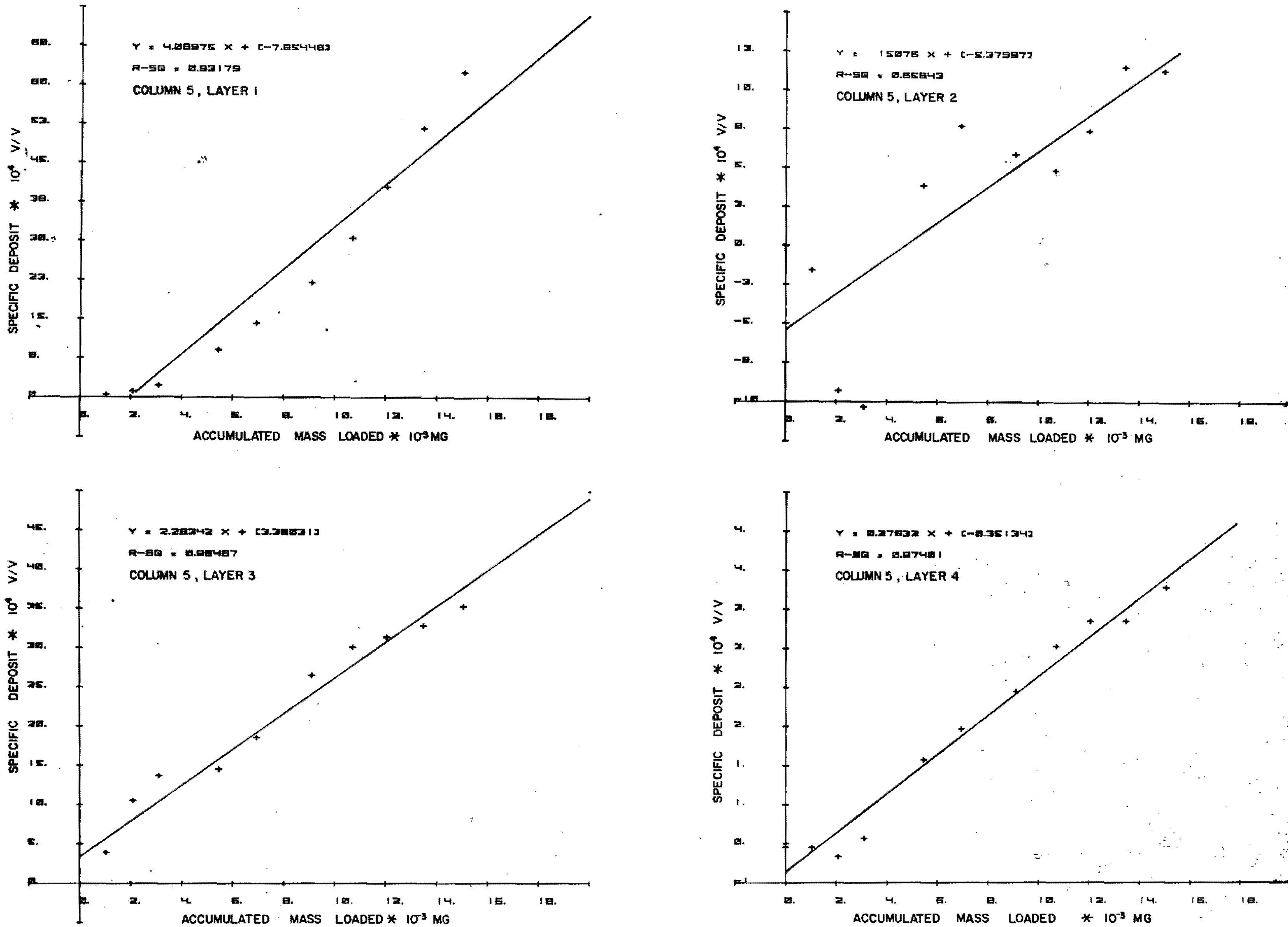



Figure 19. Individual layer specific deposits for column 5 as a function of AML.

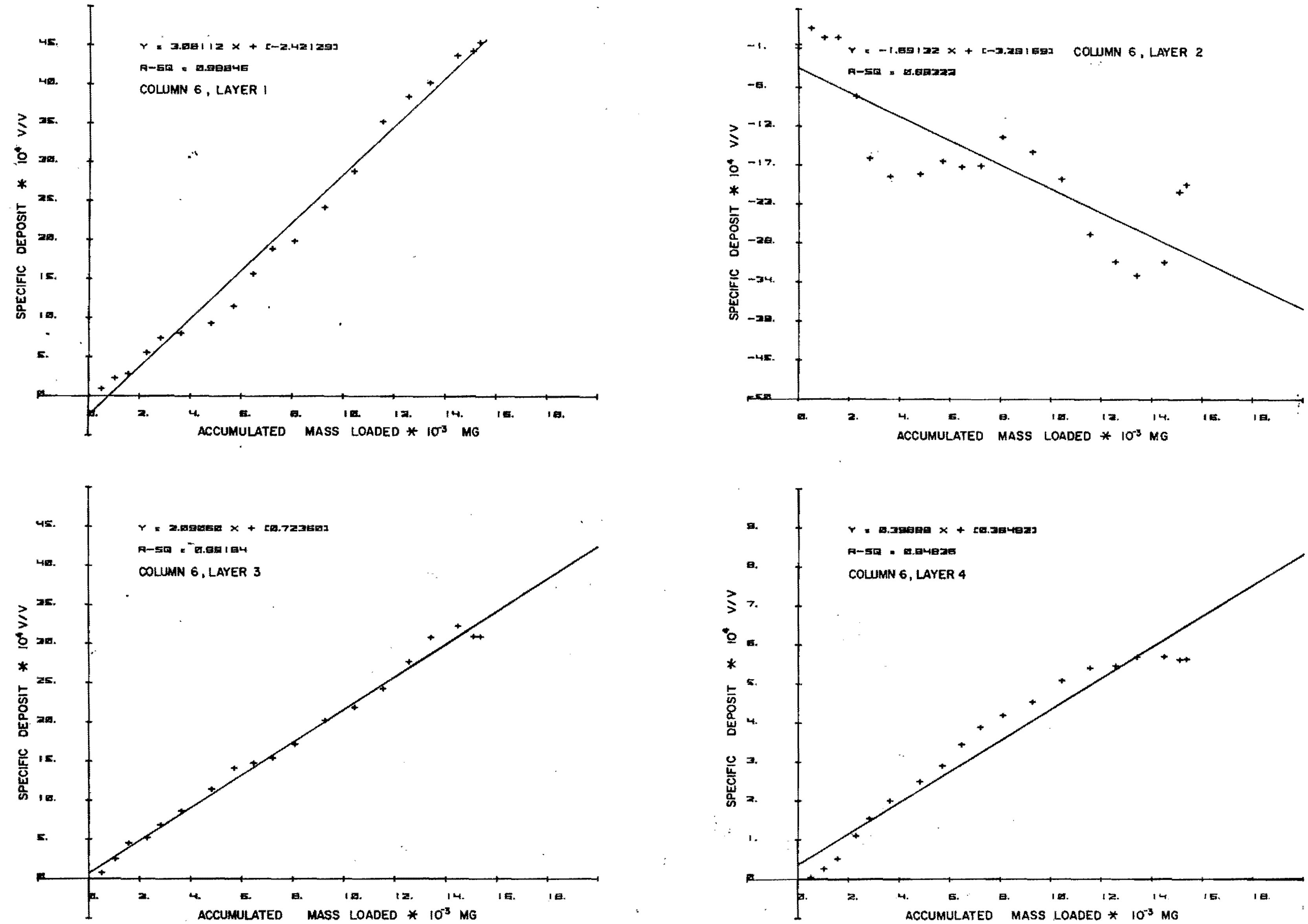



Figure 20. Individual layer specific deposits for column 6 as a function of AML.

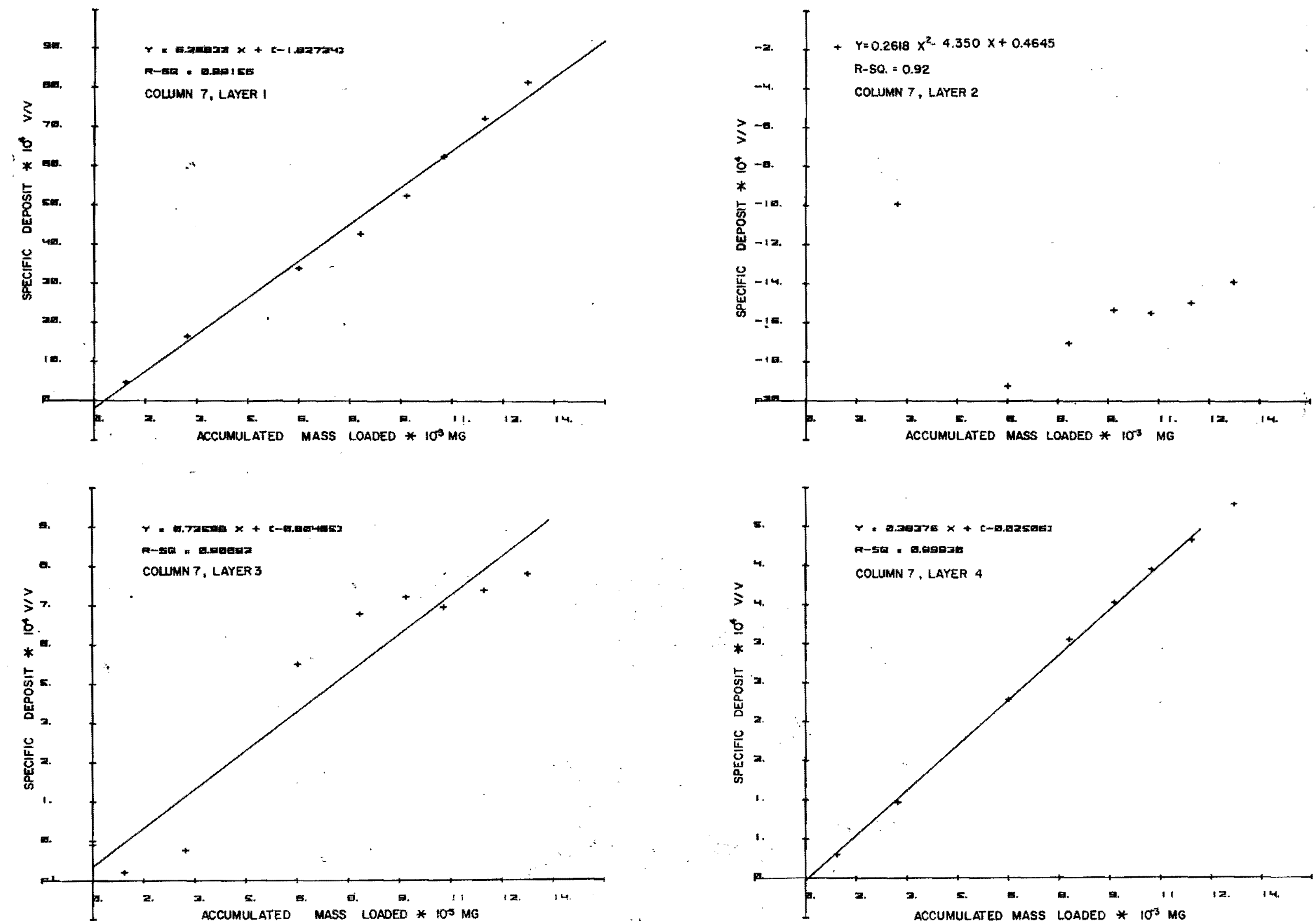



Figure 21. Individual layer specific deposits for column 7 as a function of AML.

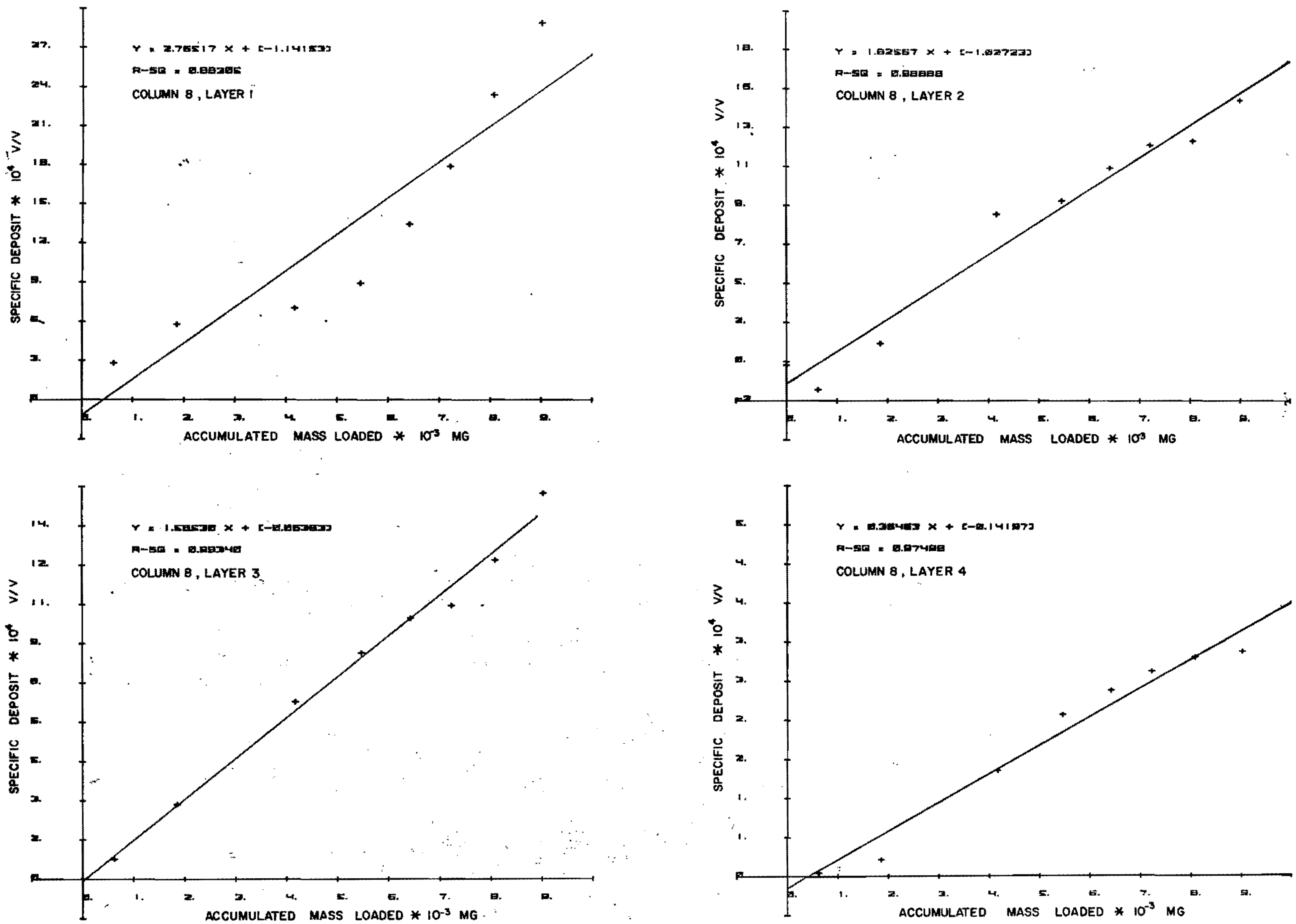



Figure 22. Individual layer specific deposits for column 8 as a function of AML.

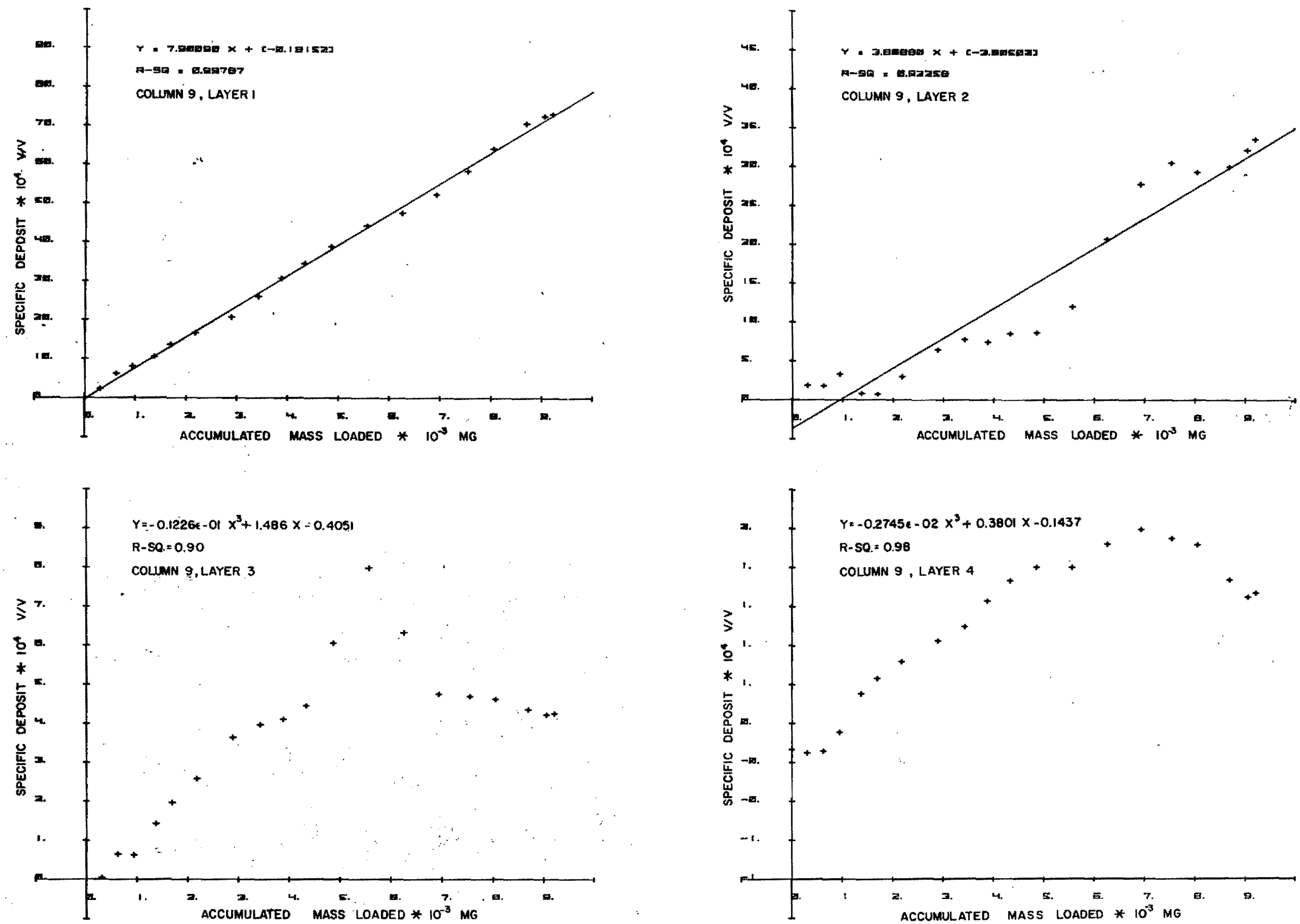



Figure 23. Individual layer specific deposits for column 9 as a function of AML.

Table 13. Sand phase filter term, λ.

| DML Range | Column | DHL cm/day | DLOAD ℓ/day | Layer | Slope dσ/dAML v/v/mass loaded | λ $cm^{-1}$ |
|---|---|---|---|---|---|---|
| III | 1 | 65.50 | 10.04 | 1 | .1634ε-06[a] | .1788ε-01[a] |
| | | | | 2 | .8841ε-07 | .9672ε-02 |
| | | | | 3 | .8982ε-07 | .9826ε-02 |
| | | | | 4 | .7520ε-07 | .8227ε-02 |
| III | 2 | 65.50 | 10.04 | 1 | .4369ε-06 | .4780ε-01 |
| | | | | 2 | F (AML) | F (AML) |
| | | | | 3 | .1756ε-06 | .1921ε-01 |
| | | | | 4 | .4001ε-07 | .4377ε-02 |
| III | 4 | 46.78 | 7.17 | 1 | .3745ε-06 | .4097ε-01 |
| | | | | 2 | .1769ε-06 | .1935ε-01 |
| | | | | 3 | .8093ε-07 | .8853ε-02 |
| | | | | 4 | .5736ε-07 | .6275ε-02 |
| II | 5 | 46.78 | 7.17 | 1 | .4070ε-06 | .4452ε-01 |
| | | | | 2 | .1151ε-06 | .1259ε-01 |
| | | | | 3 | .2283ε-06 | .2497ε-01 |
| | | | | 4 | .2763ε-07 | .3022ε-02 |
| II | 7 | 28.08 | 4.30 | 1 | .6268ε-06 | .6850ε-01 |
| | | | | 2 | 1/F (AML) | 1/F (AML) |
| | | | | 3 | .7260ε-07 | .7935ε-02 |
| | | | | 4 | .3838ε-07 | .4195ε-02 |
| I | 3 | 65.50 | 10.04 | 1 | .2614ε-06 | .2860ε-01 |
| | | | | 2 | F (AML) | F (AML) |
| | | | | 3 | F (AML) | F (AML) |
| | | | | 4 | .4771ε-07 | .5219ε-02 |
| I | 8 | 28.08 | 4.30 | 1 | .2765ε-06 | .3022ε-01 |
| | | | | 2 | .1826ε-06 | .1996ε-01 |
| | | | | 3 | .1565ε-06 | .1710ε-01 |
| | | | | 4 | .3646ε-07 | .3985ε-02 |
| | 6 | 46.78 | 7.17 | 1 | .3081ε-06 | .3370ε-01 |
| | | | | 2 | -.1691ε-06 | -.1850ε-01 |
| | | | | 3 | .2091ε-06 | .2287ε-01 |
| | | | | 4 | .3989ε-07 | .4364ε-02 |
| | 9 | 28.08 | 4.30 | 1 | .7901ε-06 | .8635ε-01 |
| | | | | 2 | .3869ε-06 | .4228ε-01 |
| | | | | 3 | F (AML) | F (AML) |
| | | | | 4 | F (AML) | F (AML) |

[a]Read as $0.1634 \times 10^{-6}$ and $0.1788 \times 10^{-1}$

Table 14. Sand phase filter term, λ, grouped according to DML.

| DML Range III | Layer | Column 1 cm$^{-1}$ | Column 2 cm$^{-1}$ | Column 4 cm$^{-1}$ | | Composite λ cm$^{-1}$ | Standard Deviation |
|---|---|---|---|---|---|---|---|
| | 1 | .1788ε-01[a] | .4780ε-01[a] | .4097ε-01[a] | | .3555ε-01[a] | .1568ε-01[a] |
| | 2 | .9672ε-02 | F (AML) | .1935ε-01 | | .1451ε-01 | .6843ε-02 |
| | 3 | .9826ε-02 | .1921ε-01 | .8853ε-02 | | .1263ε-01 | .5719ε-02 |
| | 4 | .8227ε-02 | .4377ε-02 | .6275ε-02 | | .6260ε-02 | .1975ε-02 |
| DML Range II | | Column 5 cm$^{-1}$ | Column 7 cm$^{-1}$ | | | | |
| | 1 | .4452ε-01 | .6850ε-01 | | | .5651ε-01 | .1696ε-01 |
| | 2 | .1259ε-01 | 1/F (AML) | | | .1259ε-01 | - |
| | 3 | .2497ε-01 | .7935ε-02 | | | .1645ε-01 | .1205ε-01 |
| | 4 | .3022ε-02 | .4195ε-02 | | | .3608ε-02 | .8294ε-03 |
| ≤ DML Range I | | Column 3 | Column 8 | Column 6 | Column 9 | | |
| | 1 | .2860ε-01 | .3022ε-01 | .3370ε-01 | .8635ε-01 | .4472ε-01 | .2784ε-01 |
| | 2 | F (AML) | .1996ε-01 | 1/F (AML) | .4228ε-01 | .3112ε-01 | .1578ε-01 |
| | 3 | F (AML) | .1710ε-01 | .2287ε-01 | F (AML) | .1998ε-01 | .4080ε-02 |
| | 4 | .5219ε-02 | .3985ε-02 | .4364ε-02 | F (AML) | .4523ε-02 | .6321ε-03 |

[a] Read as $0.1788 \times 10^{-1}$, $0.4780 \times 10^{-1}$, $0.4097 \times 10^{-1}$, $0.3555 \times 10^{-1}$, and $0.1568 \times 10^{-1}$.

where $DZ = Z_1 - Z_0$ represents the thickness of the sand layer being analyzed. Therefore:

$$CSS_{OUT} = CSS_{IN} * e^{-\lambda * (DZ)} \quad . \quad . \quad . \quad . \quad (81)$$

where concentrations may have units of mg/ℓ or volume of algae/volume of filtrate.

ISF Model

The ISF model which was utilized for calibration of laboratory data consisted of two basic phases: the SAL phase (A) and the sand phase (B):

A.

$$C_{OUTF} = C_{IN} * \left[1. - \left(d \frac{SALC}{dAML}\right) * AREA\right] - \frac{cd * SALC * 10^3}{DHL}$$

SAL model to predict the final [VSS] out of the SAL, $C_{OUTF}$. . . . . . . . . . (52)

B. Solution a

$CSS_{OUT} = CSS_{IN} * (1. - \lambda * DZ)$

Solution b

$$CSS_{OUT} = CSS_{IN} * e^{-\lambda * (DZ)}$$

Sand model to predict the [VSS] out of each sand layer, $CSS_{OUT}$.

. . . . . . . . (81)

The sand phase was described in terms of Ives' basic rapid sand filtration model. This model treats the sand as a physical removal (straining) mechanism.

It was hypothesized that the SAL controls the hydraulics of the ISF process. In order to verify this hypothesis, the filter columns of laboratory filter experiments 3-6 were analyzed for approach velocity immediately after SAL removal. Because experiment 2 columns 6 and 7 were operated until the end of the laboratory experimentation (column 6 ran 66 days and plugged on April 7, 1978; column 7 ran 73 days and plugged on April 4, 1978) they were also included in this approach velocity experiment. For the other columns of experiment 2 and all the columns of experiment 1, this approach velocity experiment was not peformed because of the need to analyze the sand phase of these systems following the operation of each column. The procedure for the approach velocity experiment was to add tap water to the columns and to measure approach velocities. The results are listed in Table 15. The clean filter approach velocity$^{-1}$ measured prior to experiment 1 was 61 sec/inch. The results of the approach velocity experiment substantiate that it was the SAL that controlled the hydraulics of the ISF system because SAL removal after operation returned the approach velocity$^{-1}$ to that of the clean filter approach velocity$^{-1}$.

The data input (for the laboratory phase) to the ISF model is listed in Appendix B and consists of four sets of data (Tables 36-39). Raw VSS data, in mg/ℓ, for all the sand layers consisted of those sets of data in which all levels within the filter column produced samples (Table 36). Because unsaturated conditions existed in the ISF system, incomplete data sets resulted when sample ports would not operate during the filter run. The first ports not to give samples were the deeper ports, and, with continued operation, ports at higher levels within the columns subsequently failed to give samples. The consequence was that more data were available for column influent and effluent ports than for ports within the sand phase. In order to utilize all the influent and effluent data, these data were read into the program and are listed in Table 37. Approach velocity$^{-1}$ data, in sec/inch (Table 38) and total and soluble organic carbon data, in mg C/ℓ (Table 39) are also listed.

Identification of Influent Algae

The algal species present in the algal culturing tank were identified for laboratory filter experiment 1 to determine the density of the influent algae added to the columns in experiment 1 (Table 16). The density of the algae was calculated to be $7.137 \times 10^5$ mg/ℓ (DEN in model), and the density in terms of mg/cm$^3$ was $7.137 \times 10^2$ (RHO in model).

The assumption was made that the algae of the SAL were identical to those species present in the influent; therefore, the same density value was utilized in calculations involving SAL density. This assumption was verified upon examination of the algal species present in the SAL at the termination of laboratory experiment 1 (Table 17). The data in this table represent the algal counts on 5 gram samples of SAL (wet weight) suspended in 100 ml of distilled water. Also included in this table is algal identification information on the top inch of the sand phase. This identification was necessary because the assumption was also made that the density of the sand phase specific deposit was equal to the density of the influent algae. This final assumption was valid for the top inch of sand (Table 17) but because no significant concentration of algae was detected below the 1 inch depth, the assumption cannot be verified below a 1 inch depth. The biomass in the pore space of the sand phase below 1 inch of an ISF was assumed to be bacterial. This bacterial biomass was assumed to have a density identical to that of the influent algae. Algal identification data for laboratory filter experiments 2-6 are listed in Table 18.

Table 15. Data verifying that the SAL controls the hydraulics of the ISF system.

| Run No. | Column No. | Approach Velocity$^{-1}$, sec/inch: Last Day of Operation | Approach Velocity$^{-1}$, sec/inch: After SAL Removed |
|---|---|---|---|
| 2 | 6 | 6741. | 29. |
| | 7 | 16936. | 31. |
| 3 | 1 | 1609. | 93. |
| | 2 | 11991. | 67. |
| | 3 | 3234. | 87. |
| | 4 | 10952. | 63. |
| | 5 | 9022. | 113. |
| 4 | 1 | 8475. | 49. |
| | 3 | 10582. | 69. |
| | 8 | 1184. | 115. |
| | 2 | 30637. | 66. |
| | 4 | 271. | 109. |
| 5 | 5 | 3119. | 58. |
| | 8 | 7898. | 47. |
| | 9 | 646. | 82. |
| | 4 | 9763. | 56. |
| | 3 | 14963. | 76. |
| 6 | 1 | 13228. | 57. |
| | 2 | 7268. | 60. |
| | 4 | 3873. | 65. |
| | 5 | 6110. | 60. |
| | 3 | 2837. | 103. |

Table 16. Algal density data for laboratory filter run 1.

| 1977 Date | *Chlorella sp.* $\mu^3$/ml | *Coelosphaerium sp.* $\mu^3$/ml | *Scenedesmus sp.* $\mu^3$/ml | Diatoms $\mu^3$/ml | *Oscillatoria sp.* $\mu^3$/ml | *Ankistrodesmus sp.* $\mu^3$/ml | A. Total $\mu^3$/ml | B. VSS mg/l µg/ml | $(B/A)*10^{12}$ Density mg dry wt / ℓ wet vol |
|---|---|---|---|---|---|---|---|---|---|
| 9/21 | 3.19ε07 | 1.93ε08 | 3.71ε06 | 2.95ε05 | 8.25ε05 | - | 2.30ε08 | 83. | 3.61ε05 |
| 9/28 | 2.21ε07 | 2.08ε08 | 7.43ε06 | 4.43ε05 | 1.55ε05 | - | 2.38ε08 | 121.5 | 5.11ε05 |
| 10/6 | 3.20ε07 | 5.53ε07 | 1.24ε06 | 1.78ε06 | 6.90ε04 | - | 9.04ε07 | 111.5 | 1.23ε06 |
| 10/14 | 3.29ε07 | 5.42ε07 | 2.48ε06 | 1.78ε06 | 1.38ε05 | - | 9.15ε07 | 93.5 | 1.02ε06 |
| 10/27 | 2.88ε07 | 7.39ε07 | 9.31ε06 | 5.93ε05 | - | - | 1.13ε08 | 85. | 7.52ε05 |
| 11/4 | 1.23ε07 | 5.23ε07 | 1.86ε06 | 1.57ε06 | - | 7.76ε05 | 6.88ε07 | 78. | 1.13ε06 |
| 11/23 | 1.23ε07 | 1.86ε07 | 3.73ε06 | 1.23ε07 | 4.14ε05 | 1.55ε06 | 4.89ε07 | 56. | 1.15ε06 |

ΣTotal = 8.806ε08 $\mu^3$/ml  ΣVSS = 628.5 µg/ml

$$\text{Run 1 Density} = \left(\frac{628.5\ \mu g/ml}{8.806\varepsilon08\ \mu^3/ml}\right) * \left(10^{-3}\ \frac{mg}{\mu g}\right) * \left(10^{12}\ \frac{\mu^3}{cc}\right) * \left(10^{3}\ \frac{cc}{\ell}\right) = 7.137\varepsilon05\ \frac{\text{mg dry weight}}{\ell\ \text{wet volume}}$$

[a]Read as $3.19 \times 10^7$.

Table 17. Algal identification for SAL and 0-1" sand layer for laboratory filter run 1 columns.

| 1977 Date | Column | *Chlorella sp.* $\mu^3$/ml | *Coelosphaerium sp.* $\mu^3$/ml | *Scenedesmus sp.* $\mu^3$/ml | Diatoms $\mu^3$/ml | *Oscillatoria sp.* $\mu^3$/ml | *Ankistrodesmus sp.* $\mu^3$/ml | Total $\mu^3$/5 g wet weight |
|---|---|---|---|---|---|---|---|---|
| 11/8 | 3 SAL | 7.19ε07[a] | 1.24ε08 | 3.10ε07 | 4.92ε07 | - | 1.94ε07 | 2.96ε10 |
| | 3 0-1" | 3.31ε07 | 2.91ε07 | 3.73ε06 | 3.15ε06 | 5.52ε05 | - | 4.96ε09 |
| 12/9 | 6 SAL | 3.12ε07 | 3.40ε07 | 4.35ε07 | 1.49ε07 | 8.28ε05 | 3.56ε06 | 1.28ε10 |
| | 6 0-1" | 1.23ε07 | 1.01ε07 | 9.98ε06 | 2.00ε06 | - | 5.93ε05 | 3.50ε09 |
| 11/5 | 8 SAL | 6.16ε07 | 1.37ε08 | 3.10ε07 | 4.94ε06 | - | - | 2.35ε10 |
| | 8 0-1" | 1.15ε07 | 3.22ε07 | 4.97ε06 | 3.95ε05 | - | - | 4.91ε09 |
| 12/9 | 9 SAL | 1.23ε07 | 1.10ε07 | 4.97ε06 | 2.93ε06 | 2.76ε05 | 2.96ε05 | 3.18ε09 |
| | 9 0-1" | 1.48ε07 | 1.88ε07 | 9.93ε06 | 3.73ε06 | 5.52ε05 | 5.93ε05 | 4.84ε09 |

[a]Read as $7.19 \times 10^7$.

Table 18. Algal identification for laboratory filter run 2 (2/1/78-4/14/78) and SAL experiments, runs 3-6 (3/11/78-4/14/78).

| 1978 Date | *Chlorella sp.* $\mu^3$/ml | *Coelosphaerium sp.* $\mu^3$/ml | *Scenedesmus sp.* $\mu^3$/ml | Diatoms $\mu^3$/ml | *Oscillatoria sp.* $\mu^3$/ml | *Cryptomonas sp.* $\mu^3$/ml | *Microcystis sp.* $\mu^3$/ml | Total $\mu^3$/ml | VSS mg/l μg/ml |
|---|---|---|---|---|---|---|---|---|---|
| 1/26 | 3.29ε06 | 1.47ε07 | 2.24ε07 | 7.84ε05 | - | - | - | 4.12ε07 | - |
| 1/27 | 4.93ε06 | 1.68ε07 | 1.61ε07 | 8.16ε05 | - | - | - | 3.86ε07 | - |
| 2/4 | 1.64ε06 | 1.61ε07 | 1.74ε07 | 9.73ε05 | - | - | - | 3.61ε07 | 63.5 |
| 2/28 | 6.57ε06 | 5.01ε06 | 9.93ε06 | 1.10ε06 | - | 5.49ε05 | 6.73ε06 | 2.99ε07 | 57.5 |
| 3/7 | 3.29ε06 | 5.97ε06 | 1.74ε07 | 1.65ε06 | - | - | 2.69ε07 | 5.52ε07 | 79.5 |
| 3/11 | 8.22ε06 | 1.11ε07 | 1.49ε07 | 3.21ε06 | 1.10ε06 | - | 2.69ε07 | 6.54ε07 | 70.5 |
| 3/18 | 1.15ε07 | 8.42ε06 | 1.61ε07 | 1.57ε06 | 2.76ε05 | - | 6.73ε06 | 4.46ε07 | 82.5 |
| 4/8 | 1.64ε06 | 6.93ε06 | 2.48ε06 | 7.06ε05 | 1.38ε06 | - | 6.73ε06 | 1.99ε07 | 64.5 |
| 4/15 | 1.64ε06 | 4.58ε06 | - | 3.14ε05 | 2.76ε05 | - | 4.71ε07 | 5.39ε07 | - |
| 4/16 | 6.57ε06 | 5.76ε06 | - | 3.14ε05 | 1.38ε06 | - | 3.36ε07 | 4.76ε07 | - |

[a]Read as $3.29 \times 10^6$.

## SECTION IV

## ISF MODEL CALIBRATION

Calibration of the ISF model represented adjustment of the coefficients from both the SAL and sand portions of the model. The SAL model is represented as:

$$C_{OUTF} = C_{IN} * \left[ 1. - \left( d \frac{SALC}{dAML} \right) * AREA \right] - \frac{cd * SALC * 10^3}{DHL} \quad \ldots\ldots\ldots (52)$$

The decay coefficient is the only coefficient present in the SAL phase model. The sand phase model is represented as:

$$CSS_{OUT} = CSS_{IN} * e^{-\lambda * (DZ)} \quad \ldots\ldots (81)$$

There are four sand filter coefficients (one for each sand layer) which require adjustment for each of the DML ranges. It was the simultaneous adjustment of these coefficients on laboratory experiment 1 data such that the predicted [VSS] out of each sand layer matched the actual measured [VSS] out of each sand layer which calibrated the ISF model. "Special" correlation coefficient calculations were made on actual versus predicted VSS effluent concentration data sets to provide a quantitative measurement of the agreement between values predicted by the model and those measured in the laboratory.

The final sets of coefficients are listed in Table 19. In the sand phase model ($CSS_{OUT} = CSS_{IN} * e^{-\lambda * (DZ)}$), $e^{-\lambda*(DZ)}$ represents the fraction of the VSS entering the layer that remains in the flow as it passes from the layer; therefore, $1 - e^{-\lambda*(DZ)}$ represents the fraction of influent VSS to the layer which is removed by the layer (Table 20). For example, 80 percent of the VSS entering layer 4 of columns of DML Range III will be removed by that layer.

The special correlation coefficient, $R_s$ (Sarma et al. 1969) is defined as:

$$R_s = \left(2 \sum_{i=1}^{N} O_i P_i - \sum_{i=1}^{N} P_i^2\right) / \sum_{i=1}^{N} O_i^2 \quad \ldots (82)$$

in which

O = actual (measured) value
P = predicted (model) value
N = number of actual and predicted values

The best agreement between predicted and actual values yields $R_s$ values of +1. The results of the special correlation coefficient calculations are listed in Table 21.

In comparison of $R_s$ values between columns, only filter column 9 (99 mg/day loaded) showed decreased special correlation coefficient values. Within any one column,

Table 19. ISF coefficients.

| DML Range No. | Columns | Decay Coef. $day^{-1}$ | Layer(1) λ $cm^{-1}$ | Layer(2) λ $cm^{-1}$ | Layer(3) λ $cm^{-1}$ | Layer(4) λ $cm^{-1}$ |
|---|---|---|---|---|---|---|
| III | 1,2,4 | .3909ε-01[a] | .5119ε-01 | .5086ε-01 | .1263ε-01 | .2610ε-01 |
| II | 5,7 | .3201ε-01 | .4521ε-01 | .1259ε-01 | .5330ε-01 | .1816ε-01 |
| I | 3,8 | .2561ε-01 | .3578ε-01 | .3112ε-01 | .1998ε-01 | .2328ε-01 |
| <I | 6 | .1388ε-01 | .4472ε-01 | .3112ε-01 | .1998ε-01 | .1073ε-01 |
| <I | 9 | .3618ε-01 | .7727ε-01 | .4107ε-01 | .2398ε-01 | .1311ε-01 |

[a]Read as $0.3909 \times 10^{-1}$.

the best results were obtained in the upper layers of the filter. Column effluent (effluent from layer 4) showed the lowest correlation in all nine columns. Both of these observations were concluded to occur because of analytical error in the measurement of [VSS] at the lower concentration ranges. Errors resulted from analytical procedures which exceeded the sensitivity constraints of those procedures. At low [VSS] levels (for example < 10 mg/ℓ), it is necessary to filter more than the 125 mℓ of sample obtained in this research to ensure accuracy and precision in analytical technique. Analytical precision suffers at low concentration levels regardless of sample size utilized because small amounts of contamination (volatile matter) will invalidate low level measurements.

The samples taken from within the sand phase were limited as to sample size because an attempt was made in sampling to catch the frontal wave as it passed through the filter and because problems of unsaturated flow conditions decreased sample volumes (eventually no sample was obtained within the filter prior to plugging). This same reasoning cannot be applied to the column effluent samples. Column effluent samples were expected to be < 10 mg VSS/ℓ; however, sample sizes were not increased to account for the problems of exceeding analytical sensitivity. It is recommended, therefore, that future research in this area specify sample sizes of 250 mℓ within the filter column (whenever possible) and a minimum of 1 ℓ sample size for the effluent samplings because sufficient sample is available at the hydraulic loading rates studied.

It must be noted that decreased DML values resulting in decreased $R_s$ values could occur also because of increased number of episodes (samplings) in the lower DML ranges. Given lower DML levels, the column will operate for longer periods of time and will not reach unsaturated flow conditions in the sand phase as rapidly as will higher DML filters. The consequence was, that, at lower DML levels, more samples (data points) were available for the special correlation coefficient analysis. Increased numbers of data sets (actual versus predicted [VSS]) will, in of itself, tend to decrease $R_s$ values.

In order to graphically represent the calibration of the ISF model utilizing laboratory filter experiment 1 data, actual and predicted values were plotted versus AML (for the period of operation of filter units) for the columns from each of the DML ranges (Figures 24-32).

Table 20. Fraction of influent VSS removed by layer.

| DML Range No. | Column Nos. | Layer(1) | Layer(2) | Layer(3) | Layer(4) |
|---|---|---|---|---|---|
| III | 1,2,4 | 0.23 | 0.12 | 0.09 | 0.80 |
| II | 5,7 | 0.21 | 0.03 | 0.34 | 0.67 |
| I | 3,8 | 0.17 | 0.08 | 0.14 | 0.76 |
| <I | 6 | 0.20 | 0.08 | 0.14 | 0.48 |
| <I | 9 | 0.32 | 0.10 | 0.17 | 0.55 |

Table 21. Special correlation coefficients for predicted and actual [VSS] effluent values from sand layers for calibration of ISF model utilizing laboratory filter run 1 data.

| DML Range No. | Column No. | No. of Episodes (Samples) | Layer No. | $R_s$ |
|---|---|---|---|---|
| III | 1 | 4 | 1 | 0.95 |
| | | | 2 | 0.92 |
| | | | 3 | 0.92 |
| | | | 4 | 0.82 |
| III | 2 | 4 | 1 | 0.99 |
| | | | 2 | 0.96 |
| | | | 3 | 0.85 |
| | | | 4 | -2.58 |
| III | 4 | 9 | 1 | 0.97 |
| | | | 2 | 0.96 |
| | | | 3 | 0.94 |
| | | | 4 | 0.57 |
| II | 5 | 10 | 1 | 0.96 |
| | | | 2 | 0.87 |
| | | | 3 | 0.94 |
| | | | 4 | 0.52 |
| II | 7 | 8 | 1 | 0.86 |
| | | | 2 | 0.93 |
| | | | 3 | 0.95 |
| | | | 4 | 0.88 |
| I | 3 | 10 | 1 | 0.94 |
| | | | 2 | 0.90 |
| | | | 3 | 0.86 |
| | | | 4 | 0.65 |
| I | 8 | 8 | 1 | 0.92 |
| | | | 2 | 0.92 |
| | | | 3 | 0.71 |
| | | | 4 | 0.67 |
| <I | 6 | 19 | 1 | 0.96 |
| | | | 2 | 0.91 |
| | | | 3 | 0.90 |
| | | | 4 | 0.72 |
| <I | 9 | 19 | 1 | 0.83 |
| | | | 2 | 0.75 |
| | | | 3 | 0.66 |
| | | | 4 | 0.49 |

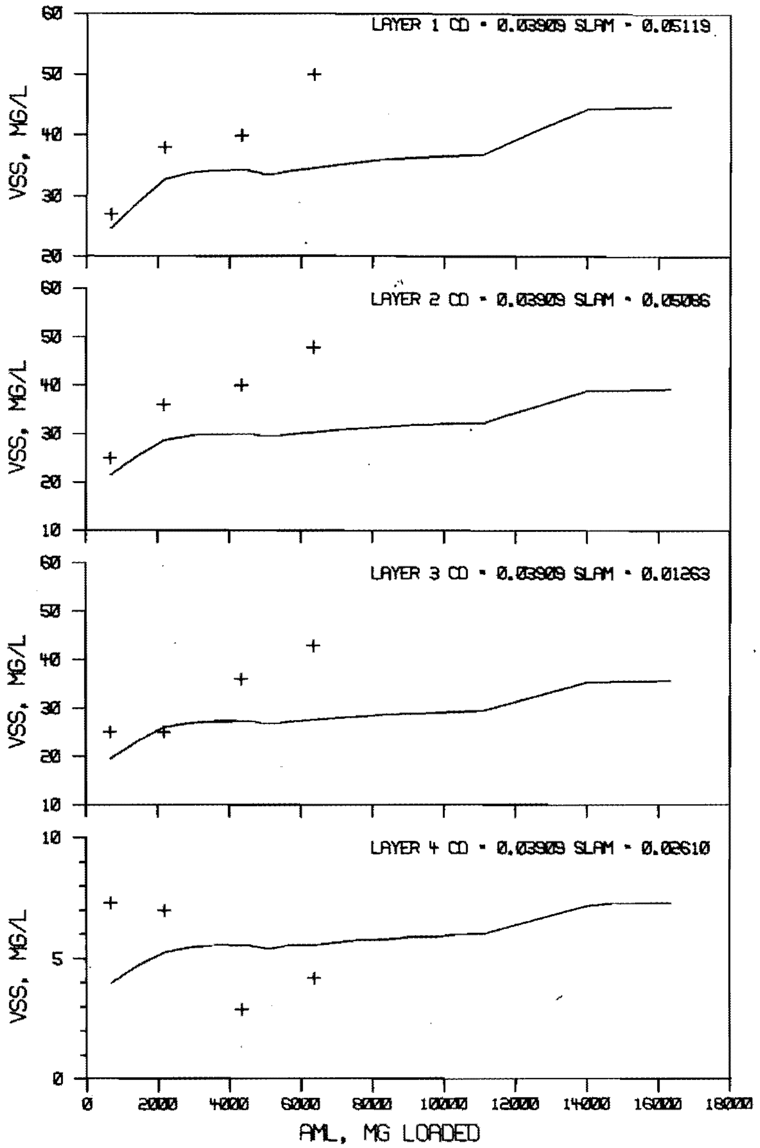



Figure 24. Predicted (line) and actual (+) sand layer effluent (VSS) for column 1. Calibration of ISF model.

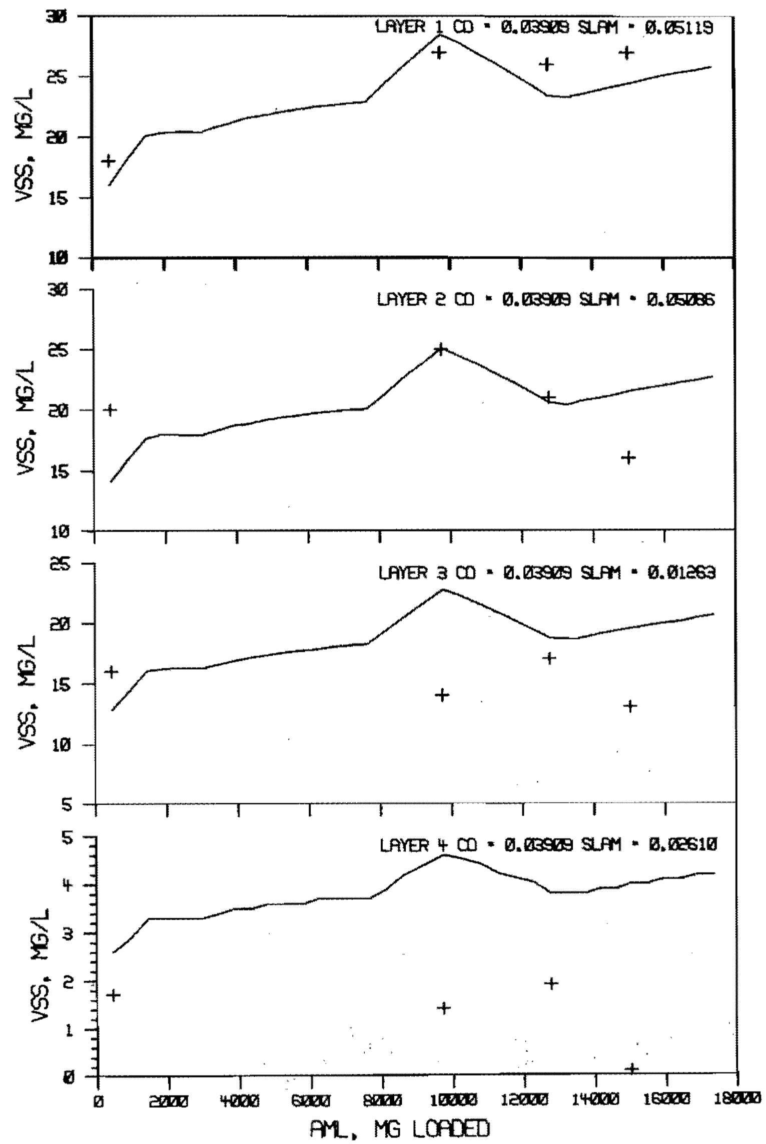



Figure 25. Predicted (line) and actual (+) sand layer effluent (VSS) for column 2. Calibration of ISF model.

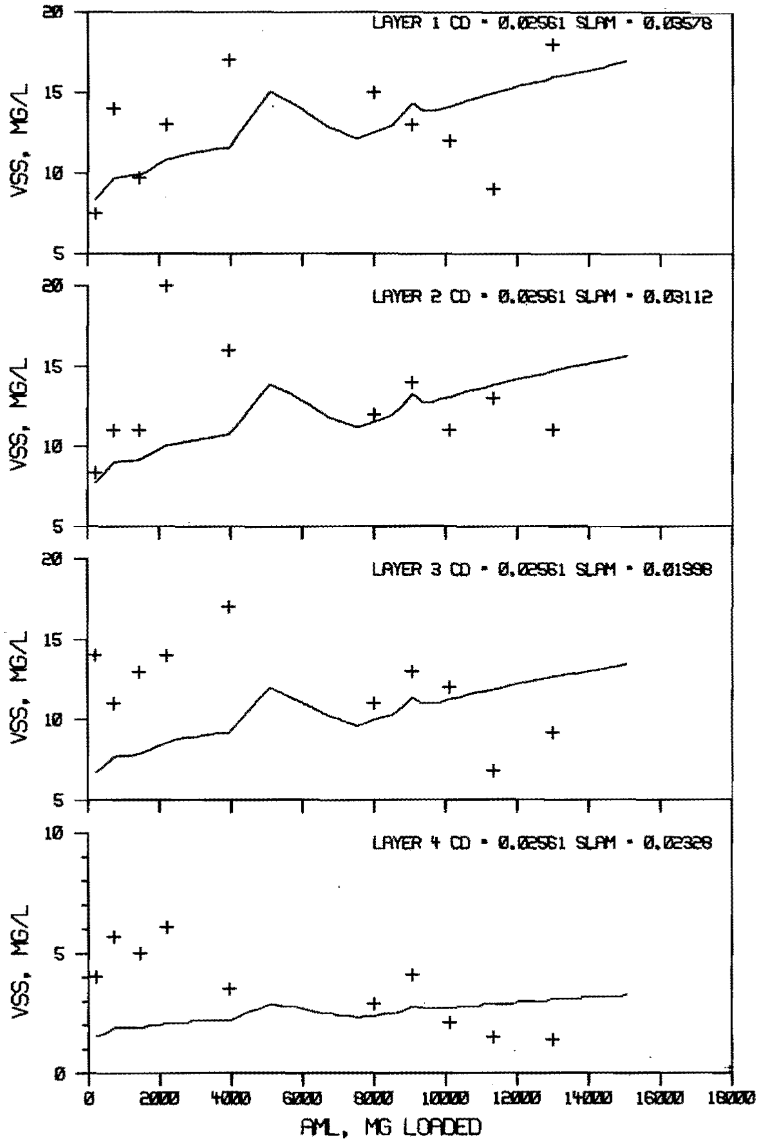



Figure 26. Predicted (line) and actual (+) sand layer effluent (VSS) for column 3. Calibration of ISF model.

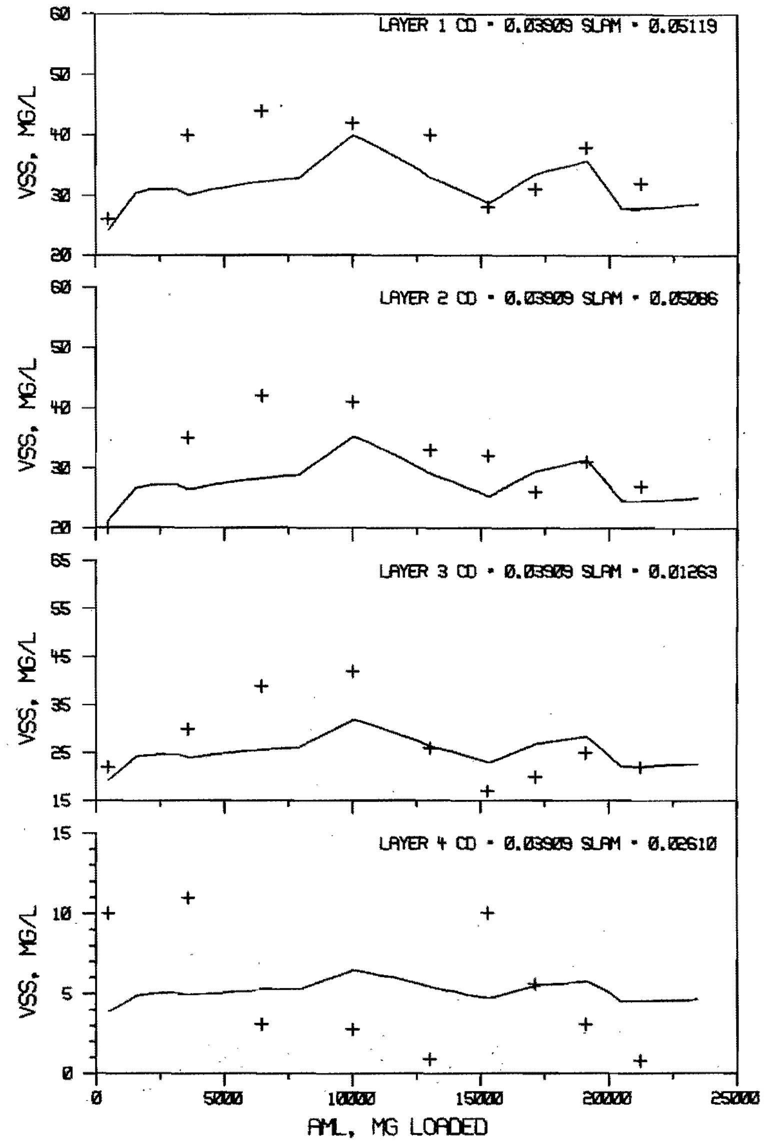



Figure 27. Predicted (line) and actual (+) sand layer effluent (VSS) for column 4. Calibration of ISF model.

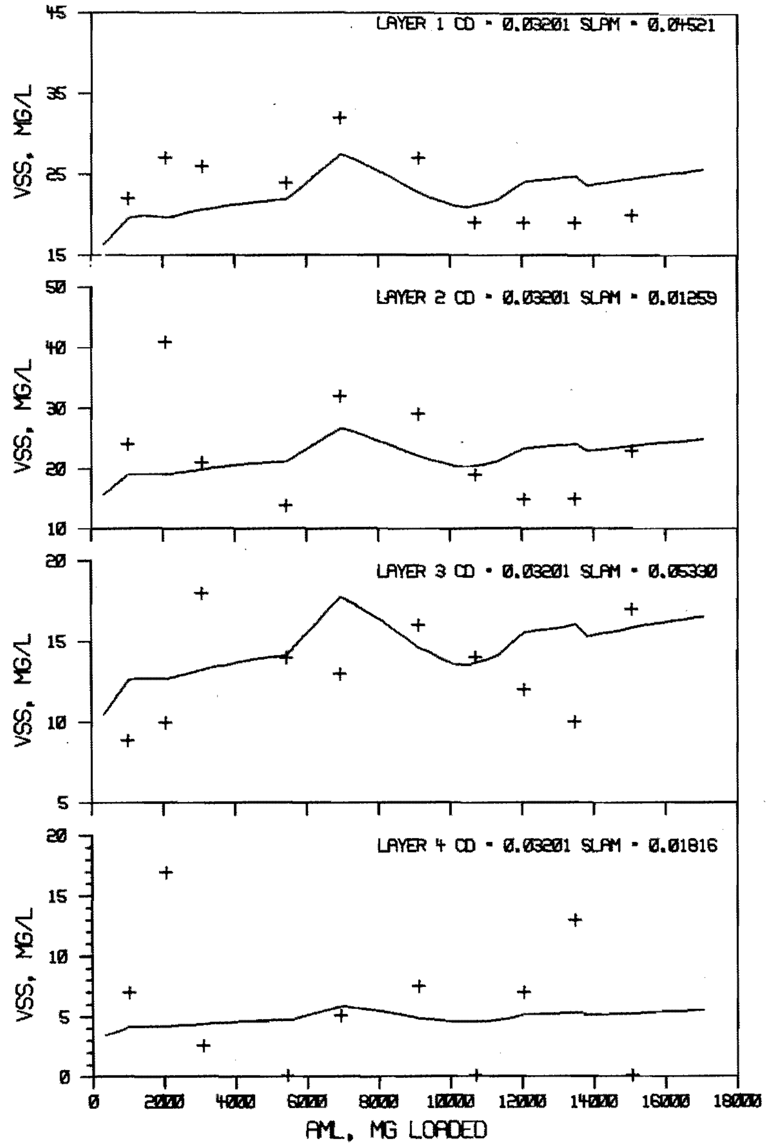



Figure 28. Predicted (line) and actual (+) sand layer effluent (VSS) for column 5. Calibration of ISF model.

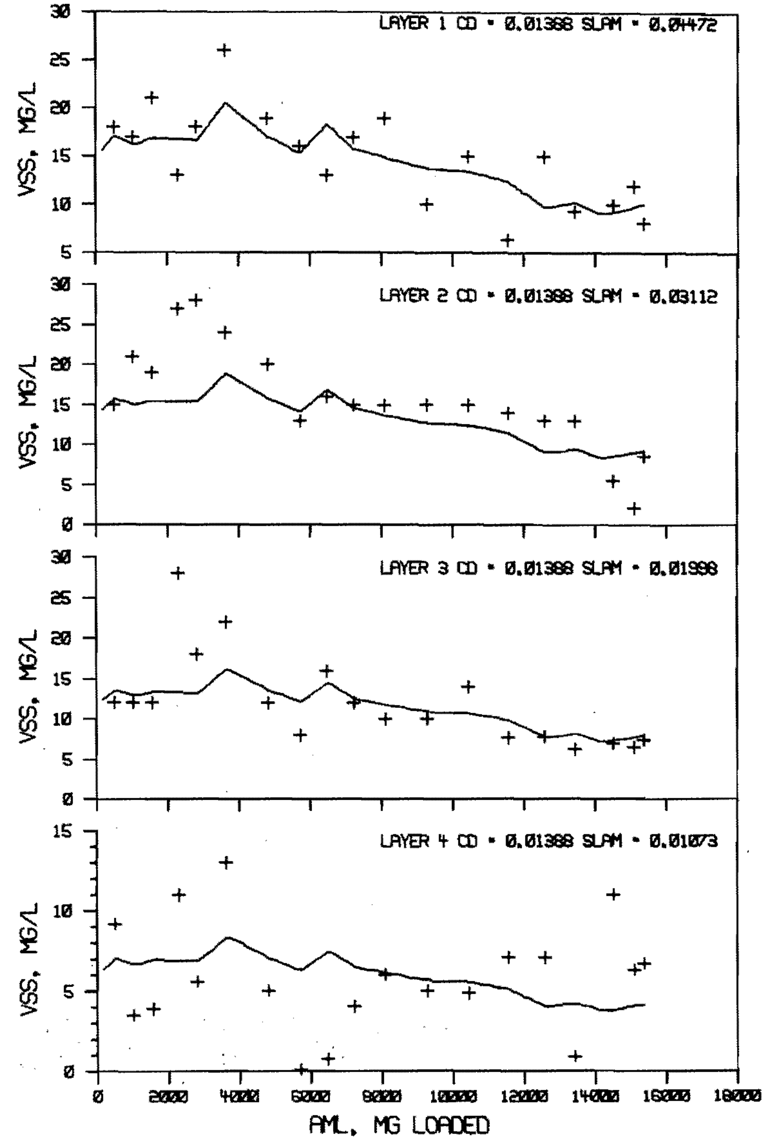



Figure 29. Predicted (line) and actual (+) sand layer effluent (VSS) for column 6. Calibration of ISF model.

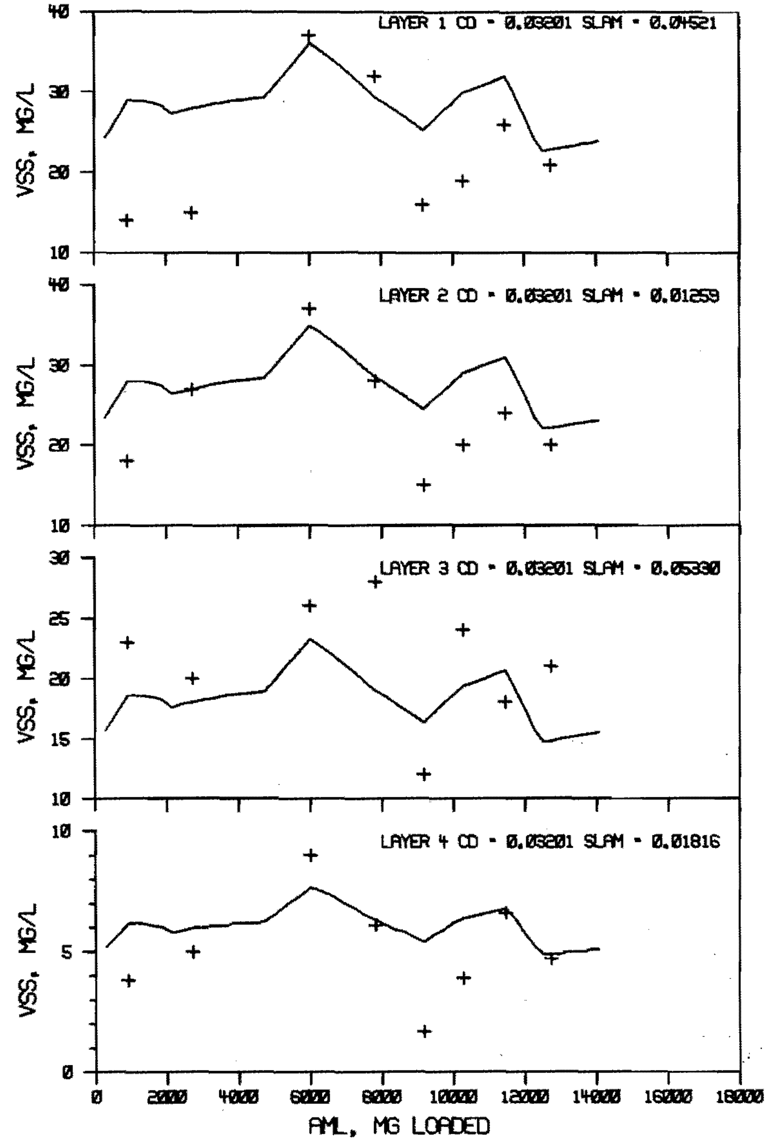



Figure 30. Predicted (line) and actual (+) sand layer effluent (VSS) for column 7. Calibration of ISF model.

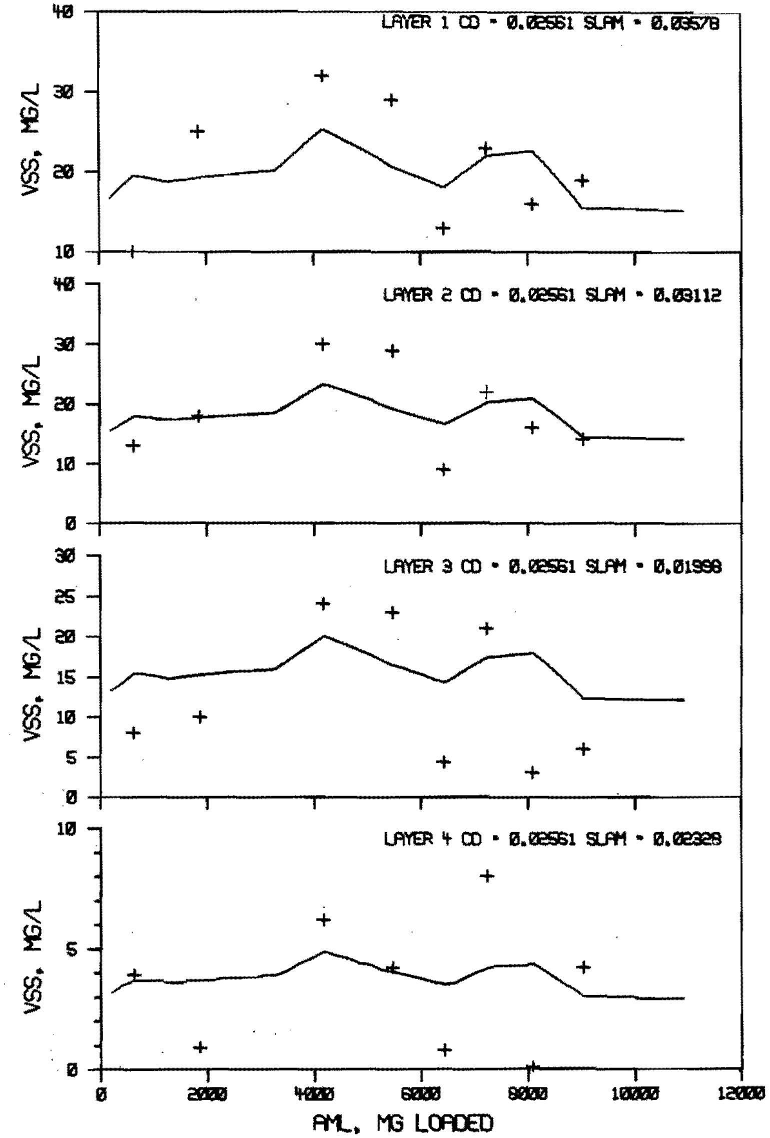



Figure 31. Predicted (line) and actual (+) sand layer effluent (VSS) for column 8. Calibration of ISF model.

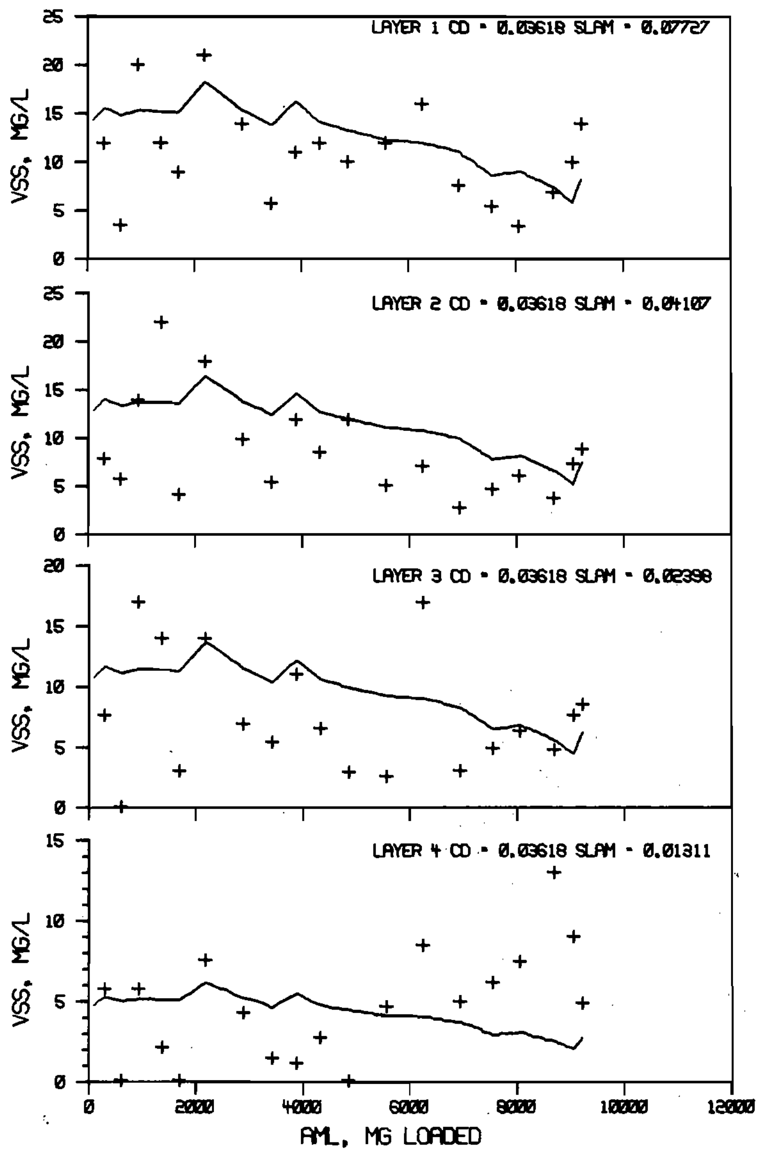



Figure 32. Predicted (line) and actual (+) sand layer effluent (VSS) for column 9. Calibration of ISF model.

## SECTION V

## ISF MODEL VALIDATION

Data collected by Harris (1977) and Tupyi (1977) were used to validate the ISF model. Both Harris and Tupyi utilized six (25 feet by 36 feet) field scale ISF systems on wastewater stabilization pond effluent from the ponds at Logan, Utah. The field mass loading data (DML, AML) are quantified in terms of laboratory scale filter units for ISF model validation. The field data are listed in Appendices C and D. Included in these data are water temperature measurements for the filter influent. Because the field temperatures often differed from the temperature in the chlorination building at the Logan wastewater stabilization ponds (where the model variables were tested to develop the ISF model), a temperature correction for the biological activity term (cd, decay coefficient) of the SAL model was required. The temperature range in the chlorination building during the laboratory phase of the experimentation was 20 $\pm$ 2°C; therefore, cd measured in the laboratory was assumed to be cd at 20°C. The value of the decay coefficient at field temperature (DECAY) was:

$$DECAY = cd * \Psi^{(T-20)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

in which

$\Psi$ = temperature activity coefficient
T = temperature, °C

The value of $\Psi$ for SAL of the ISF was assumed to be 1.03. This value is in the range for temperature activity coefficients for trickling filter systems (Clark and Ungersma 1972). The assumed value was based upon the believed similarity between the biological film of the trickling filter and the SAL of the ISF system.

Filter effluent quality, quantified by [VSS], was predicted. The computer program is listed in Appendix E. The actual and predicted filter effluent [VSS] was plotted for the period of filter operation for 17 of the filter runs completed by Harris (1977). These plots are represented in Figures 33-38. The special correlation coefficient (Equation 82) was utilized to estimate the accuracy of the ISF model in prediction of filter effluent VSS concentrations. $R_s$ values for the Harris (1977) data as well as data from the 0.17 mm $\varepsilon'$ filter units for the Tupyi (1977) data are listed in Table 22.

In the 17 filter experiments displayed in Figures 33 through 38, nine experiments exhibited agreement between predicted and actual filter effluent [VSS] values (Figure 33: experiment 1-filters 1, 2, 3; Figure 34: experiment 1-filters 4, 5; Figure 36: experiment 4-filter 1; Figure 37: experiment 7-filter 2; Figure 38: experiment 9-filters 4, 5). In six of the filter experiments, effluent [VSS] values predicted were less than 7 mg/ℓ for corresponding actual effluent [VSS] values which were less than 2 mg/ℓ (Figure 34: experiment 2-filter 1; Figure 35: experiment 2-filter 6, experiment 3-filters 1, 6; Figure 36: experiment 5-filter 1; Figure 37: experiment 6-filter 1). Only two filter runs exhibited poor predictions of filter effluent [VSS] values (Figure 36: experiment 4-filter 6; Figure 37: experiment 9-filter 2). In both cases, predicted values exceeded actual values. Upon examination of the [VSS] influent data (Appendix C) to these filter units, it was concluded that the model failed because of excessive variation in influent [VSS] in these two field scale systems. Experiment 4-filter 6 contained 13 episodes (samplings) and experiment 9-filter 2 contained 4 episodes. The influent ranged from 4.6 to 109.1 mg/ℓ [VSS] for both filters.

### Effective Sand Size Variation

The laboratory experimentation phase of this research and the field scale ISF systems studied by Harris (1977) utilized 0.17 mm effective sand size ($\varepsilon'$) media. Process variables were tested and the ISF model was developed, calibrated, and validated using filter units which contained only 0.17 mm $\varepsilon'$ sand. To quantify the effects of changes of $\varepsilon'$ on operational scale systems, additional validation was performed utilizing data gathered by Tupyi (1977). These field data are listed in Appendix D. In his study, Tuypi operated the same field scale filtration units as did Harris (1977); however, Tupyi implemented $\varepsilon'$ as a variable in his study.

Design criteria for intermittent sand filtration systems specify $0.20 \leq \varepsilon' \leq 0.50$ sand media (Marshall and Middlebrooks 1974). Although Tupyi (1977) recommended the use of 0.17 mm $\varepsilon'$ sand to meet the State of Utah, Class C regulations for effluent $BOD_5$ and SS concentrations, it was established in the study by Tupyi that 0.40 mm $\varepsilon'$ sand is capable of meeting these regulations under certain conditions.

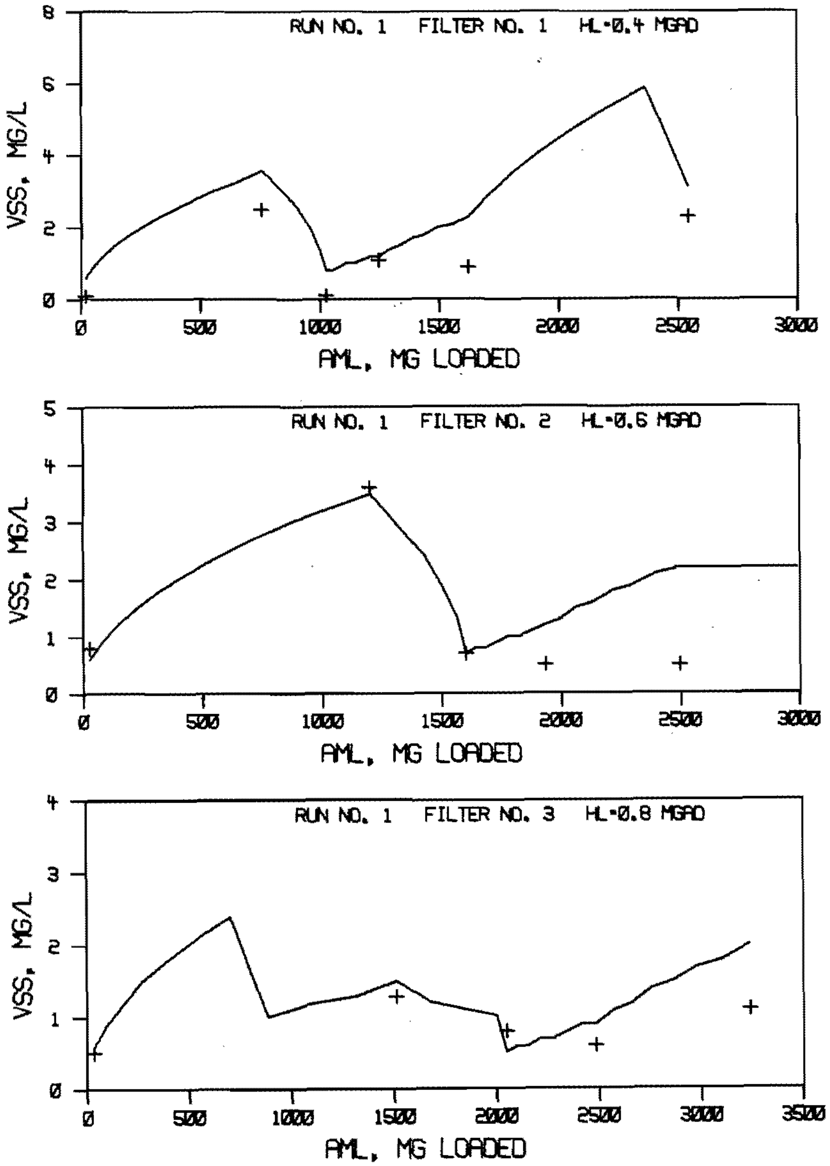



Figure 33. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

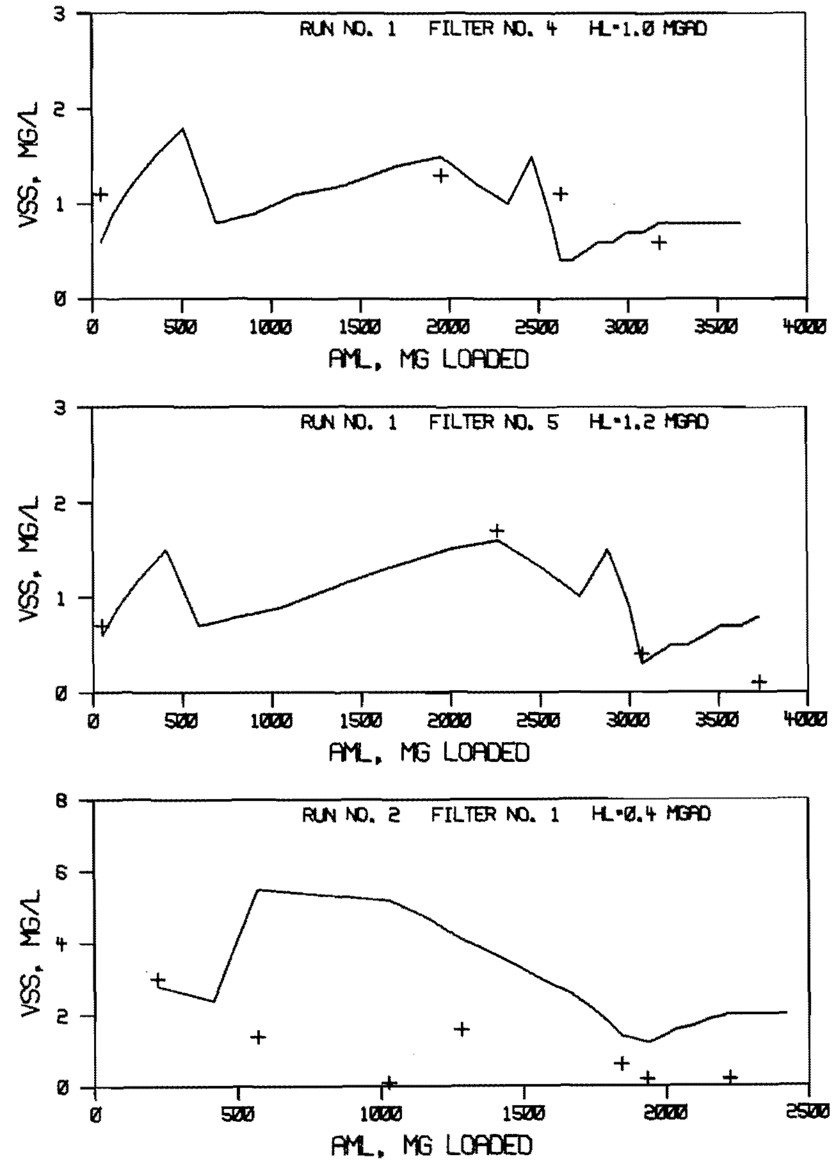



Figure 34. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

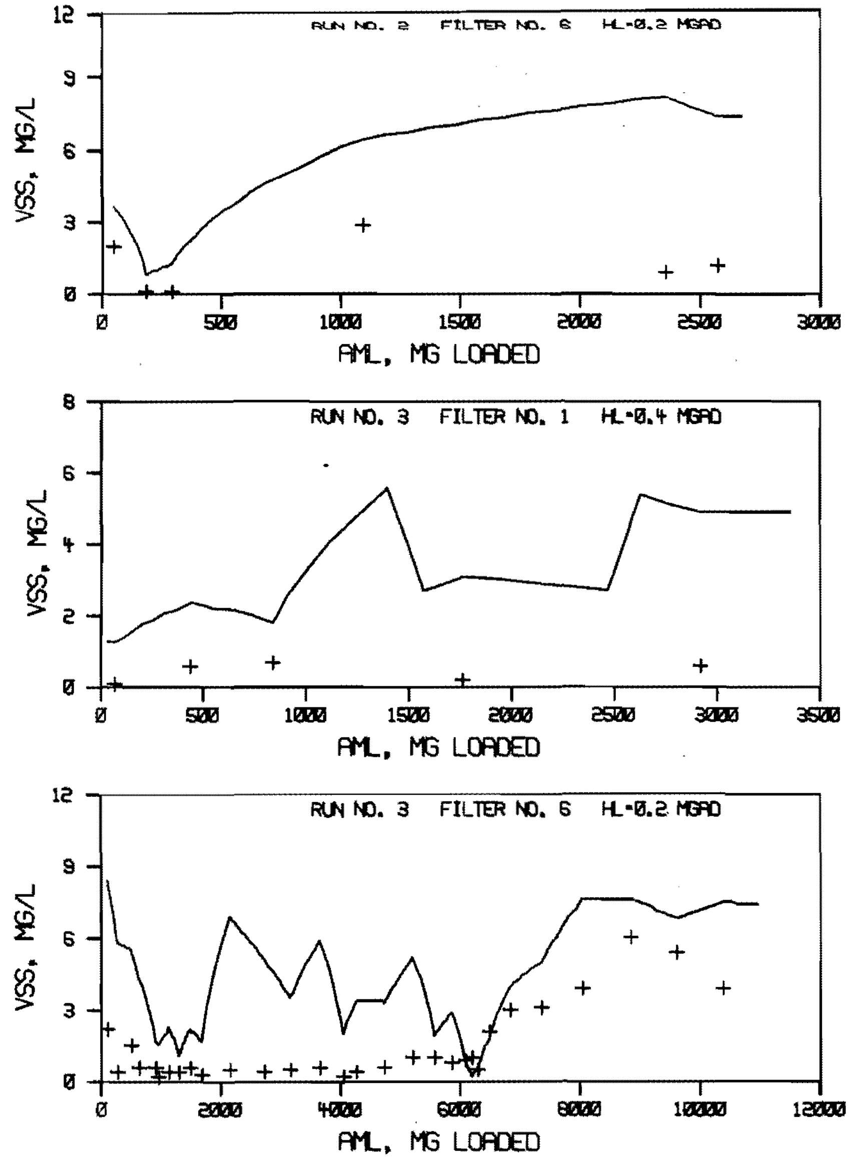



Figure 35. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

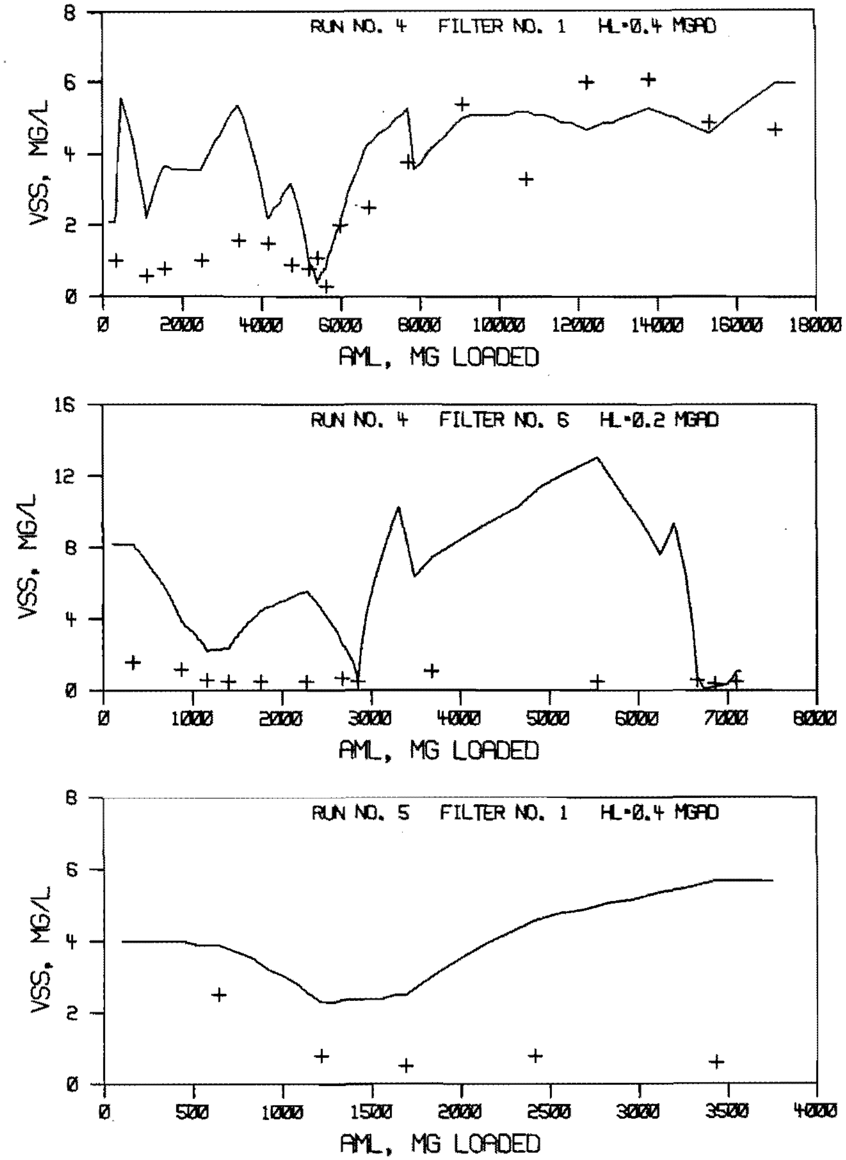



Figure 36. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

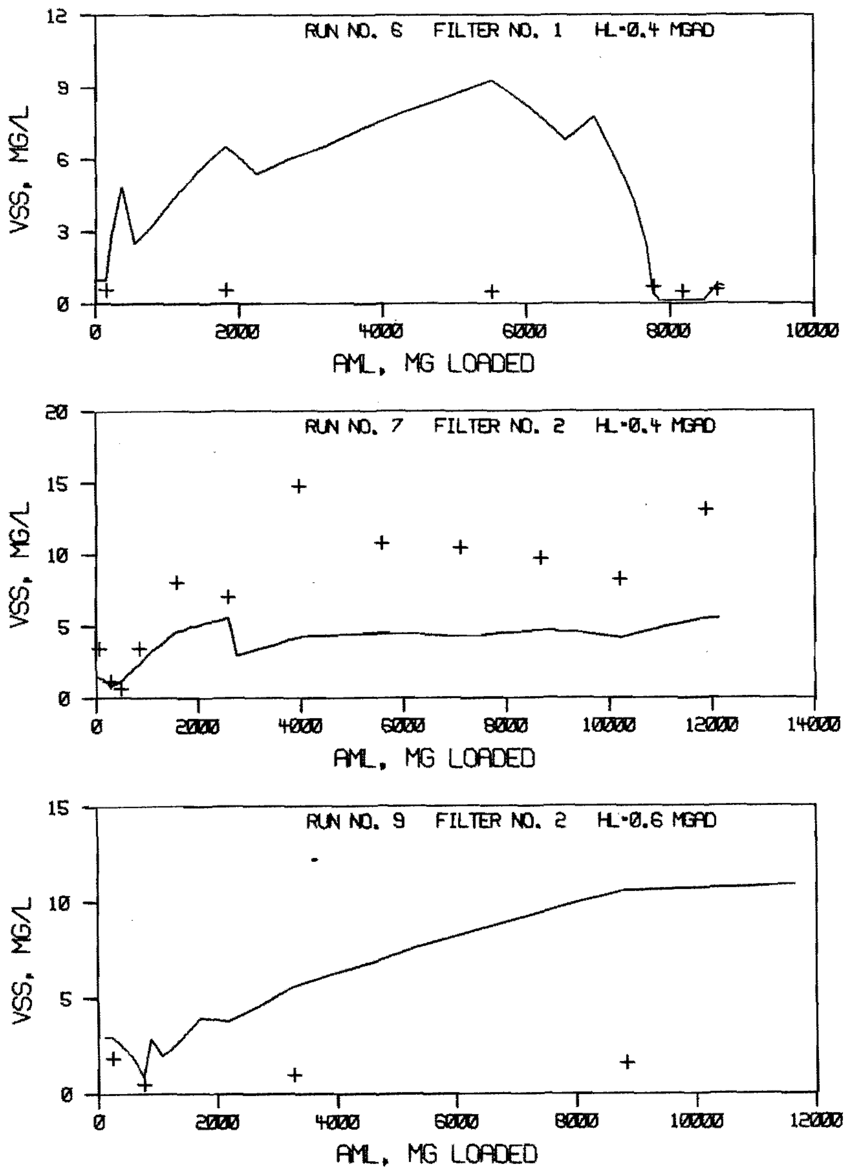



Figure 37. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

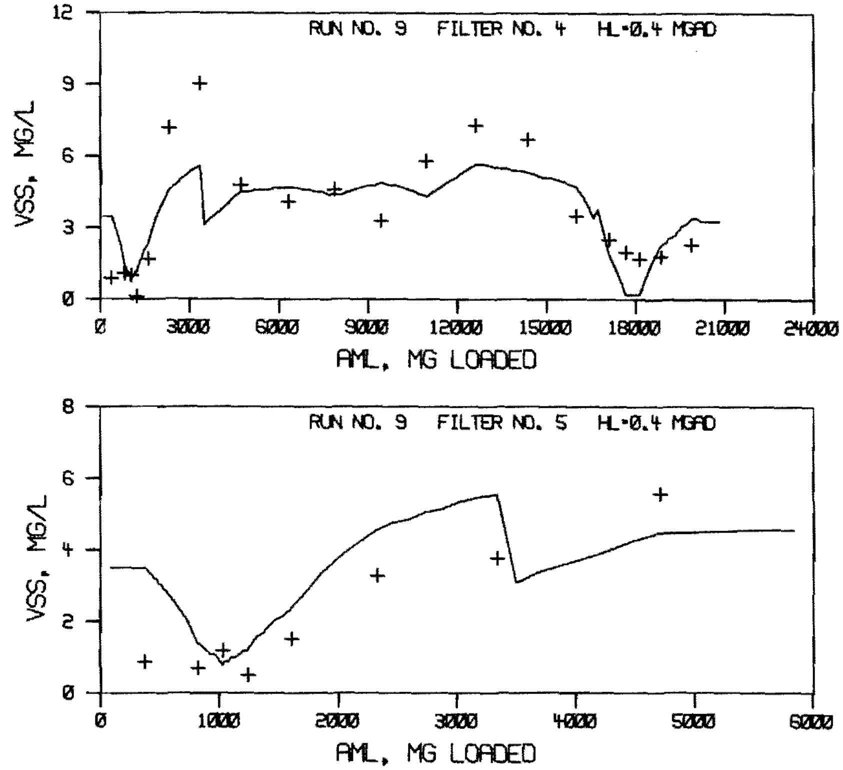



Figure 38. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm.

It was hypothesized that changes in ε' (above the 0.17 mm used to develop the ISF model) can be quantified by adjusting the sand phase filter efficiency term, λ. The filters operated by Tupyi (1977) consisted of 0.17, 0.40, and 0.68 mm ε' media. The ISF model was run utilizing these data, and actual and predicted filter effluent [VSS] values were plotted for the period of operation of the filter units. The predicted [VSS] effluent values for the 0.17 mm ε' sand were in agreement with those actual values measured, and special correlation coefficient values are listed in Table 22. The results of the ISF model for the 0.17 mm ε' sand are displayed in Figure 39. Of the three filters analyzed, only experiment 4-filter 1 showed any variation of predicted versus actual filter effluent [VSS]; however, the differences were minimal. The predicted values were all less than 7 mg/ℓ [VSS] while the corresponding actual values were consistently less than 4 mg/ℓ [VSS]. The ISF model was unable to predict these low [VSS] given influent [VSS] ranging from 5.5-62.4 mg/ℓ [VSS].

The predicted effluent [VSS] values for the 0.40 and 0.68 mm ε' media were consistently less than the actual measured [VSS] for the effluent from these filters. This discrepancy resulted because the sand phase filtration terms, λ, in the ISF model (model developed utilizing filters containing 0.17 mm ε' sand) are greater than those λ values for filters consisting of sand with larger effective sand sizes. The λ coefficients were adjusted so that the predicted effluent [VSS] aligned with those measured by Tupyi (1977). The effects of λ adjustment were quantified by calculating the special correlation coefficient (Equation 82). The $R_s$ values for some of the reduced λ terms are listed in Table 23.

Adjustment of the λ coefficients consisted of an iterative scheme which decreased λ by 10 percent for each iteration. The predicted and actual values were compared for each iteration, and it was concluded that both the 0.40 and 0.68 mm ε' filter systems would validate the ISF model as developed if λ values were decreased by the same constant correction factor:

$$\lambda_{0.40 \text{ mm } \varepsilon'} = \lambda_{0.68 \text{ mm } \varepsilon'} = (\lambda_{0.17 \text{ mm } \varepsilon'}) * 0.3138 \quad . \quad (83)$$

The reduced λ values are listed in Table 24, and the fractions of influent VSS (to the sand layers) removed are listed in Table 25. In comparing these removals with those of the 0.17 mm ε' media (Table 20), it was concluded that the larger sand sizes were only one-half to one-third (approximately) as efficient as the 0.17 mm ε' media in removing VSS from the

Table 22. Special correlation coefficients relating actual (measured) and predicted (ISF model) effluent VSS concentrations for field data; ε' = 0.17 mm (Harris 1977, Tupyi 1977).

| Run No. | Filter No. | No. of Episodes (Samples) | $R_s$ | Study |
|---|---|---|---|---|
| 1 | 1 | 6 | 0.66 | Harris (1977) |
| | 2 | 5 | 0.76 | |
| | 3 | 5 | 0.75 | |
| | 4 | 4 | 0.82 | |
| | 5 | 4 | 0.85 | |
| 2 | 1 | 7 | -2.86 | |
| | 6 | 6 | -6.56 | |
| 3 | 1 | 5 | -25.02 | |
| | 6 | 30 | -1.15 | |
| 4 | 1 | 19 | 0.73 | |
| | 6 | 13 | -36.48 | |
| 5 | 1 | 5 | -4.98 | |
| 6 | 1 | 6 | -54.02 | |
| 7 | 2 | 12 | 0.67 | |
| 9 | 2 | 4 | -12.95 | |
| | 4 | 20 | 0.88 | |
| | 5 | 8 | 0.76 | |
| 2 | 1 | 7 | 0.52 | Tupyi (1977) |
| 3 | | 24 | 0.54 | |
| 4 | | 15 | -0.23 | |

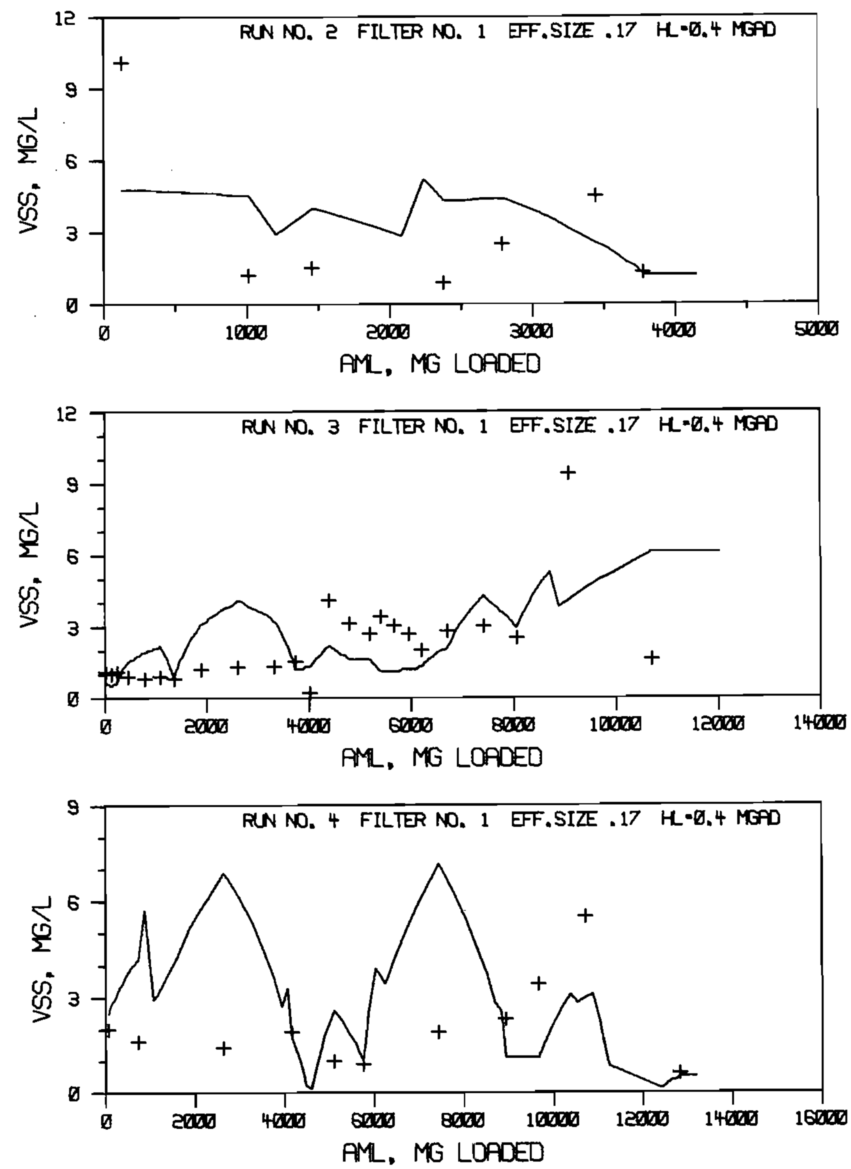



Figure 39. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Tupyi (1977).

Table 23. Special correlation coefficients relating actual (measured) and predicted (ISF model) effluent VSS concentrations for field units (Tupyi 1977) containing media ≥ 0.28 mm effective sand size (ε').

| Run No. | Filter No. | No. of Episodes (Samples) | ε' mm | $R_s$ | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | λ | 0.8100λ | 0.5314λ | 0.3874λ | 0.3138λ |
| 2 | 2 | 9 | 0.40 | 0.54 | −0.96 | −0.98 | 0.91 | 0.84 |
| 3 | | 26 | | 0.44 | 0.62 | 0.62 | 0.86 | 0.89 |
| 5 | 5 | 21 | 0.40 | 0.31 | 0.83 | 0.83 | 0.76 | 0.82 |
| 6 | | 7 | | 0.29 | 0.85 | 0.85 | 0.79 | 0.86 |
| 7 | | 4 | | 0.38 | 0.46 | 0.46 | 0.92 | 0.96 |
| 8 | | 6 | | 0.35 | 0.59 | 0.59 | 0.81 | 0.85 |
| 1 | 3 | 10 | 0.68 | 0.53 | | | 0.95 | 0.86 |
| 2 | | 30 | | 0.29 | | | 0.76 | 0.83 |

filtered wastewater lagoon effluent. It was also concluded (from observed magnitude of removals for the larger ε' media) that the sand phase affects the filtration process in only a minor way for the larger ε' media. The SAL portion of the ISF model almost totally dominates the removal of filter influent VSS. It was assumed that the SAL model remained unchanged for the larger ε' sand systems.

Because of lack of data for ε' values intermediate between 0.17 and 0.40 mm, it was also assumed that the ISF λ coefficients would be valid for ε' < 0.28 mm (0.28 mm ε' is the mean value of 0.17 and 0.40 mm ε').

Implementation of the model for operating ISF systems where ε' ≥ 0.28 mm involves using the reduced values of λ (Table 24). The program used to predict [VSS] contains a step which reduces λ coefficients (Table 19) established in model development and calibration.

The predicted and actual [VSS] field data for the 0.40 mm and 0.68 mm ε' ISF systems ($[\lambda_{0.17\ mm}\ \varepsilon']*0.3138$) are graphically displayed in Figures 40, 41, and, 42 respectively. In all cases, the model predictions were accurate estimates as to what Tupyi measured as actual filter effluent [VSS] for the larger ε' filtration systems (Table 23).

Table 24. Sand phase filtration term (λ) for ISF systems containing effective sand size media ≥ 0.28 mm.

| DML Range No. | Layer (1) λ $cm^{-1}$ | Layer (2) λ $cm^{-1}$ | Layer (3) λ $cm^{-1}$ | Layer (4) λ $cm^{-1}$ |
|---|---|---|---|---|
| III | .1606ε-01 | .1596ε-01 | .3963ε-02 | .8190ε-02 |
| II | .1419ε-01 | .3951ε-02 | .1673ε-01 | .5699ε-02 |
| I | .1123ε-01 | .9765ε-02 | .6270ε-02 | .7305ε-02 |
| <I | .1403ε-01 | .9765ε-02 | .6270ε-02 | .3367ε-02 |
| <I | .2425ε-01 | .1289ε-01 | .7525ε-02 | .4114ε-02 |

Table 25. Fraction of influent VSS removed by layer for ISF systems containing effective sand size media ≥ 0.28 mm.

| DML Range No. | Layer (1) | Layer (2) | Layer (3) | Layer (4) |
|---|---|---|---|---|
| III | 0.08 | 0.04 | 0.03 | 0.39 |
| II | 0.07 | 0.01 | 0.12 | 0.29 |
| I | 0.06 | 0.02 | 0.05 | 0.36 |
| <I | 0.07 | 0.02 | 0.05 | 0.19 |
| <I | 0.11 | 0.03 | 0.06 | 0.22 |

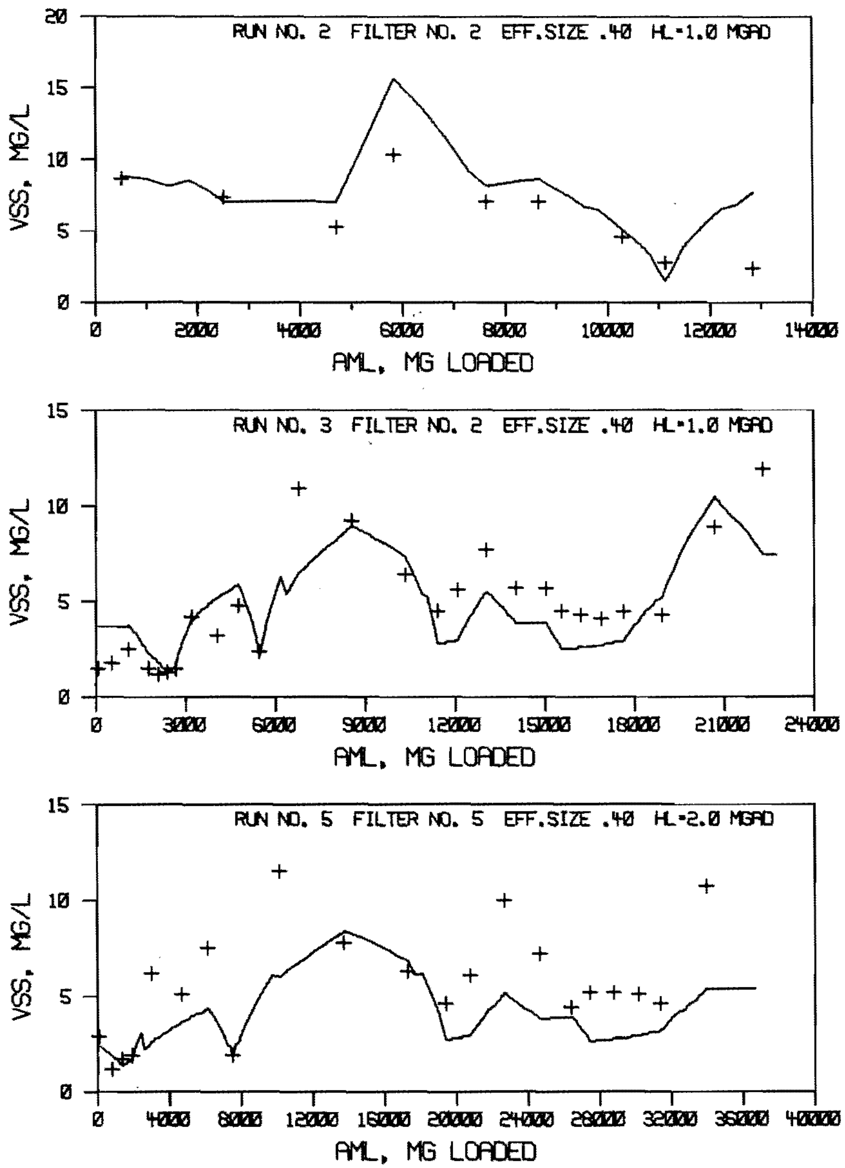



Figure 40. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Tupyi (1977).

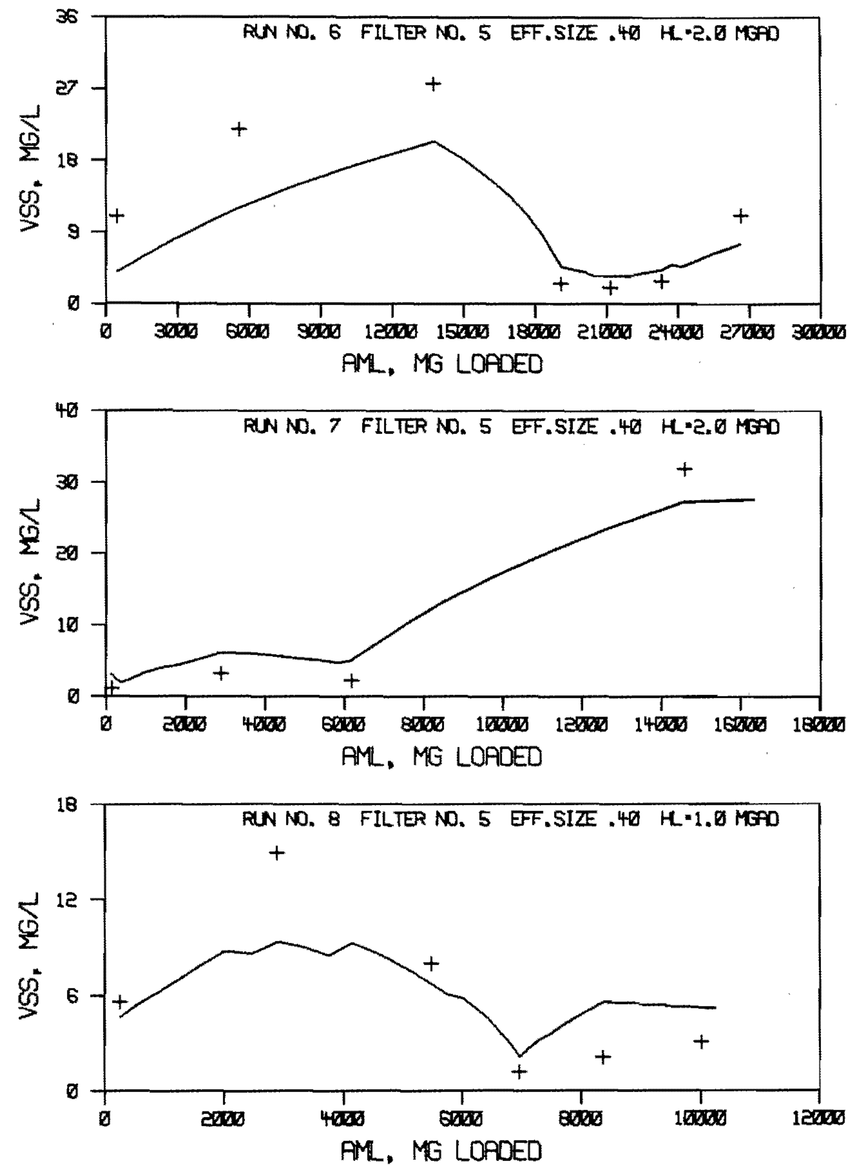



Figure 41. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Tupyi (1977).

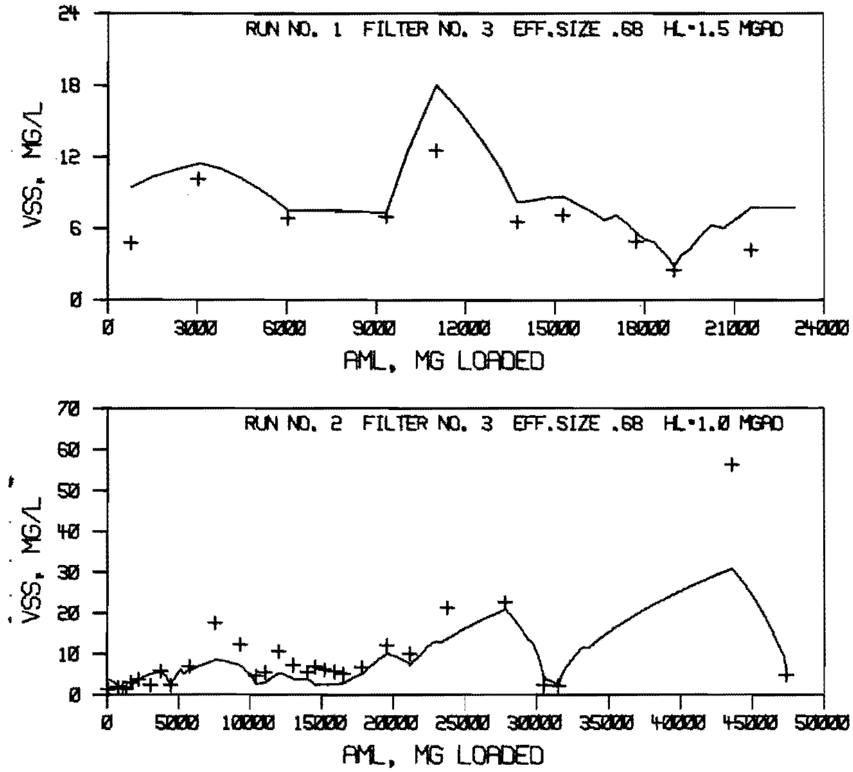



Figure 42. Predicted (line) and actual (+) ISF effluent (VSS) for ISF model validation using field scale units studied by Tupyi (1977).

SECTION VI

ALTERNATE ISF MODELS

The ISF model consists of two distinct portions (SAL and sand phases). The sand phase model (Equation 81) was developed utilizing four sand layers; therefore, a set of four empirical λ coefficients were quantified for each of five DML ranges (Table 19). This 20 empirical λ coefficient sand phase model should describe the operation of any field operational ISF system operated at or below the DML ranges studied in this research.

A modified ISF model was developed in which a functional relationship between λ and filter depth was substituted for the 20 empirical λ coefficients. A third model was described which simplified the modified ISF model by removing the SAL component of the model. This simplification was rationalized because the distinct SAL which developed in the laboratory did not develop to the same extent in the field. Desiccation and wind factors in the field caused disturbances of the SAL which did not occur in the laboratory. Removal of the SAL portion from the modified ISF model required that the mass of algae which was deposited to the SAL (saturation type function, Equation 39) in the first two models be distributed instead to the top layer of sand. The functional relationship between λ and depth was then recalculated to describe a simplified ISF model in which the sand accounted for all removal of VSS from the wastewater stabilization pond effluent being filtered.

In both the modified and simplified ISF models, the sand layers (Table 9) were changed such that the integration process was utilized upon 30 1-inch (2.54 cm) layers of sand. The fact that the layer thickness (DZ) was decreased to 1 inch and that both subsequent alternate ISF models utilized a functional relationship for λ, negated model calibration. If the functional relationship(s) for λ are valid, each alternate ISF model should accurately predict filter effluent quality.

## Modified ISF Model

Sand phase filter terms calculated from laboratory data (listed in Table 13) were plotted versus filter depth (Figure 43). The depth for each of the four layers (Table 9)

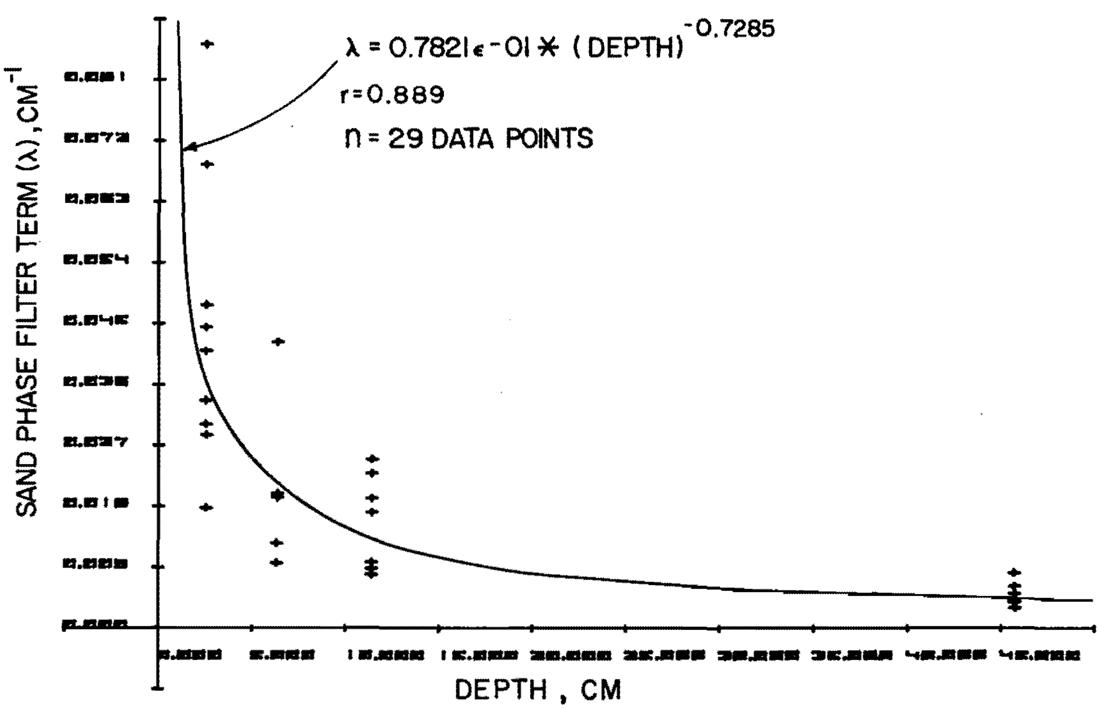



Figure 43. Sand phase filter term as a function of filter depth for the modified ISF model.

was assumed to be the mean depth for that layer (layer 1: 2.54 cm; layer 2: 6.35 cm; layer 3: 11.43 cm; layer 4: 45.72 cm). The functional relationship between $\lambda$ and filter depth in cm was concluded to be:

$$\lambda = 0.7821\varepsilon\text{-}01 * (\text{DEPTH})^{-0.7285} \quad . \quad . \ (84)$$

where the linear regression correlation coefficient was 0.889 for the ln-ln plot of these data. The values of $\lambda$ calculated for each 1 inch layer (Equation 84) were substituted into the sand phase model (Equation 81). Filter effluent was predicted as the effluent value from the 30th layer. The data for two of the laboratory columns are graphically displayed in Figures 44 and 45 (columns 5 and 6 respectively). This modified ISF model included the SAL model (Equation 52).

The special correlation coefficient (Equation 82) was utilized to quantify the accuracy of the modified ISF model in predicting actual laboratory effluent (VSS) values. The $R_s$ values, listed in Table 26, will be discussed after the simplified ISF model has been developed. Included in Table 26 are $R_s$ values for the ISF model and the simplified ISF model so that analyses of the comparisons between the ISF model and the two alternate ISF models utilizing laboratory data were possible.

## Simplified ISF Model

The simplified ISF model describes the ISF unit as a one phase (sand) system. The algal mass which was distributed to the SAL in the two previous models was instead forced

Table 26. Special correlation coefficients relating actual (measured) and predicted (model) effluent VSS concentrations for laboratory data.

| | | | | $R_s$ | | |
|---|---|---|---|---|---|---|
| Run No. | Column No. | Episodes (No. of Samples) | Layer No. | ISF Model (20 Empirical $\lambda$ Coefficients; SAL Included) | Modified ISF Model ($\lambda$ = F(depth); SAL Included) | Simplified ISF Model ($\gamma$ = F(depth); Without SAL) |
| 1 | 1 | 4 | 1 | 0.95 | 0.93 | 0.94 |
| | | | 2 | 0.92 | 0.91 | 0.91 |
| | | | 3 | 0.92 | 0.88 | 0.85 |
| | | | 4 | 0.82 | -0.70 | -0.03 |
| | 2 | 4 | 1 | 0.99 | 0.98 | 0.98 |
| | | | 2 | 0.96 | 0.96 | 1.00 |
| | | | 3 | 0.85 | 0.91 | 0.98 |
| | | | 4 | -2.53 | -27.50 | -16.70 |
| | 3 | 10 | 1 | 0.94 | 0.92 | 0.94 |
| | | | 2 | 0.90 | 0.87 | 0.91 |
| | | | 3 | 0.86 | 0.80 | 0.84 |
| | | | 4 | 0.65 | 0.63 | 0.85 |
| | 4 | 9 | 1 | 0.97 | 0.96 | 0.97 |
| | | | 2 | 0.96 | 0.96 | 0.94 |
| | | | 3 | 0.94 | 0.92 | 0.90 |
| | | | 4 | 0.57 | -0.66 | 0.08 |
| | 5 | 10 | 1 | 0.96 | 0.95 | 0.98 |
| | | | 2 | 0.87 | 0.85 | 0.88 |
| | | | 3 | 0.94 | 0.91 | 0.90 |
| | | | 4 | 0.52 | 0.43 | 0.56 |
| | 6 | 19 | 1 | 0.96 | 0.94 | 0.89 |
| | | | 2 | 0.91 | 0.88 | 0.78 |
| | | | 3 | 0.90 | 0.88 | 0.74 |
| | | | 4 | 0.72 | 0.72 | 0.63 |
| | 7 | 8 | 1 | 0.86 | 0.90 | 0.69 |
| | | | 2 | 0.93 | 0.96 | 0.91 |
| | | | 3 | 0.95 | 0.96 | 0.96 |
| | | | 4 | 0.88 | -0.10 | 0.00 |
| | 8 | 8 | 1 | 0.92 | 0.90 | 0.89 |
| | | | 2 | 0.92 | 0.90 | 0.90 |
| | | | 3 | 0.71 | 0.76 | 0.70 |
| | | | 4 | 0.67 | 0.00 | -0.06 |
| | 9 | 19 | 1 | 0.83 | 0.79 | 0.87 |
| | | | 2 | 0.75 | 0.68 | 0.80 |
| | | | 3 | 0.66 | 0.61 | 0.74 |
| | | | 4 | 0.49 | 0.42 | 0.56 |

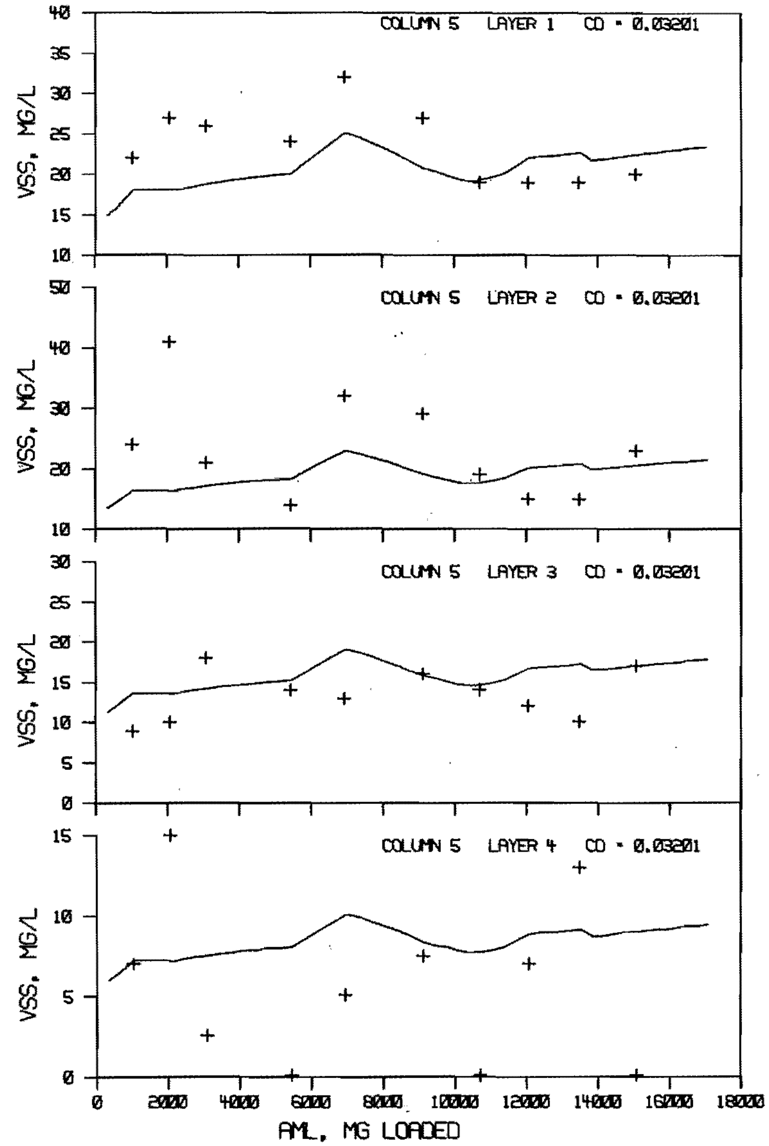



Figure 44. Predicted (line) and actual (+) sand layer effluent (VSS) for column 5. Modified ISF model with λ as a function of depth.

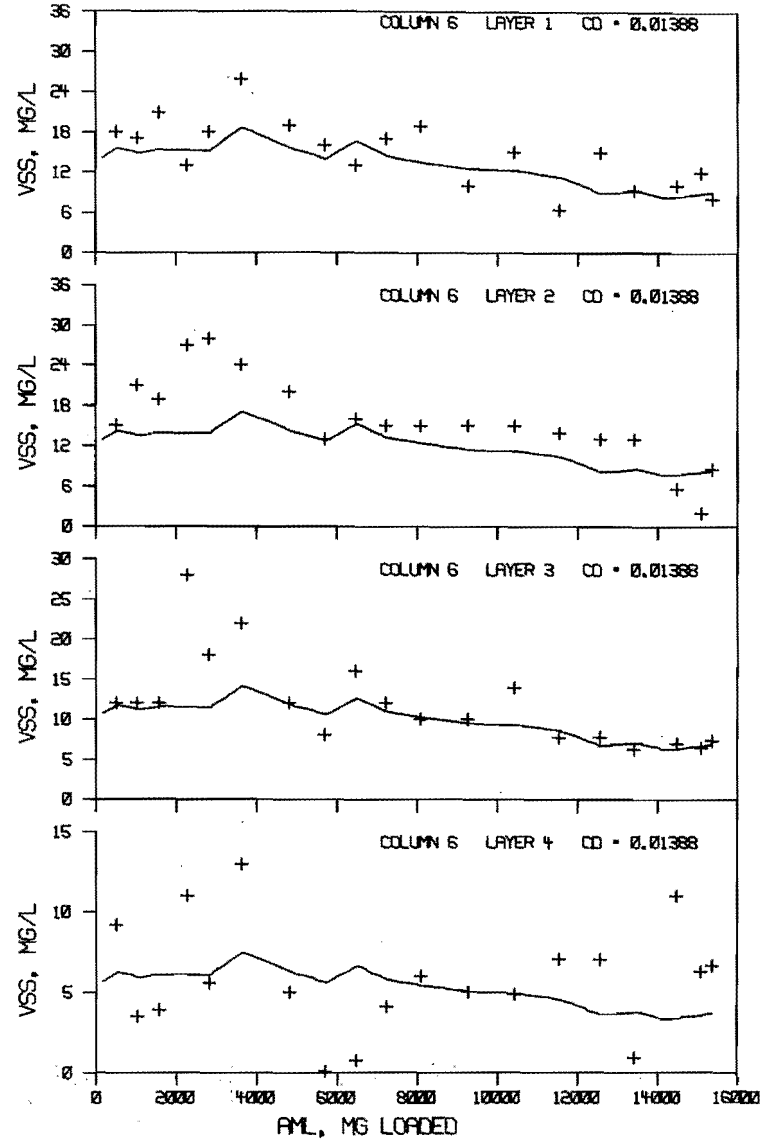



Figure 45. Predicted (line) and actual (+) sand layer effluent (VSS) for column 6. Modified ISF model with λ as a function of depth.

into the top layer (two inches, Table 9) of sand. The sand phase filter term was designated in this formulation, as γ. The values of γ were recalculated for the top layer of sand, and pertinent data are listed in Table 27. These values of γ, and those filter terms (λ) for layers two, three, and four (Table 9) listed in Table 13 were plotted versus mean filter depth (Figure 46) to obtain the functional relationship between γ and depth:

$$\gamma = 0.1828 * (\text{DEPTH})^{-0.9934} \quad . \quad . \quad . \quad . \quad (85)$$

where the linear regression correlation coefficient was 0.933 for the ln-ln plot of these data. The γ values for each one inch layer calculated from Equation 85 were substituted into Equation 81 to obtain predicted filter effluent (VSS) values. The data for columns 5 and 6 are represented in Figures 47 and 48, respectively. This simplified ISF model does not include the SAL model.

The special correlation coefficient was calculated to determine the accuracy of the simplified ISF model in predicting actual

Table 27. Sand phase filter term, γ, for sand layer (1) of laboratory filter run 1.

| DML Range No. | Column No. | DHL cm/day | DLOAD ℓ/day | Slope dσ/dAML V/V/Mass Loaded | γ $cm^{-1}$ |
|---|---|---|---|---|---|
| III | 1 | 65.50 | 10.04 | 0.5768ε-07 | 0.6310ε-01 |
| III | 2 | 65.50 | 10.04 | 0.8787ε-07 | 0.9613ε-01 |
| III | 4 | 46.78 | 7.17 | 0.7822ε-06 | 0.8556ε-01 |
| II | 5 | 46.78 | 7.17 | 0.8779ε-06 | 0.9603ε-01 |
| II | 7 | 28.08 | 4.30 | 0.1138ε-05 | 0.1243 |
| I | 3 | 65.50 | 10.04 | 0.7843ε-06 | 0.8580ε-01 |
| I | 8 | 28.08 | 4.30 | 0.9032ε-06 | 0.9871ε-01 |
| <I | 6 | 46.78 | 7.17 | 0.6682ε-06 | 0.7309ε-01 |
| <I | 9 | 28.08 | 4.30 | 0.9739ε-06 | 0.1064 |

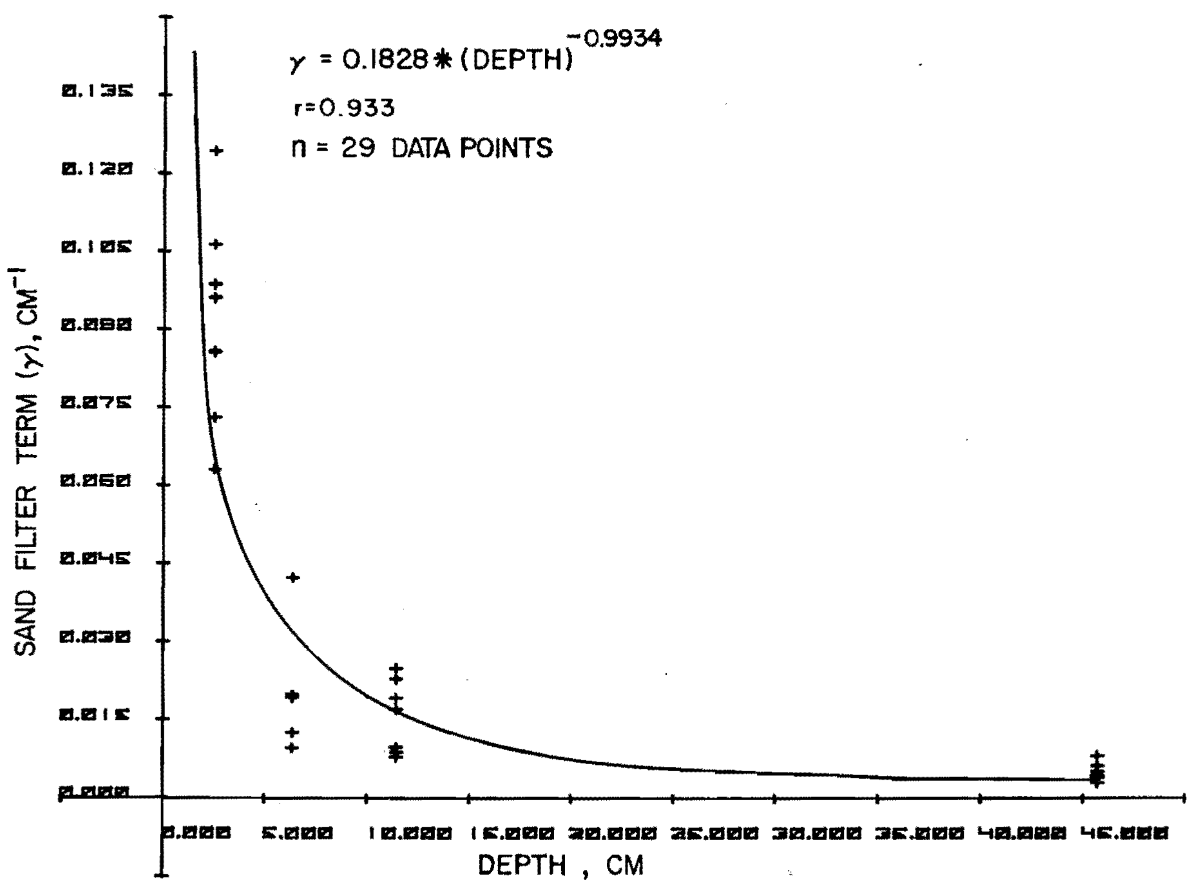



Figure 46. Sand filter term as a function of filter depth for simplified ISF (sand phase) model.

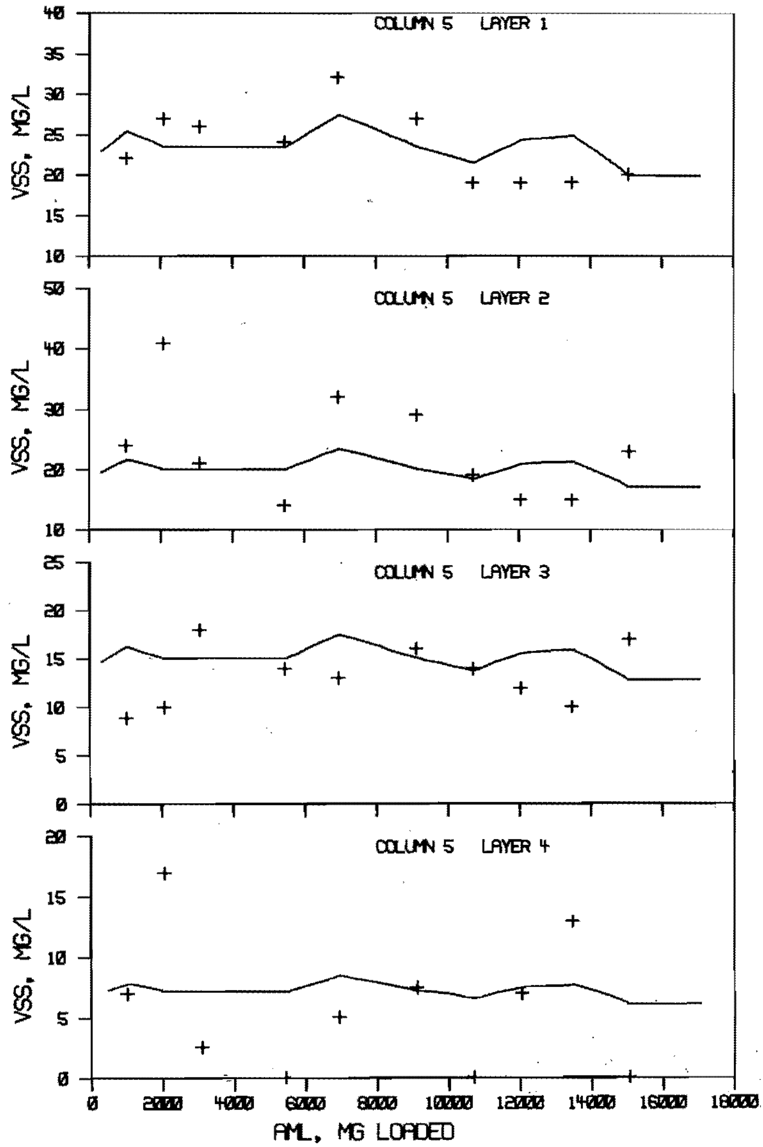



Figure 47. Predicted (line) and actual (+) sand layer effluent (VSS) for column 5. Simplified ISF model with γ as a function of depth.

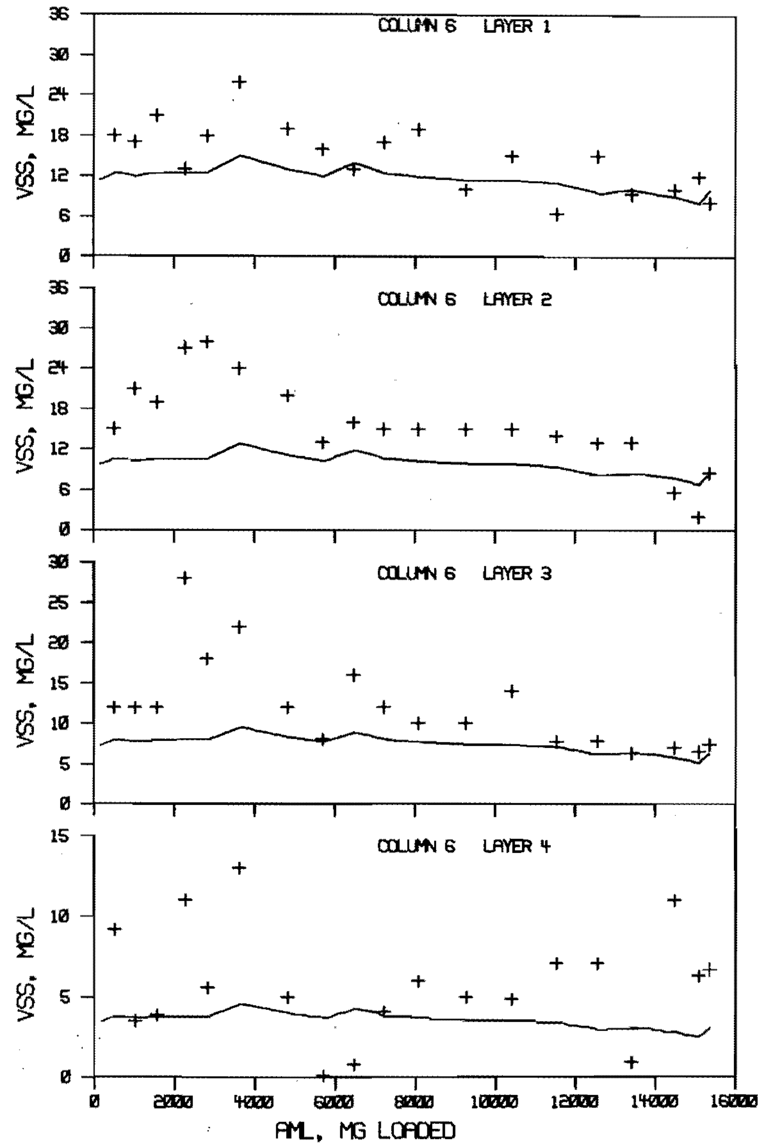



Figure 48. Predicted (line) and actual (+) sand layer effluent (VSS) for column 6. Simplified ISF model with γ as a function of depth.

laboratory effluent values (Table 26). Comparison of the three models for the top three layers (Table 9) resulted in the conclusion that there was no consistent difference in accuracy among the three models for the laboratory data. In layer four (Table 9), the ISF model was better in four of the nine columns. Because the actual (measured) data for the laboratory filter effluent was suspect (analytical values were at or below procedure sensitivity) and because five of the nine columns gave comparable results, the three models were concluded to be equivalent in ability to predict the laboratory data. As a test on the field data, the three models were compared in Section VII (validation of the modified ISF and simplified ISF models).

## SECTION VII

## VALIDATION OF ALTERNATE ISF MODELS

Field data collected by Harris (1977) and Tupyi (1977) were run on the computer utilizing both alternate models. The field mass loading data (DML, AML) are quantified in terms of laboratory scale filter units for the validation of the alternate ISF models. The modified ISF model consisted of a SAL component (from the ISF model) and a sand phase component where $\lambda$ was described as a function of filter depth (Equation 84). The simplified ISF model consisted of only a sand phase component where the sand phase filter term, $\gamma$, was described as a function of filter depth (Equation 85).

In analyzing those filter units which contained media of larger effective sand size than 0.17 mm (the 0.40 and the 0.68 mm $\varepsilon'$ units), the correction factor utilized to describe the decreased VSS removals of the larger $\varepsilon'$ media was 0.3138.

The special correlation coefficients (Equation 82), calculated utilizing all of the field data for the alternate ISF models, are listed in Table 28. Included in this table are $R_s$ values for the ISF model so that the predictions from each of the alternate models and the predictions from the ISF model could be compared.

Table 28. Special correlation coefficients relating actual (measured) and predicted (model) effluent VSS concentrations for the field data (Harris 1977, Tupyi 1977).

| Run No. | Filter No. | No. of Episodes (Samples) | Effective Sand Size, mm | ISF Model (20 Empirical $\lambda$ Coefficients) | Modified ISF Model ($\lambda$=F (depth); SAL Included) | Simplified ISF Model ($\gamma$=F (depth); Without SAL) |
|---|---|---|---|---|---|---|
| (Harris, 1977) | | | | | | |
| 1 | 1 | 6 | 0.17 | 0.66 | -0.53 | 0.45 |
| | 2 | 5 | 0.17 | 0.76 | 0.51 | 0.79 |
| | 3 | 5 | 0.17 | 0.75 | 0.00 | 0.42 |
| | 4 | 4 | 0.17 | 0.82 | 0.47 | 0.42 |
| | 5 | 4 | 0.17 | 0.85 | 0.49 | 0.51 |
| 2 | 1 | 7 | 0.17 | -2.86 | -6.29 | -1.77 |
| | 6 | 6 | 0.17 | -6.56 | -13.04 | -2.65 |
| 3 | 1 | 5 | 0.17 | -25.02 | -56.97 | -28.74 |
| | 6 | 30 | 0.17 | -1.15 | -3.16 | -0.05 |
| 4 | 1 | 19 | 0.17 | 0.73 | -0.03 | 0.76 |
| | 6 | 13 | 0.17 | -36.48 | -101.32 | -50.09 |
| 5 | 1 | 5 | 0.17 | -4.98 | -10.03 | -1.78 |
| 6 | 1 | 6 | 0.17 | -54.02 | -295.93 | -179.07 |
| 7 | 2 | 12 | 0.17 | 0.67 | 0.90 | 0.76 |
| 9 | 2 | 4 | 0.17 | -12.95 | -97.62 | -42.58 |
| | 4 | 20 | 0.17 | 0.88 | 0.67 | 0.82 |
| | 5 | 8 | 0.17 | 0.76 | 0.31 | 0.94 |
| (Tupyi, 1977) | | | | | | |
| 2 | 1 | | 0.17 | 0.52 | 0.24 | 0.33 |
| 3 | | | 0.17 | 0.54 | 0.22 | 0.57 |
| 4 | | | 0.17 | -0.23 | -2.67 | -1.30 |
| 2 | 2[a] | | 0.40 | 0.84 | 0.48 | -0.48 |
| 3 | | | 0.40 | 0.89 | 0.89 | 0.92 |
| 5 | 5[a] | | 0.40 | 0.82 | 0.85 | 0.90 |
| 6 | | | 0.40 | 0.86 | 0.95 | 0.96 |
| 7 | | | 0.40 | 0.96 | 0.93 | 0.90 |
| 8 | | | 0.40 | 0.85 | 0.95 | 0.55 |
| 1 | 3[a] | | 0.68 | 0.86 | 0.28 | -0.33 |
| 2 | | | 0.68 | 0.83 | 0.92 | 0.90 |

[a] $\lambda_{0.68\ \text{mm}\ \varepsilon'} = \lambda_{0.40\ \text{mm}\ \varepsilon'} = \left(\lambda_{0.17\ \text{mm}\ \varepsilon'}\right) * 0.3138$

Modified ISF Model

Predicted and actual filter effluent VSS concentrations were plotted versus AML for both sets of field data. The modified ISF model was more accurate than the ISF model in only one of the 17 filter runs (Harris 1977) analyzed (experiment 7-filter 2). The graphical representation of this single case along with two other filters (experiment 9-filters 4, 5) are presented in Figure 49. In these latter two filters, as well as the other 14 filters, the modified ISF model was less accurate than the ISF model in predicting the filter effluent (VSS) values measured in the Harris study (Table 28).

In the statistical analysis of the field data from Tupyi (1977), the modified ISF model was more accurate than the ISF model in three of the 11 filters studied (Figure 50: experiment 6-filter 5, experiment 8-filter 5, experiment 2-filter 3). Comparable results were obtained in three of the remaining nine filters (Figure 51: experiment 3-filter 2, experiment 7-filter 5, experiment 5-filter 5).

Simplified ISF Model

Better results were obtained when the second alternate ISF model was applied to the field data (Table 28). Predicted filter ef-

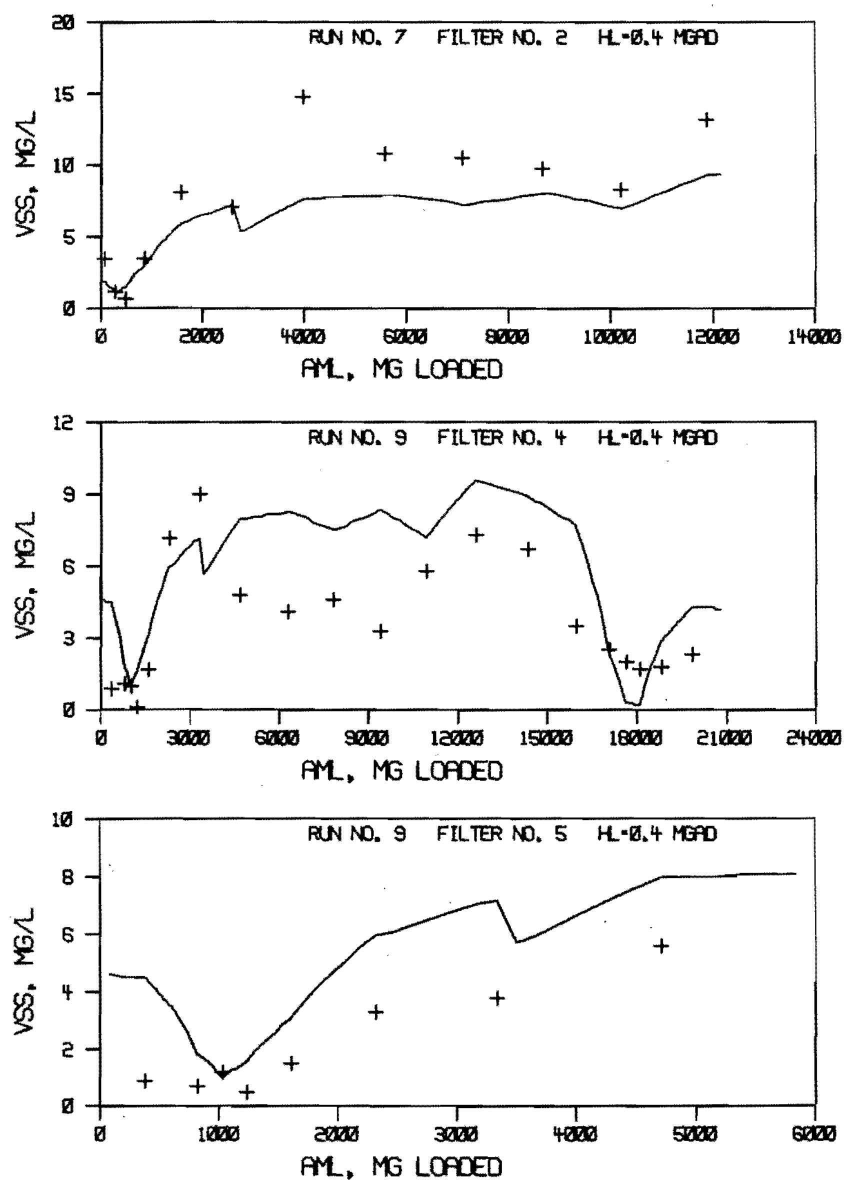



Figure 49. Predicted (line) and actual (+) ISF effluent (VSS) for modified ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm. Modified ISF model with λ as a function of depth.

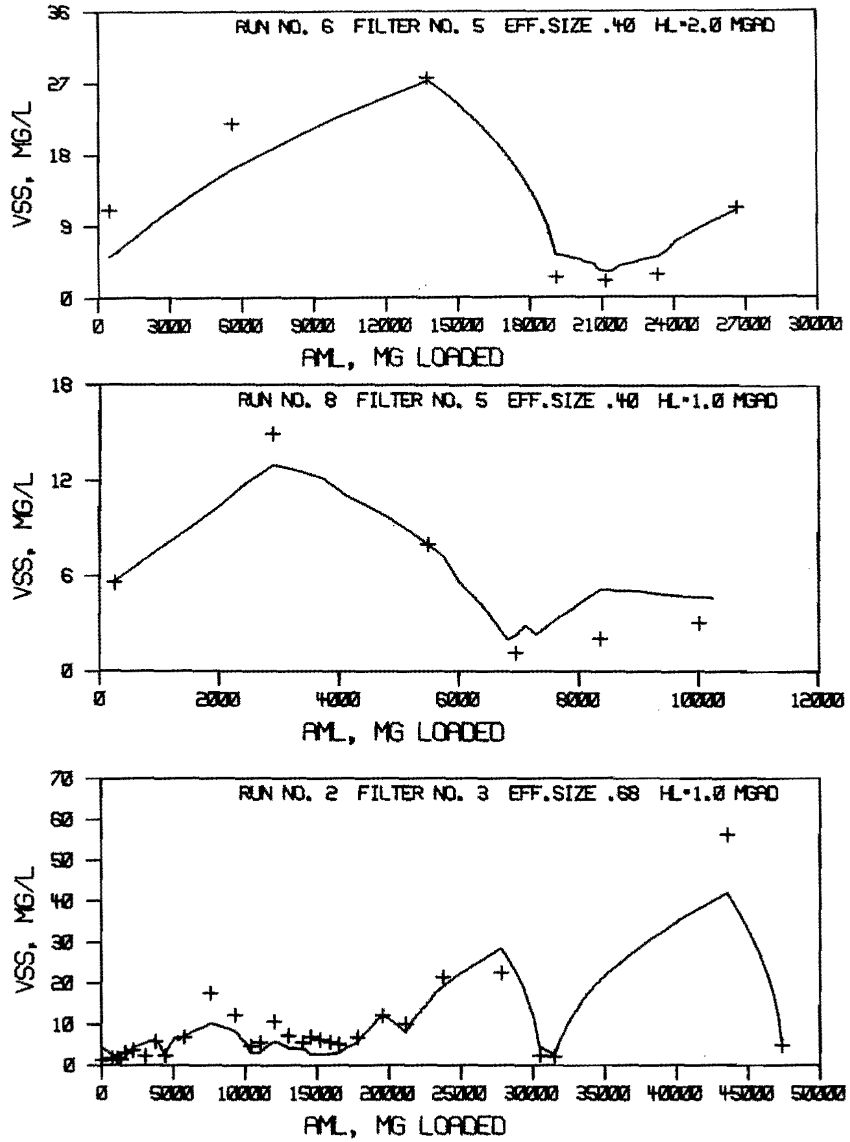



Figure 50. Predicted (line) and actual (+) ISF effluent (VSS) for modified ISF model validation using field scale units studied by Tupyi (1977). Modified ISF model with λ as a function of depth.

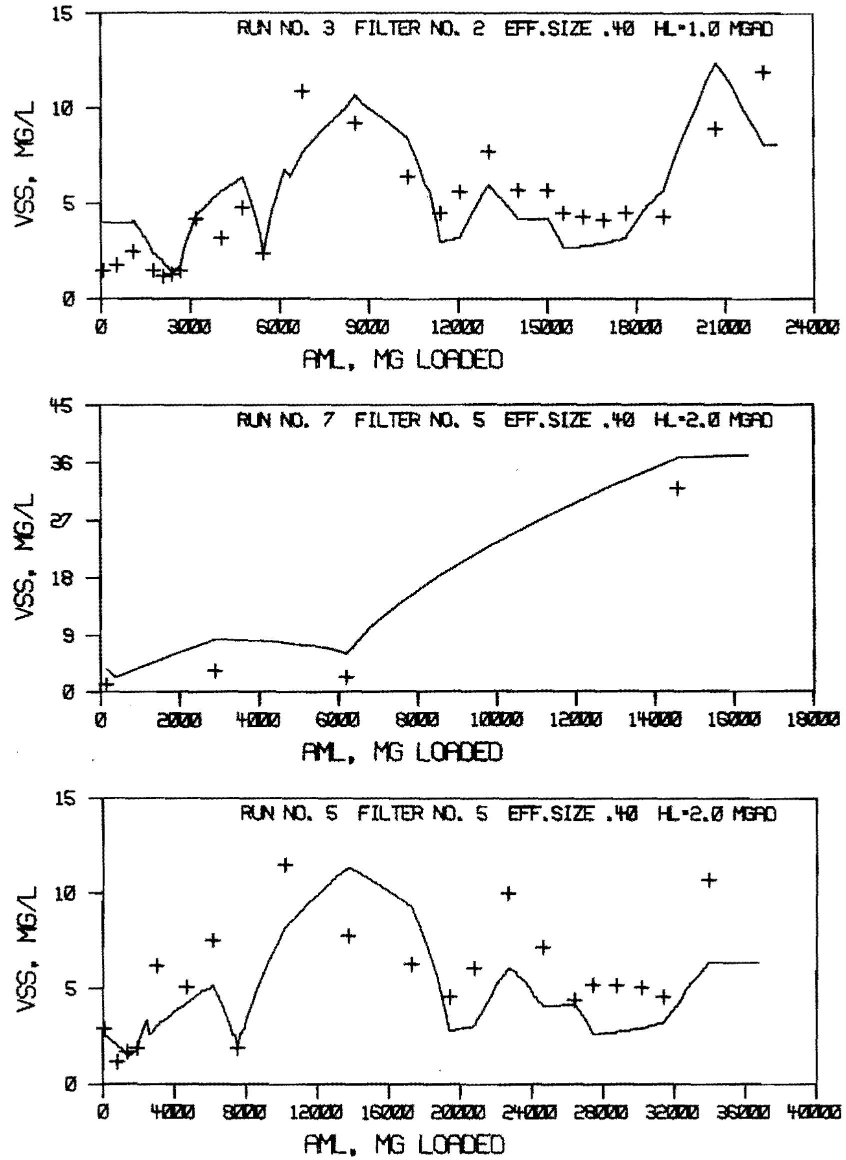



Figure 51. Predicted (line) and actual (+) ISF effluent (VSS) for modified ISF model validation using field scale units studied by Tupyi (1977). Modified ISF model with λ as a function of depth.

fluent (VSS) values were calculated utilizing the simplified ISF model and were plotted with actual (VSS) values versus AML for the Harris field data. The simplified model yielded more accurate predictions of filter effluent (VSS) quality than the ISF model in two of the 17 filters studied by Harris (Figure 52: experiment 7-filter 2, experiment 9-filter 5). Comparable results were obtained in 11 of the remaining 15 filters; four of the 11 cases are represented in Figures 52 and 53 (experiment 1-filter 2 and experiment 4-filter 1, experiment 9-filter 4, experiment 3-filter 6). The simplified ISF model was less accurate than the ISF model in four cases (Table 28: experiment 1-filters 1, 3, 4, 5). In these four cases, the VSS concentrations predicted by the simplified ISF model were consistently less than 3 mg/ℓ while the corresponding actual VSS concentrations were consistently less than 1 mg/ℓ.

Predicted and actual filter effluent VSS concentrations were plotted versus AML for the Tupyi field data (Figures 54 and 55). The computer program is listed in Appendix F. The simplified model was more accurate than the ISF model in three of the 11 filters analyzed (Figure 54: experiment 5-filter 5, experiment 6-filter 5, experiment 2-filter 3). Comparable results were obtained in three of the remaining eight filters (Figure 55: experiment 3-filters 1, 2, experiment 7-filter 5).

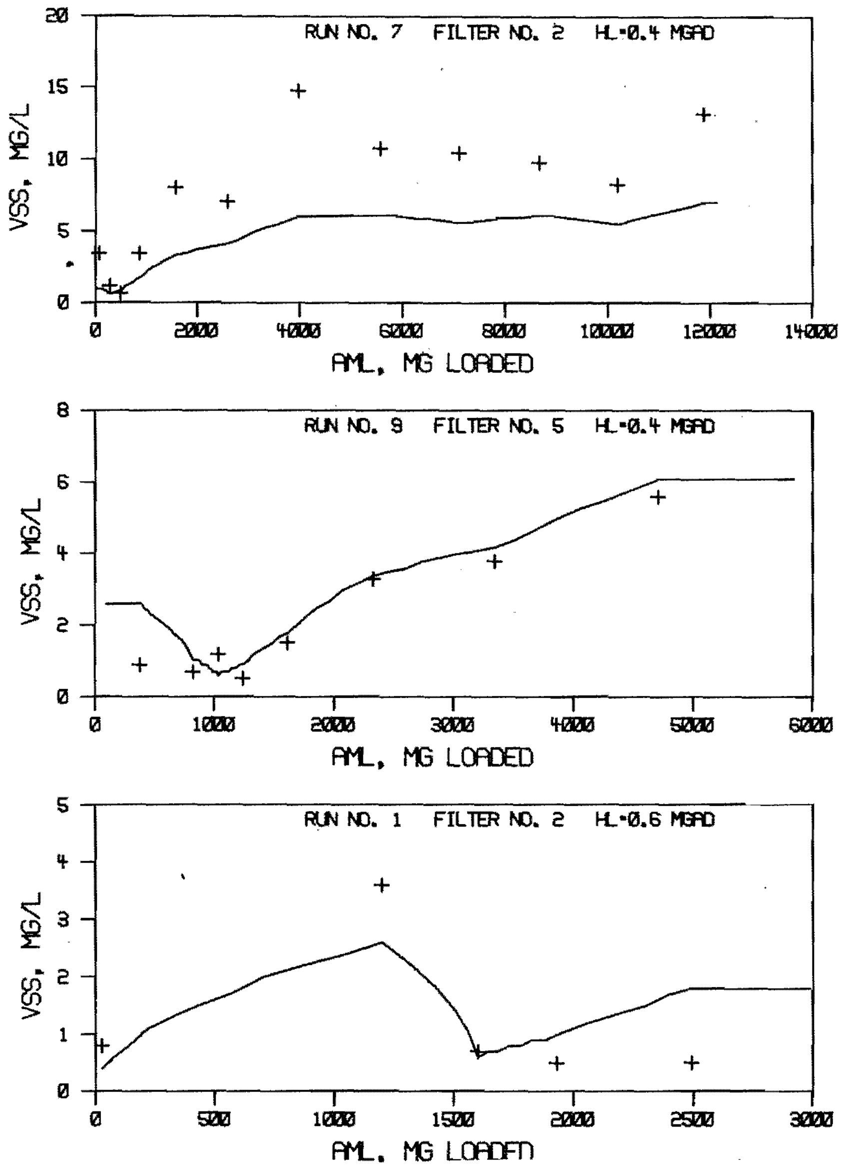



Figure 52. Predicted (line) and actual (+) ISF effluent (VSS) for simplified ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm. Simplified ISF model with γ as a function of depth.

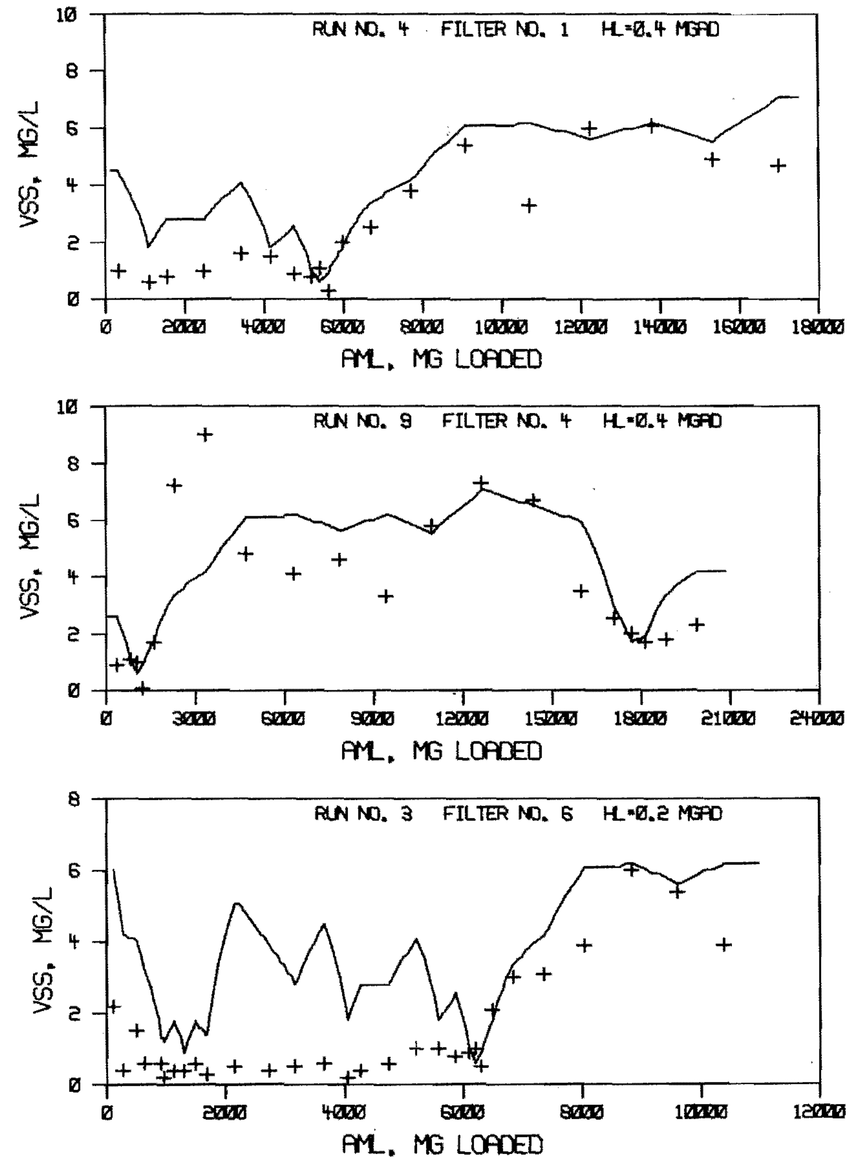



Figure 53. Predicted (line) and actual (+) ISF effluent (VSS) for simplified ISF model validation using field scale units studied by Harris (1977), effective sand size 0.17 mm. Simplified ISF model with γ as a function of depth.

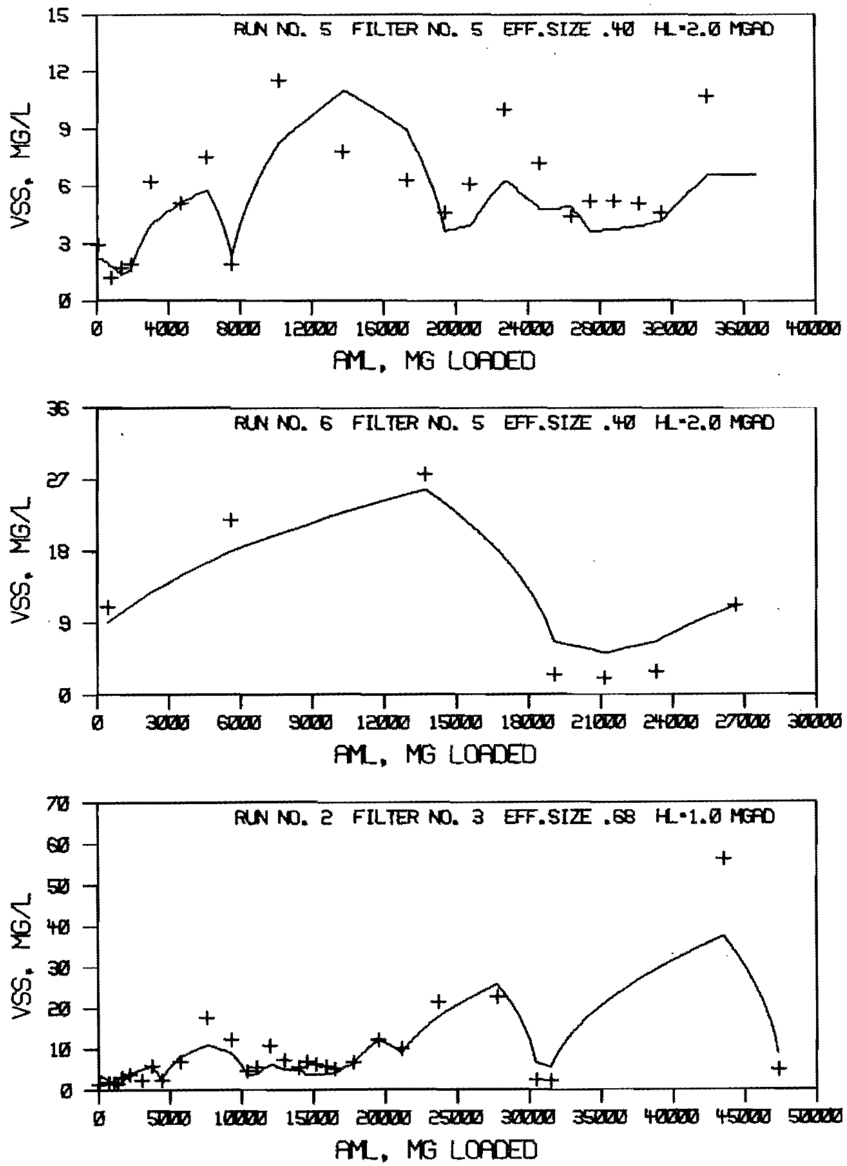



Figure 54. Predicted (line) and actual (+) ISF effluent (VSS) for simplified ISF model validation using field scale units studied by Tupyi (1977). Simplified ISF model with γ as a function of depth.

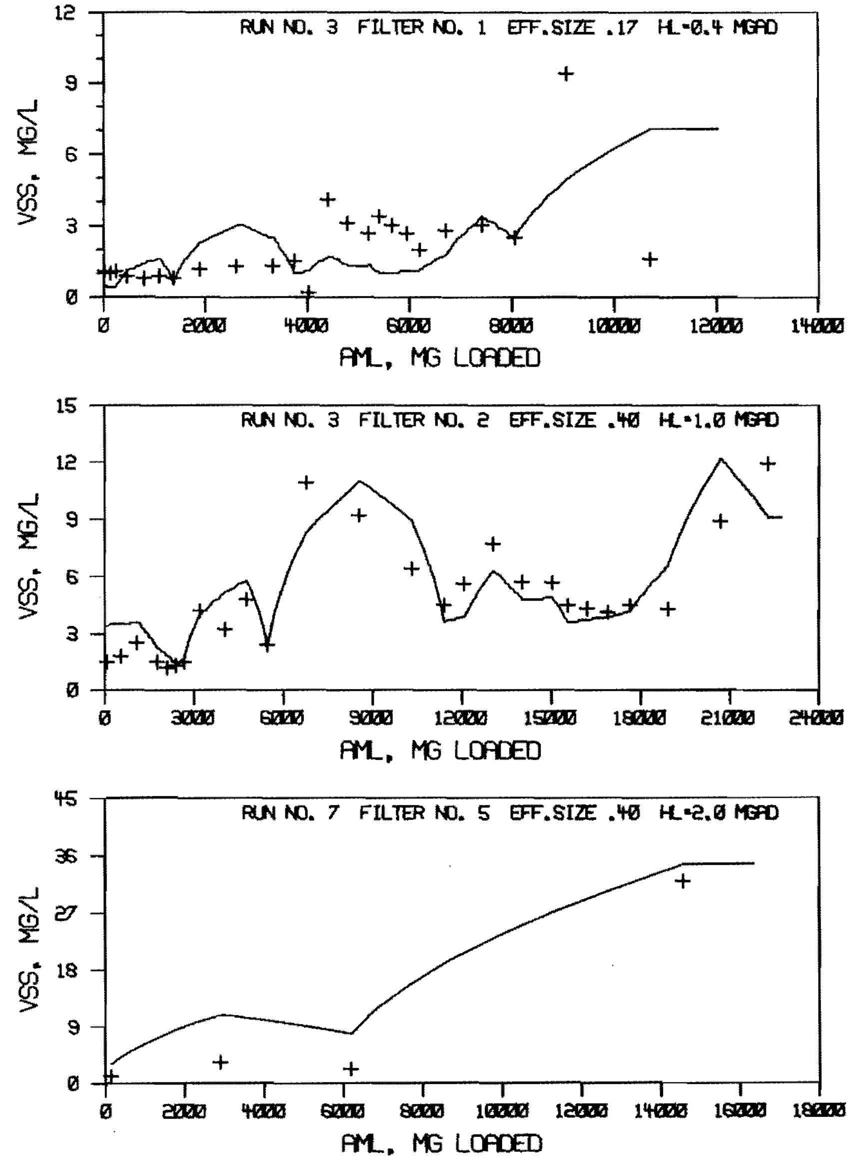



Figure 55. Predicted (line) and actual (+) ISF effluent (VSS) for simplified ISF model validation using field scale units studied by Tupyi (1977). Simplified ISF model with γ as a function of depth.

SECTION VIII

# DESIGN CONSIDERATIONS

## ISF Filtering Efficiency

In the simplified ISF model, the sand filter is divided into 30 one inch (2.54 cm) layers; each layer having a $\gamma$ value (Equation 85). In 30 steps, the VSS concentration in the wastewater stabilization pond effluent was decreased such that the same removal was obtained at all input VSS concentrations and hydraulic loading levels analyzed in this research. The linear relationship between effluent and influent [VSS] is presented (Figure 56) for 0.17 mm $\varepsilon'$ filters and for filters containing 0.40 or 0.68 mm $\varepsilon'$ media. The simplified ISF model quantified 84.6 percent VSS removal for 0.17 mm $\varepsilon'$ filters and 44.4 percent VSS removal for the 0.40 and 0.68 mm $\varepsilon'$ filters.

Application of this simplified ISF model is subject to limitations concerning hydraulic loading rates and total mass loaded to the filter units. The maximum hydraulic loading rate utilized in the laboratory phase of this research was 0.7 mgad. Laboratory data were used to develop $\gamma$ as a function of filter depth (Equation 85); therefore, a maximum allowable hydraulic loading rate of 0.7 mgad is applicable to the simplified ISF model.

The highest mass loading utilized in the laboratory was 687 mg/day/column. The expression equating laboratory DML rates and field scale mass loading rates is:

$$\begin{bmatrix} \text{Daily Mass Loading to} \\ \text{Laboratory Filter (DML)} \end{bmatrix} = \begin{bmatrix} \text{Hydraulic Loading} \\ \text{to Field Unit} \end{bmatrix} * [VSS] * 14.388 \qquad (86)$$

(mg/day) (mgad) (mg/ℓ)

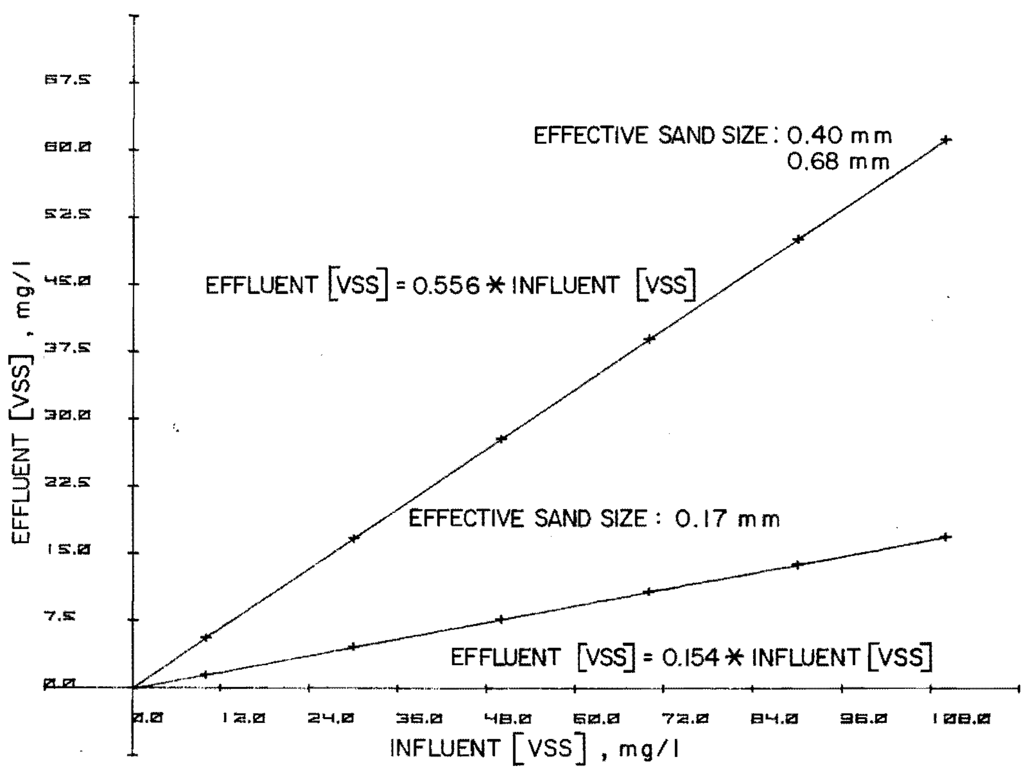



Figure 56. Effluent [VSS] as a function of influent [VSS] for 0.17 mm $\varepsilon'$ filters and 0.40, 0.68 mm $\varepsilon'$ filters: simplified ISF model.

Rearranging Equation 86 and including the maximum DML value to laboratory units (687 mg/day):

$$\begin{bmatrix} \text{Hydraulic Loading} \\ \text{to Field Unit} \end{bmatrix} = \frac{687}{14.388} * \frac{1}{[VSS]} = \frac{47.75}{[VSS]} \quad . \quad (87)$$

where hydraulic loading has units of mgad and [VSS] has units of mg/ℓ. The plot of Equation 87 (Figure 57) is a graphical representation of maximum field values of influent VSS (mg/ℓ) and hydraulic loading rates (mgad) which can be utilized in the simplified model. Any coordinate point (influent [VSS], hydraulic loading) in the shaded area of Figure 57 represents field conditions where the simplified model may be applied. The 0.7 mgad boundary has been discussed; the upper boundary for influent [VSS] is a design parameter which is estimated in terms of desired period of operation of the filter system before maintenance is required. The prediction of period of operation as a function of mass loading is described below.

## Prediction of Length of Operation of the ISF System

Length of filter operation (days) and daily mass surface loading rates ($g/m^2 \cdot day$) are inversely related. The larger the daily mass surface loading rate (SSL), the shorter will be the period of filter operation before it will require maintenance. The analysis of prediction of length of filter operation included ISF systems containing 0.17, 0.40, and 0.68 mm effective size sands. Data from the laboratory phase of this study were not used to predict the period of time between cleanings because of the availability of field data. Field data from the full scale filters were taken from the studies by Harris (1977) and Tupyi (1977). The pertinent data are listed in Tables 29, 30, and 31. The field suspended solids loading rates were calculated on the basis of mass of solids applied per unit surface area per day ($g/m^2 \cdot day$) to make it convenient to relate solids loading and hydraulic loading rates for design purposes.

The data (Tables 29, 30, and 31) were plotted to ascertain the functional relationship between length of operation and SSL values (Figures 58, 59, and 60). The functional form is

$$\text{days to plug} = A * (SSL)^{-B} \quad . \quad . \quad (88)$$

in which

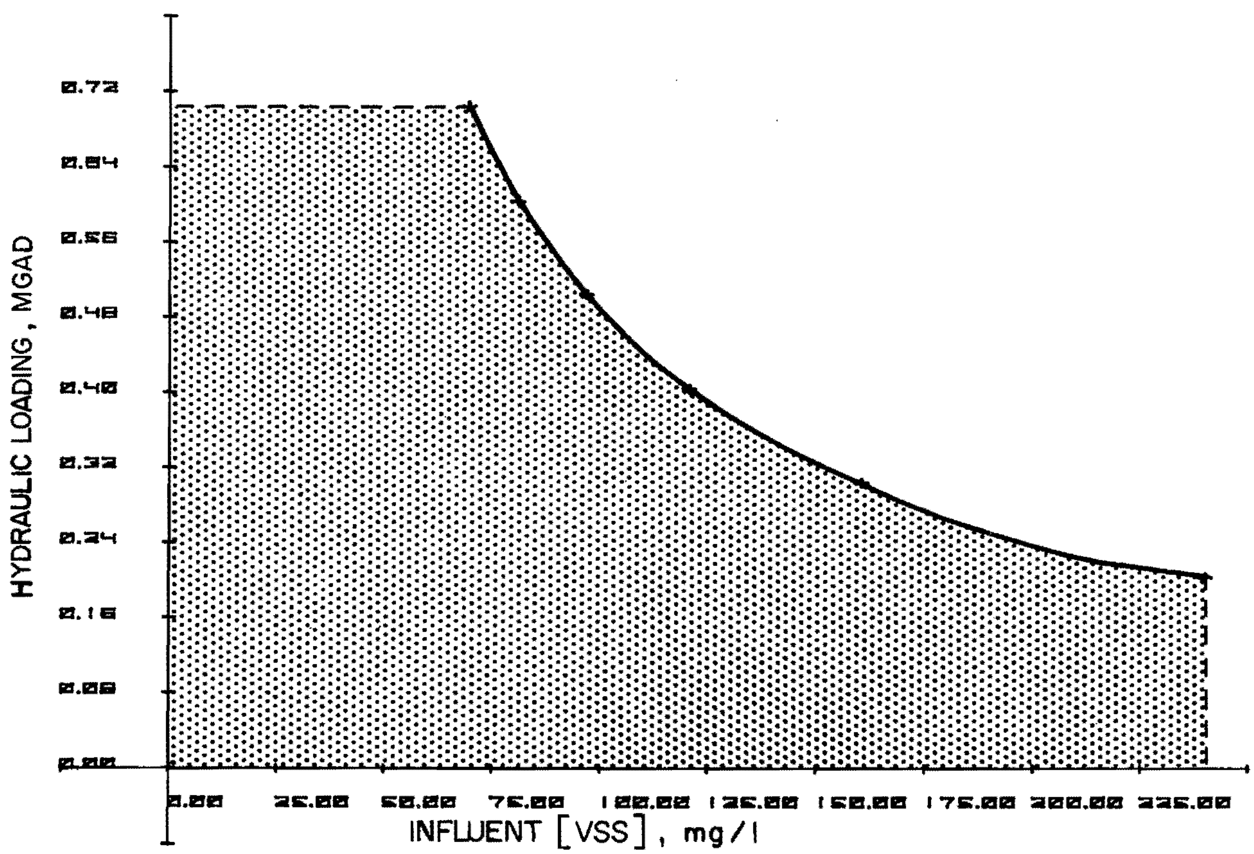



Figure 57. Operational (field scale) ISF influent VSS concentrations and hydraulic loading rates for which the simplified ISF model may be utilized (shaded area).

A = the value of the function when SSL = 1.0 $g/m^2 \cdot day$

B = the control parameter for the shape of the curve

The nonlinear decrease in days to plug with an increase in SSL was described best with a log-log relationship.

$$\log(\text{days to plug}) = \log A - B \log(\text{SSL})$$

When the log of days to plug (dependent variable) is plotted versus the log of SSL (independent variable), the slope of the linear regression line is B and the intercept is log A.

Table 29. Data for prediction of ISF period of operation for lagoon effluents during normal operation with a sand of 0.17 mm effective size (Harris 1977 and Tupyi 1977).

| Run No. | Filter No. | Days to Plug | Mean Influent Suspended Solids, mg/ℓ | Hydraulic Loading Rate, mgad | Suspended Solids Loading, SSL,[a] $g/m^2 \cdot day$ |
|---|---|---|---|---|---|
| Harris | | | | | |
| 3 | 1 | 32 | 29.1 | 0.4 | 10.89 |
| 5 | 1 | 36 | 29.3 | 0.4 | 10.96 |
| 4 | 2 | 27 | 22.8 | 0.6 | 12.80 |
| 5 | 2 | 17 | 33.4 | 0.6 | 18.74 |
| 8 | 2 | 15 | 23.4 | 0.6 | 13.13 |
| 5 | 3 | 13 | 26.0 | 0.8 | 19.45 |
| 5 | 4 | 5 | 16.5 | 1.0 | 15.43 |
| 6 | 4 | 5 | 23.1 | 1.0 | 21.61 |
| 7 | 4 | 6 | 43.5 | 1.0 | 40.69 |
| 8 | 4 | 8 | 40.8 | 1.0 | 38.16 |
| 9 | 4 | 143 | 30.8 | 0.4 | 11.52 |
| 5 | 5 | 5 | 16.5 | 1.0 | 15.43 |
| 6 | 5 | 5 | 23.1 | 1.0 | 21.61 |
| 7 | 5 | 7 | 43.5 | 1.0 | 40.69 |
| 9 | 5 | 58 | 18.9 | 0.4 | 7.07 |
| 10 | 5 | 20 | 45.7 | 0.4 | 17.10 |
| 13 | 5 | 7 | 19.9 | 1.0 | 18.61 |
| 1 | 6 | 6 | 10.9 | 2.0 | 20.39 |
| 3 | 6 | 189 | 27.4 | 0.2 | 5.13 |
| 4 | 6 | 88 | 38.6 | 0.2 | 7.22 |
| 4 | 1 | 130 | 28.1 | 0.4 | 10.51 |
| 6 | 1 | 42 | 47.4 | 0.4 | 17.73 |
| 7 | 2 | 80 | 29.1 | 0.4 | 10.89 |
| 9 | 2 | 26 | 61.4 | 0.6 | 34.46 |
| Tupyi | | | | | |
| 1 | 6 | 280 | 23.0 | 0.2 | 4.30 |
| 1 | 1 | 11 | 44.8 | 0.4 | 16.76 |
| 2 | 1 | 36 | 31.2 | 0.4 | 11.67 |
| 3 | 1 | 166 | 13.8 | 0.4 | 5.16 |
| 4 | 1 | 103 | 24.7 | 0.4 | 9.24 |

[a] [Suspended Solids Loading to the Filter (SSL), $g/m^2 \cdot day$] = [Hydraulic Loading to Filter, mgad] x [Suspended Solids Conc., mg/ℓ] x[0.9353]

The expressions predicting length of filter operation for the three effective size sands (ε') are:

$$\text{Days to plug} = 2529\,(\text{SSL})^{-1.733} \quad (\varepsilon' = 0.17\ \text{mm}) \quad . \quad . \quad (89)$$

Table 30. Data for prediction of ISF period of operation for lagoon effluents during normal operation with a sand of 0.40 mm effective size (Tupyi 1977).

| Run No. | Filter No. | Days to Plug | Mean Influent Suspended Solids, mg/ℓ | Hydraulic Loading Rate, mgad | Suspended Solids Loading, SSL, $g/m^2 \cdot day$ |
|---|---|---|---|---|---|
| 1 | 2 | 6 | 39.6 | 1.5 | 55.56 |
| 2 | 2 | 37 | 37.0 | 1.0 | 34.61 |
| 3 | 2 | 177 | 11.3 | 0.4 | 10.57 |
| 4 | 2 | 17 | 32.4 | 0.4 | 30.30 |
| 5 | 2 | 30 | 34.0 | 1.0[b] | 31.80 |
| 1 | 5 | 3 | 44.9 | 3.0 | 125.99 |
| 2 | 5 | 7 | 42.4 | 2.0 | 79.31 |
| 3 | 5 | 18 | 24.7 | 2.0 | 46.20 |
| 5 | 5 | 148 | 10.1 | 2.0 | 18.89 |
| 6 | 5 | 42 | 25.2 | 2.0 | 47.14 |
| 7 | 5 | 23 | 27.6 | 2.0 | 51.63 |
| 8 | 5 | 37 | 21.8 | 1.0 | 20.39 |

[a] [Suspended Solids Loading to the Filter (SSL), $g/m^2 \cdot day$] = [Hydraulic Loading to Filter, mgad] x [Suspended Solids Conc., mg/ℓ] x [0.9353]

[b] Loaded twice weekly.

Table 31. Data for prediction of ISF period of operation for lagoon effluents during normal operation with a sand of 0.68 mm effective size (Tupyi 1977).

| Run No. | Filter No. | Days to Plug | Mean Influent Suspended Solids, mg/ℓ | Hydraulic Loading Rate, mgad | Suspended Solids Loading, SSL, $g/m^2 \cdot day$ |
|---|---|---|---|---|---|
| 1 | 3 | 46 | 38.2 | 1.5 | 53.59 |
| 2 | 3 | 196 | 15.8 | 1.0 | 14.78 |
| 1 | 4 | 11 | 44.9 | 3.0 | 125.99 |
| 2 | 4 | 23 | 35.4 | 2.0 | 66.22 |
| 4 | 4 | 152 | 14.2 | 2.0 | 26.56 |
| 5 | 4 | 84 | 34.1 | 1.0 | 31.89 |

[a] [Suspended Solids Loading in the Filter (SSL), $g/m^2 \cdot day$] = [Hydraulic Loading to Filter, mgad] x [Suspended Solids Conc., mg/ℓ] x[0.9353]

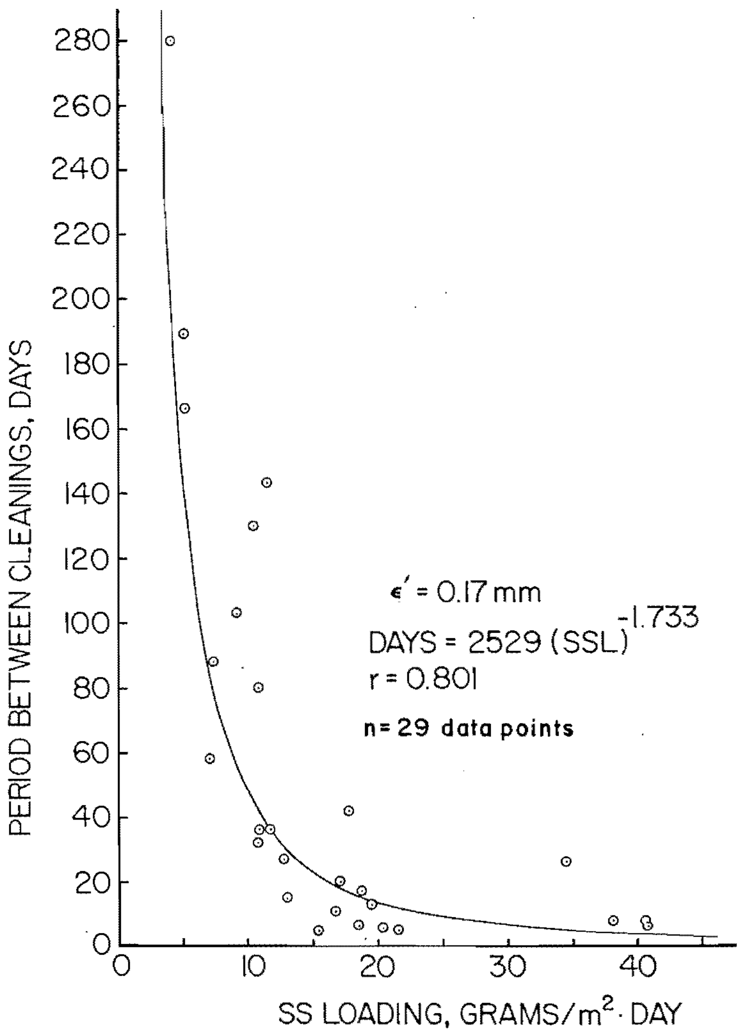



Figure 58. Period of filter operation as a function of SSL for filters containing 0.17 mm effective size sand.

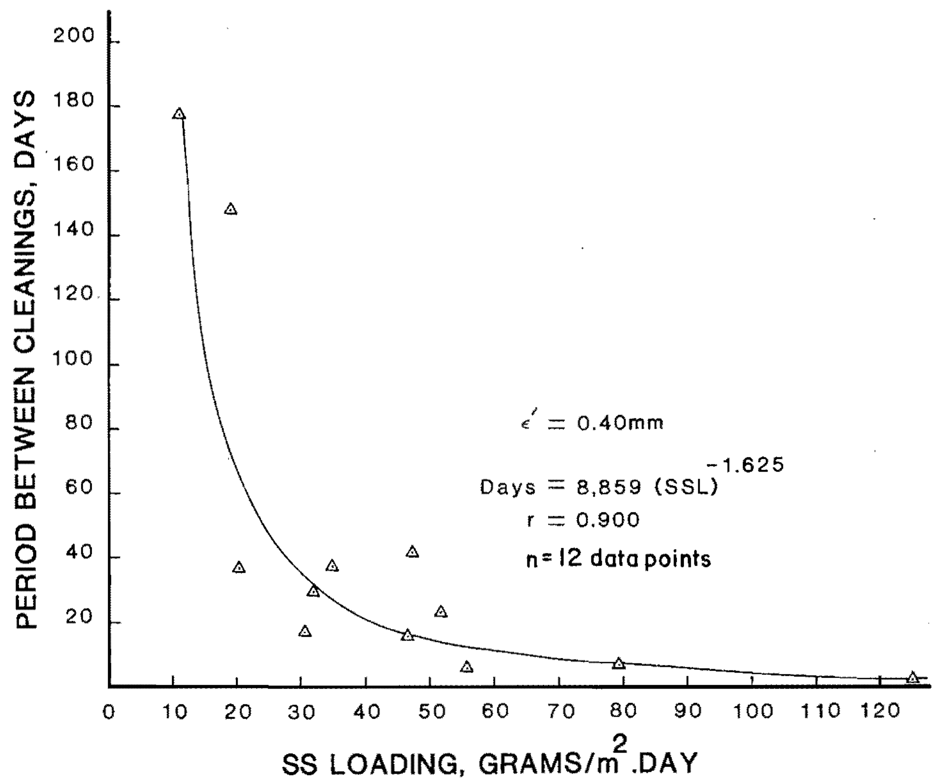



Figure 59. Period of filter operation as a function of SSL for filters containing 0.40 mm effective size sand.

$$\text{Days to plug} = 8{,}859\ (\text{SSL})^{-1.625}\ (\varepsilon' = 0.40\ \text{mm}) \quad . \quad . \ (90)$$

$$\text{Days to plug} = 12{,}350\ (\text{SSL})^{-1.445}\ (\varepsilon' = 0.68\text{mm}) \quad . \quad . \ (91)$$

The correlation coefficients for the three equations are 0.801, 0.900, and 0.979, respectively. All are significant at the 5 percent level.

It is not recommended that sands with effective sizes of greater than 0.35 mm be used to polish wastewater stabilization pond effluents if a 30 mg/ℓ $BOD_5$ and suspended solids effluent quality is required. The quality of effluent expected from the 0.40 and 0.68 mm effective size sands can be obtained from the report by Tupyi (1977).

## Prediction of Length of Filter Operation for Lagoon Effluents Having Calcium Carbonate Precipitation Problems

Upon examination of all the field data (Harris 1977), it was observed that there was a definite decrease in the period of operation for some of the filter units as compared to the run time predicted by Equations 89, 90, and 91. Therefore, a special case was defined for situations where high algal growth (and resultant high pH) in secondary wastewater stabilization ponds occurred in the presence of high calcium hardness. At pH levels greater than 8.3 pH units, the bicarbonate-carbonate equilibrium system shifts towards increased carbonate concentrations. Given the presence of calcium ion ($Ca^{++}$, prevalent in hard waters), the following precipitation reaction occurs:

$$Ca^{++} + CO_3^{=} \rightarrow CaCO_3 \downarrow \quad . \quad . \quad . \quad . \quad . \quad . \quad . \ (92)$$

The result is that the ISF develops a "plaster-like" surface crust (Harris 1977) which shortens filter run time. Pertinent field data illustrating this phenomenon of decreased length of operation are listed in Table 32. Days to plug were plotted versus corresponding SSL values in order to obtain the functional relationship between these two parameters for the special case (Figure 61). The functional form is:

$$\text{Days to plug} = 319\ (\text{SSL})^{-1.119} \quad . \quad . \quad . \ (93)$$

with a correlation coefficient of 0.948 calculated when the log of the days to plug was plotted versus the log of the SSL. In comparing the results of Equations 89-91

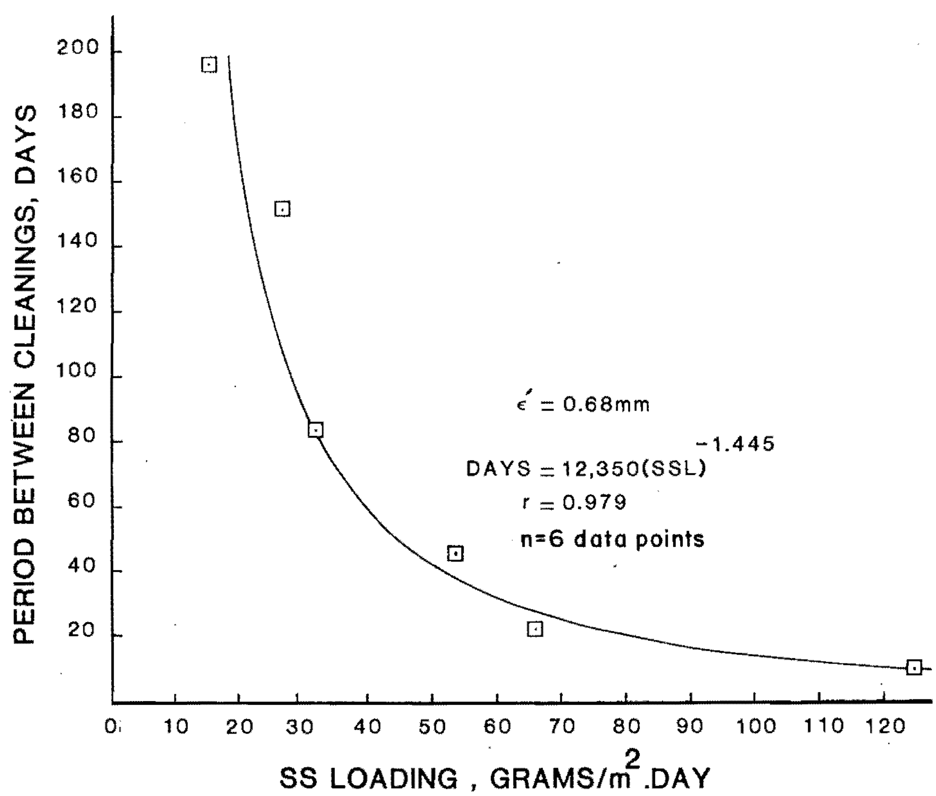



Figure 60. Period of filter operation as a function of SSL for filters containing 0.68 mm effective size sand.

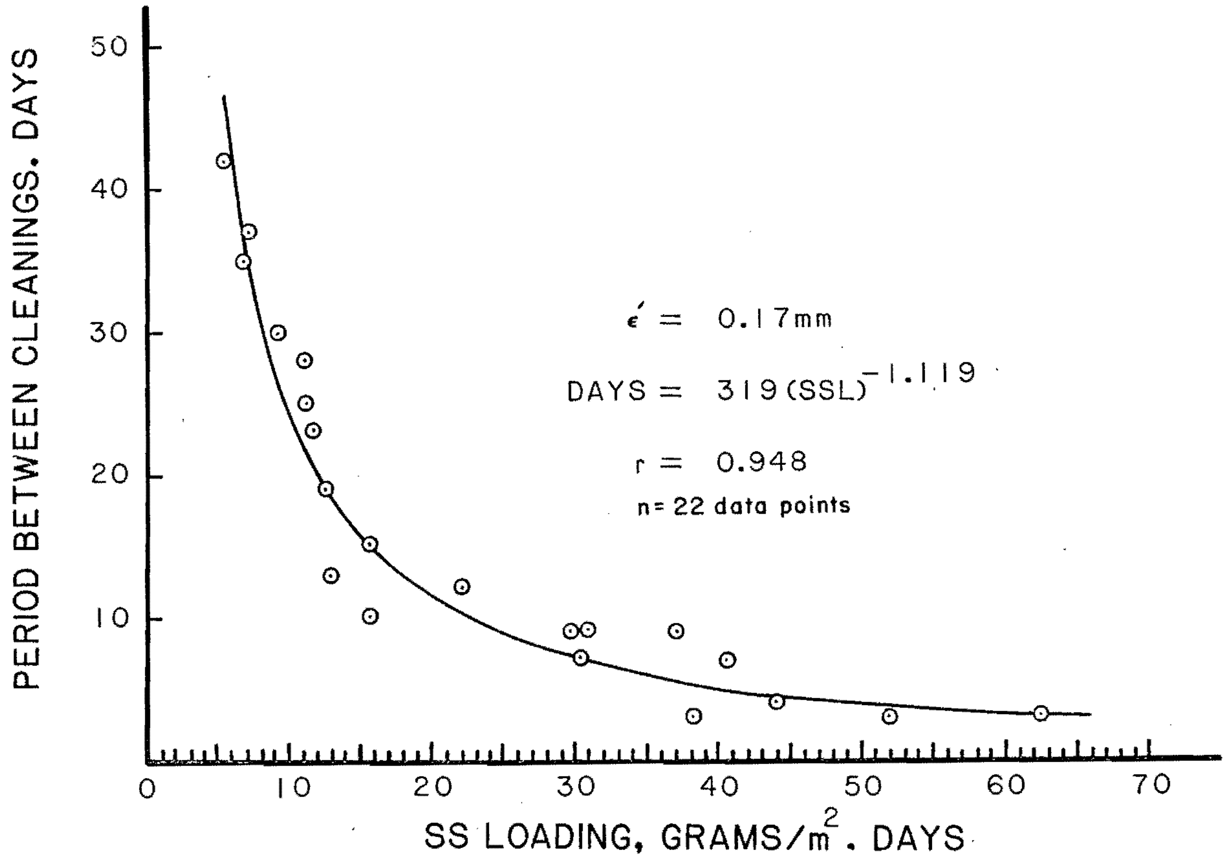



Figure 61. Period of filter operation as a function of SSL for lagoon effluents having calcium carbonate precipitation problems.

Table 32. Data for prediction of ISF period of operation for lagoon effluents having calcium carbonate precipitation problems (from Harris 1977).

| Run No. | Filter No. | Days to Plug | Mean Influent Suspended Solids mg/ℓ | Hydraulic Loading Rate, mgad | Suspended Solids Loading, SSL,[a] g/m²·day | pH Mean Influent pH Unit |
|---|---|---|---|---|---|---|
| 1 | 1 | 37 | 19.6 | 0.4 | 7.33 | 8.8 |
| 2 | 1 | 25 | 29.9 | 0.4 | 11.19 | 8.6 |
| 1 | 2 | 35 | 12.4 | 0.6 | 6.96 | 8.7 |
| 2 | 2 | 9 | 55.2 | 0.6 | 30.98 | 9.1 |
| 3 | 2 | 12 | 39.5 | 0.6 | 22.17 | 8.8 |
| 6 | 2 | 15 | 27.8 | 0.6 | 15.60 | 8.5 |
| 1 | 3 | 30 | 12.4 | 0.8 | 9.28 | 8.7 |
| 2 | 3 | 7 | 54.3 | 0.8 | 40.63 | 9.2 |
| 3 | 3 | 9 | 39.8 | 0.8 | 29.78 | 8.8 |
| 4 | 3 | 19 | 16.8 | 0.8 | 12.57 | 8.4 |
| 1 | 4 | 28 | 11.9 | 1.0 | 11.13 | 8.8 |
| 2 | 4 | 3 | 55.7 | 1.0 | 52.10 | 9.2 |
| 3 | 4 | 4 | 47.1 | 1.0 | 44.05 | 8.8 |
| 4 | 4 | 10 | 16.8 | 1.0 | 15.71 | 8.5 |
| 1 | 5 | 23 | 10.5 | 1.2 | 11.79 | 8.8 |
| 2 | 5 | 3 | 55.7 | 1.2 | 62.52 | 9.2 |
| 3 | 5 | 9 | 39.8 | 1.0 | 37.23 | 8.8 |
| 4 | 5 | 10 | 16.8 | 1.0 | 15.71 | 8.5 |
| 8 | 5 | 3 | 40.8 | 1.0 | 38.16 | 8.7 |
| 2 | 6 | 42 | 29.6 | 0.2 | 5.54 | 8.9 |
| 11 | 5 | 7 | 32.6 | 1.0 | 30.49 | 8.6 |
| 12 | 5 | 13 | 13.9 | 1.0 | 13.00 | 8.9 |

[a] [Suspended Solids Loading to the Filters (SSL) g/m²·day] = [Hydraulic Loading to Filter mgad] x [Suspended Solids Conc., mg/ℓ] x [0.9353]

and 93 (both with 0.17 mm effective size sand) over the range of SSL levels studied in the field, it was concluded that filtration systems receiving wastewater stabilization pond effluents having calcium carbonate precipitation problems will operate for approximately one half the period of time as compared to those effluents without calcium carbonate precipitation problems at suspended solids loading rates of 10 $g/m^2 \cdot day$. However, at suspended solids loading rates greater than 10 $g/m^2 \cdot day$ the period of operation between cleanings becomes essentially equal. This is attributable to the characteristics of the log-log relationship where the line of best fit becomes asymptotic. Also, at higher suspended solids loadings the formation of the crust requires more time than is available before the filter plugs from trapping solids.

## Application of Equations

Table 33 shows the period of operation between cleanings for 0.17 mm effective size sands for various hydraulic loading rates and filter influent suspended solids concentrations. The periods of operation were calculated using Equation 89, and an example calculation is shown in Table 33. Therefore, the results should be used only as a guide to estimate the frequency of cleaning that can be expected in a field operation. As shown in Figure 58, considerable variation from the prediction equation can be expected.

Table 33. Period of operation for 0.17 mm effective size sand for various hydraulic loading rates and filter influent suspended solids concentrations based on Equation 89.

| Hydraulic Loading Rate, mgad | Period of Operation for 0.17 mm Effective Size Sand, Days — Concentration of Suspended Solids in Filter Influent, mg/ℓ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| 0.1 | 854 | 423 | 257 | 175 | 127 | 97 | 77 | 63 | 53 |
| 0.2 | 257[a] | 127 | 77 | 53 | 38 | 29 | 23 | 19 | 16 |
| 0.3 | 127 | 63 | 38 | 26 | 19 | 15 | 12 | 9 | 8 |
| 0.4 | 77 | 38 | 23 | 16 | 12 | 9 | 7 | 6 | 5 |
| 0.5 | 53 | 26 | 16 | 11 | 8 | 6 | 5 | 4 | 3 |
| 0.6 | 38 | 19 | 12 | 8 | 6 | 4 | 3 | 3 | 2 |

[a]Period of operation =

$$2529 \left[ \begin{pmatrix} \text{Hydraulic} \\ \text{Loading} \\ \text{Rate,} \\ \text{mgad} \end{pmatrix} \begin{pmatrix} \text{Filter Influent} \\ \text{Suspended} \\ \text{Solids Conc.,} \\ \text{mg}/\ell \end{pmatrix} (0.9353) \right]^{-1.733}$$

$$= 2529 \quad [(0.2)(20)(0.9353)]^{-1.733} = 257 \text{ days}$$

# SECTION IX

## SUMMARY AND CONCLUSIONS

Design parameters based upon influent suspended (SS) and volatile suspended solids (VSS) concentrations and hydraulic loading rates were evaluated in this research. Functional relationships and coefficients describing the efficiency of the ISF process were developed based upon laboratory data from filter units containing 0.17 mm effective sand size ($\varepsilon'$) media. Adequate SS and VSS removals were observed for the 0.17 mm $\varepsilon'$ sand filters. Field data from other studies using filter units containing 0.17, 0.40, and 0.68 mm $\varepsilon'$ sand were also evaluated using the models. Sand sizes larger than 0.17 mm $\varepsilon'$ did not produce effluents satisfying a federal secondary standard of 30 mg/ℓ of SS when the filter influent suspended solids were predominantly algae.

On the basis of the analysis of the special correlation coefficient ($R_s$) values for the laboratory filter units (Table 26) and for the field units (Table 28), it was concluded that the ISF and simplified ISF models were comparable in predicting ISF effluent (VSS) quality. The simplified ISF model consists of a single component (the sand phase) which contains no empirical coefficients; instead, a single functional relationship (Equation 85) defines the sand phase filter term, $\gamma$. It is the simplified ISF model which can most easily be utilized by engineers in analysis of the design parameters of influent VSS concentration levels and hydraulic loading rates.

# SECTION X

## RECOMMENDATIONS FOR FURTHER STUDY

Filtration systems containing sand media of $\varepsilon'$ values intermediate to the 0.17 and 0.40 mm $\varepsilon'$ sand should be evaluated. The sand phase filter term ($\gamma$) should be developed for these intermediate $\varepsilon'$ values so that the simplified ISF model could be used with all size sands.

ISF systems receiving wastewater stabilization pond effluents containing algal species other than those present in the Logan lagoon system should be evaluated to determine the effects of variation of algal populations upon the performance of the ISF process in polishing wastewater stabilization pond effluents.

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## APPENDIX A

## DETERMINATION OF INITIAL ESTIMATES FOR THE SAL DECAY COEFFICIENTS WHICH WERE UTILIZED IN ISF MODEL CALIBRATION

### Method 2: Simplified Empirical Definition of the Final VSS Concentration Out of the SAL, $C_{OUTE}$

An alternate development of the SAL Model decay coefficient was achieved by empirically defining the final VSS concentration out of the SAL ($C_{OUTE}$) without consideration of the physical removal and sloughing concepts. Such development of $C_{OUT}$ included analysis of [VSS] within the sand column as a function of depth. Given this functional relationship, the [VSS] at zero depth was $C_{OUTE}$. Figure 7 indicated that most of the specific deposit, $\sigma$, occurred near the surface of the sand. Since mass flux is assumed to totally account for this $\sigma$ (Equation 66) [VSS] would also exhibit a similar nonlinear decrease with depth. The natural log (ln) of [VSS] was plotted versus filter depth for each episode (sampling) for each column of laboratory filter run 1; the data are listed in Table 34. Included in this table are column influent [VSS] as well as 2 inch effluent [VSS]; $C_{OUTE}$ should have values intermediate between these two concentrations. To graphically display the functional relationship between the decrease in [VSS] with filter depth, column 1 (DML 687 mg/day) data are represented in Figure 62.

Given known values for $C_{OUTE}$, Equation 49 can be solved directly for the empirical decay coefficient, ce:

$$\text{ce, day}^{-1} = \left( C_{IN} * \left[ 1. - d \frac{SALC}{dAML} \right] - C_{OUTE} \right) * \frac{DHL * 10^{-3}}{SALC} \quad . \ . \ . \ . \ . \ . \ . \ . \quad (94)$$

The values of ce, so determined were plotted versus AML in order to determine whether it was a coefficient (constant). The magnitude of ce varied initially and was constant thereafter. Mean ce values for each column were calculated utilizing these latter values and are listed in Table 35.

The approximate estimates for the decay coefficient (ce, underlined values in Table 35) were utilized as initial guesses for the values of cd in the SAL model (Equation 52) when the ISF model was calibrated using laboratory data.

Table 34. $C_{OUTE}$, the final [VSS] out of the SAL, as calculated from sand column layer effluent data.

| Column No. (DML Range) | Episode No. | Day No. | Column Inf. mg/ℓ | $C_{OUTE}$ mg/ℓ | 2" Eff. mg/ℓ | $R^2$ Linear Regression ln [VSS] vs Depth |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 69 | 30 | 27 | 0.99 |
| (III) | 2 | 3 | 76 | 41 | 38 | 0.99 |
| | 3 | 6 | 70 | 55 | 40 | 0.99 |
| | 4 | 9 | 67 | 65 | 50 | 0.99 |
| 2 | 1 | 1 | 46 | 25 | 18 | 0.99 |
| (III) | 2 | 20 | 55 | 31 | 27 | 0.99 |
| | 3 | 26 | 47 | 29 | 26 | 1.00 |
| | 4 | 31 | 43 | 36 | 27 | 1.00 |
| 4 | 1 | 1 | 69 | 24 | 26 | 0.82 |
| (III) | 2 | 7 | 67 | 41 | 40 | 0.99 |
| | 3 | 13 | 67 | 59 | 44 | 0.99 |
| | 4 | 20 | 77 | 60 | 42 | 0.98 |

Table 34. Continued.

| Column No. (DML Range) | Episode No. | Day No. | Column Inf. mg/ℓ | $C_{OUTE}$ mg/ℓ | 2" Eff. mg/ℓ | $R^2$ Linear Regression ln [VSS] vs Depth |
|---|---|---|---|---|---|---|
| | 5 | 26 | 66 | 53 | 40 | 1.00 |
| | 6 | 31 | 60 | 29 | 28 | 0.82 |
| | 7 | 35 | 67 | 31 | 31 | 0.99 |
| | 8 | 39 | 70 | 43 | 38 | 1.00 |
| | 9 | 44 | 52 | 43 | 32 | 1.00 |
| 5 (II) | 1 | 3 | 51 | 20 | 22 | 0.61 |
| | 2 | 6 | 47 | 24 | 27 | 0.11 |
| | 3 | 9 | 47 | 29 | 26 | 0.99 |
| | 4 | 16 | 47 | 34 | 24 | 0.99 |
| | 5 | 20 | 55 | 30 | 32 | 0.86 |
| | 6 | 26 | 47 | 28 | 27 | 0.90 |
| | 7 | 31 | 43 | 34 | 19 | 0.99 |
| | 8 | 35 | 49 | 17 | 19 | 0.89 |
| | 9 | 39 | 50 | 15 | 19 | 0.08 |
| | 10 | 44 | 40 | 40 | 20 | 0.99 |
| 7 (II) | 1 | 3 | 76 | 22 | 14 | 0.86 |
| | 2 | 9 | 67 | 24 | 15 | 0.86 |
| | 3 | 20 | 77 | 40 | 37 | 0.98 |
| | 4 | 26 | 66 | 36 | 32 | 0.99 |
| | 5 | 31 | 60 | 19 | 16 | 1.00 |
| | 6 | 35 | 67 | 26 | 19 | 0.94 |
| | 7 | 39 | 70 | 27 | 26 | 0.98 |
| | 8 | 44 | 52 | 25 | 21 | 0.98 |
| 3 (I) | 1 | 1 | 23 | 10 | 7.5 | 0.60 |
| | 2 | 3 | 25 | 13 | 14 | 0.95 |
| | 3 | 6 | 24 | 12 | 9.7 | 0.84 |
| | 4 | 9 | 25 | 18 | 13 | 0.83 |
| | 5 | 16 | 25 | 20 | 17 | 0.98 |
| | 6 | 31 | 24 | 15 | 15 | 0.99 |
| | 7 | 35 | 28 | 16 | 13 | 0.98 |
| | 8 | 39 | 25 | 15 | 12 | 0.98 |
| | 9 | 44 | 24 | 12 | 9 | 0.95 |
| | 10 | 51 | 23 | 17 | 18 | 0.97 |
| 8 (I) | 1 | 3 | 51 | 12 | 10 | 0.90 |
| | 2 | 9 | 47 | 25 | 25 | 0.98 |
| | 3 | 20 | 55 | 35 | 32 | 1.00 |
| | 4 | 26 | 47 | 35 | 29 | 1.00 |
| | 5 | 31 | 43 | 11 | 13 | 0.94 |
| | 6 | 35 | 49 | 25 | 23 | 1.00 |
| | 7 | 39 | 50 | 18 | 18 | 0.96 |
| | 8 | 44 | 40 | 14 | 19 | 0.65 |
| 6 (<I) | 1 | 3 | 25 | 16 | 18 | 0.78 |
| | 2 | 6 | 24 | 20 | 17 | 0.96 |
| | 3 | 9 | 25 | 21 | 21 | 0.96 |
| | 4 | 13 | 25 | 23 | 13 | 0.37 |
| | 5 | 16 | 25 | 25 | 18 | 0.91 |
| | 6 | 20 | 30 | 26 | 26 | 0.99 |
| | 7 | 26 | 26 | 20 | 19 | 0.94 |
| | 8 | 31 | 24 | 23 | 16 | 1.00 |
| | 9 | 35 | 28 | 22 | 13 | 0.97 |
| | 10 | 39 | 25 | 17 | 17 | 0.99 |
| | 11 | 44 | 24 | 16 | 19 | 0.83 |
| | 12 | 51 | 23 | 13 | 10 | 0.84 |
| | 13 | 58 | 23 | 17 | 15 | 0.99 |
| | 14 | 65 | 22 | 9.1 | 6.4 | 0.10 |

Table 34. Continued.

| Column No. (DML Range) | Episode No. | Day No. | Column Inf. mg/ℓ | $C_{OUTE}$ mg/ℓ | 2" Eff. mg/ℓ | $R^2$ Linear Regression ln [VSS] vs Depth |
|---|---|---|---|---|---|---|
| | 15 | 72 | 19 | 13 | 15 | 0.55 |
| | 16 | 78 | 20 | 13 | 9.4 | 0.97 |
| | 17 | 86 | 18 | 7.0 | 10 | 0.37 |
| | 18 | 91 | 16 | 5.4 | 12 | 0.01 |
| | 19 | 93 | 20 | 8.3 | 8.1 | 0.77 |
| 9 | 1 | 3 | 25 | 9.6 | 12 | 0.62 |
| (<I) | 2 | 6 | 24 | 2.1 | 3.5 | 0.45 |
| | 3 | 9 | 25 | 19 | 20 | 0.93 |
| | 4 | 13 | 25 | 20 | 12 | 0.92 |
| | 5 | 16 | 25 | 8.4 | 8.9 | 0.98 |
| | 6 | 20 | 30 | 20 | 21 | 0.94 |
| | 7 | 26 | 26 | 11 | 14 | 0.78 |
| | 8 | 31 | 24 | 6.6 | 5.8 | 0.99 |
| | 9 | 35 | 28 | 11 | 11 | 0.30 |
| | 10 | 39 | 25 | 10 | 12 | 0.92 |
| | 11 | 44 | 24 | 13 | 10 | 0.97 |
| | 12 | 51 | 23 | 5.9 | 12 | 0.05 |
| | 13 | 58 | 23 | 13 | 16 | 0.15 |
| | 14 | 65 | 22 | 4.0 | 7.6 | 0.02 |
| | 15 | 72 | 19 | 4.9 | 5.5 | 0.65 |
| | 16 | 78 | 20 | 4.7 | 3.4 | 0.41 |
| | 17 | 86 | 18 | 4.5 | 6.9 | 0.74 |
| | 18 | 91 | 16 | 8.2 | 10 | 0.05 |
| | 19 | 93 | 20 | 11 | 14 | 0.80 |

Table 35. Empirical decay coefficient, ce.

| Column(s) | Number of Values | ce $day^{-1}$ | Standard Deviation | DML Range |
|---|---|---|---|---|
| 1 | 3 | .3647ε-02 | .7781ε-01 | |
| 2 | 3 | .3914ε-01 | .2644ε-01 | |
| 3 | 9 | .1057ε-01 | .2230ε-01 | |
| 4 | 8 | .2869ε-01 | .2744ε-01 | |
| 5 | 9 | .3188ε-01 | .2666ε-01 | |
| 6 | 18 | .1929ε-01 | .2900ε-01 | |
| 7 | 7 | .4903ε-01 | .1550ε-01 | |
| 8 | 7 | .2648ε-01 | .1591ε-01 | |
| 9 | 17 | .1950 | .1338 | |
| 1,2,4 | 14 | .2556ε-01 | .4005ε-01 | III |
| 5,7 | 16 | .3938ε-01 | .2350ε-01 | II |
| 3,8 | 16 | .1753ε-01 | .2080ε-01 | |
| 3,8,6 | 34 | .1846ε-01 | .2511ε-01 | ≤I |

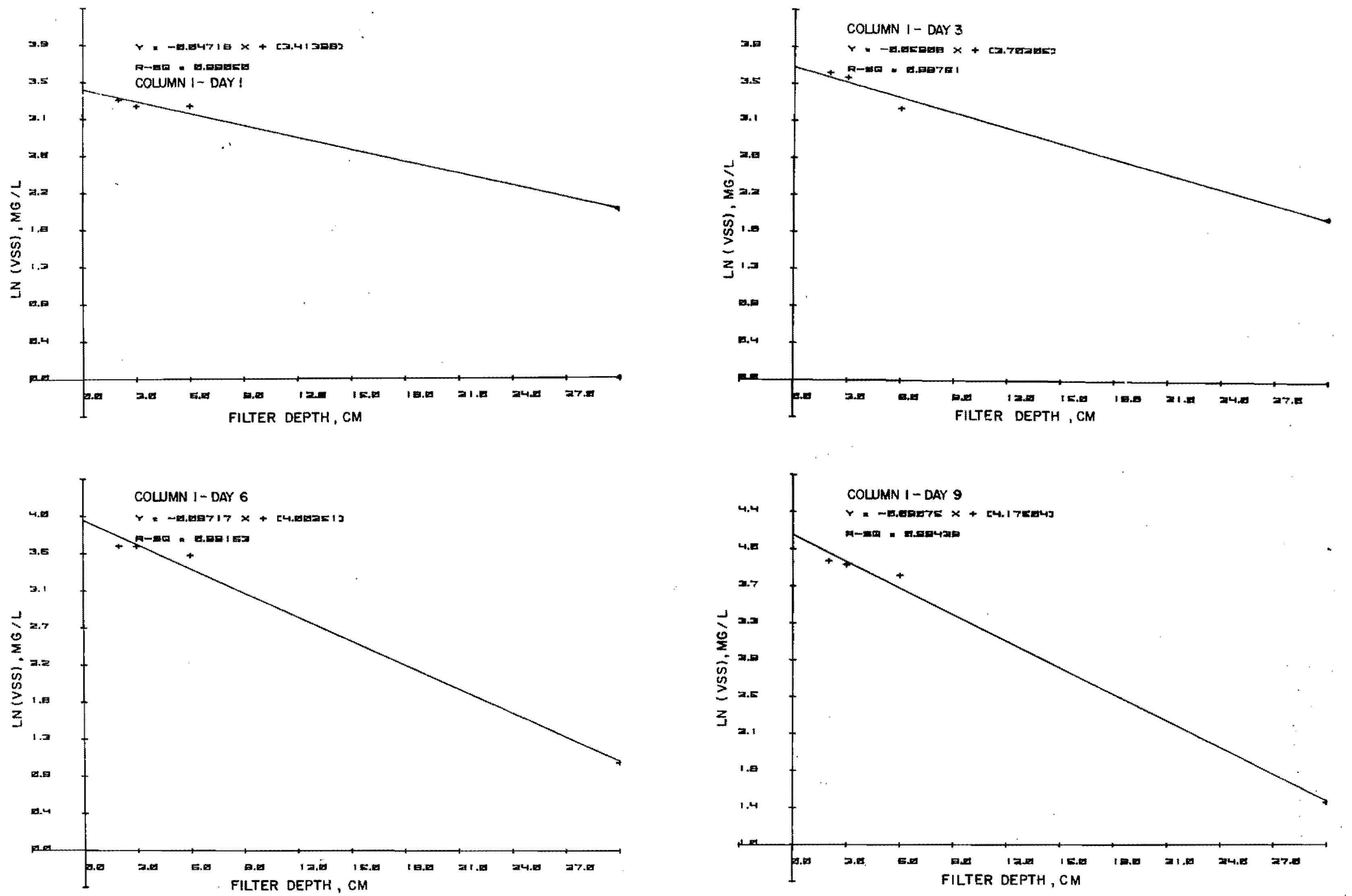


Figure 62. The functional relationship between decrease in (VSS) and filter depth for column 1.

# APPENDEX B

## DATA FOR LABORATORY PHASE OF EXPERIMENTATION

Table 36. VSS data for influent, 1 inch, 2 inch, 3 inch, 6 inch (depth ports) and effluent; mg/ℓ.

| DAY | EPI | COL | INF | 1 IN | 2 IN | 3 IN | 6 IN | EFF |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 69.0 | 33.0 | 27.0 | 25.0 | 25.0 | 7.3 |
| 3 | 2 | 1 | 76.0 | 48.0 | 38.0 | 36.0 | 25.0 | 7.0 |
| 6 | 3 | 1 | 70.0 | 40.0 | 40.0 | 40.0 | 36.0 | 2.9 |
| 9 | 4 | 1 | 67.0 | 53.0 | 50.0 | 48.0 | 43.0 | 4.2 |
| 1 | 1 | 2 | 46.0 | 17.0 | 18.0 | 20.0 | 16.0 | 1.7 |
| 20 | 2 | 2 | 55.0 | 29.0 | 27.0 | 25.0 | 14.0 | 1.4 |
| 26 | 3 | 2 | 47.0 | 31.0 | 25.0 | 21.0 | 17.0 | 1.9 |
| 31 | 4 | 2 | 43.0 | 40.0 | 27.0 | 16.0 | 13.0 | 0.0 |
| 1 | 1 | 3 | 23.0 | 19.0 | 7.5 | 8.4 | 14.0 | 4.0 |
| 3 | 2 | 3 | 25.0 | 23.0 | 14.0 | 11.0 | 11.0 | 5.7 |
| 6 | 3 | 3 | 24.0 | 19.0 | 9.7 | 11.0 | 13.0 | 5.0 |
| 9 | 4 | 3 | 25.0 | 27.0 | 13.0 | 21.0 | 14.0 | 6.1 |
| 16 | 5 | 3 | 25.0 | 42.0 | 17.0 | 16.0 | 17.0 | 3.5 |
| 31 | 6 | 3 | 24.0 | 37.0 | 15.0 | 12.0 | 11.0 | 2.9 |
| 35 | 7 | 3 | 28.0 | 21.0 | 13.0 | 14.0 | 13.0 | 4.1 |
| 39 | 8 | 3 | 25.0 | 13.0 | 12.0 | 11.0 | 12.0 | 2.1 |
| 44 | 9 | 3 | 24.0 | 15.0 | 9.0 | 13.0 | 6.8 | 1.5 |
| 51 | 10 | 3 | 23.0 | 25.0 | 18.0 | 11.0 | 9.0 | 1.4 |
| 1 | 1 | 4 | 69.0 | 56.0 | 26.0 | 17.0 | 22.0 | 10.0 |
| 7 | 2 | 4 | 67.0 | 52.0 | 40.0 | 35.0 | 30.0 | 11.0 |
| 13 | 3 | 4 | 67.0 | 49.0 | 44.0 | 42.0 | 39.0 | 3.1 |
| 20 | 4 | 4 | 77.0 | 54.0 | 42.0 | 41.0 | 42.0 | 2.8 |
| 26 | 5 | 4 | 66.0 | 37.0 | 40.0 | 33.0 | 25.0 | 0.9 |
| 31 | 6 | 4 | 50.0 | 43.0 | 28.0 | 32.0 | 17.0 | 10.0 |
| 35 | 7 | 4 | 67.0 | 38.0 | 31.0 | 26.0 | 20.0 | 5.6 |
| 39 | 8 | 4 | 70.0 | 44.0 | 38.0 | 31.0 | 25.0 | 3.1 |
| 44 | 9 | 4 | 52.0 | 32.0 | 32.0 | 27.0 | 22.0 | 0.8 |
| 3 | 1 | 5 | 51.0 | 49.0 | 22.0 | 24.0 | 8.9 | 7.0 |
| 6 | 2 | 5 | 47.0 | 60.0 | 27.0 | 41.0 | 10.0 | 17.0 |
| 9 | 3 | 5 | 47.0 | 36.0 | 26.0 | 21.0 | 18.0 | 2.6 |
| 16 | 4 | 5 | 47.0 | 43.0 | 24.0 | 14.0 | 14.0 | 0.0 |
| 20 | 5 | 5 | 55.0 | 49.0 | 32.0 | 32.0 | 13.0 | 5.1 |
| 26 | 6 | 5 | 47.0 | 54.0 | 27.0 | 29.0 | 16.0 | 7.5 |
| 31 | 7 | 5 | 43.0 | 27.0 | 19.0 | 19.0 | 14.0 | 0.0 |
| 35 | 8 | 5 | 49.0 | 26.0 | 19.0 | 15.0 | 12.0 | 7.0 |
| 39 | 9 | 5 | 50.0 | 29.0 | 19.0 | 15.0 | 10.0 | 13.0 |
| 44 | 10 | 5 | 40.0 | 36.0 | 20.0 | 23.0 | 17.0 | 0.0 |
| 3 | 1 | 6 | 25.0 | 13.0 | 18.0 | 15.0 | 12.0 | 9.2 |
| 6 | 2 | 6 | 24.0 | 19.0 | 17.0 | 21.0 | 12.0 | 3.5 |
| 9 | 3 | 6 | 25.0 | 22.0 | 21.0 | 19.0 | 12.0 | 3.9 |
| 13 | 4 | 6 | 25.0 | 48.0 | 13.0 | 27.0 | 28.0 | 11.0 |
| 16 | 5 | 6 | 25.0 | 18.0 | 15.0 | 28.0 | 18.0 | 5.6 |
| 20 | 6 | 6 | 30.0 | 30.0 | 26.0 | 24.0 | 22.0 | 13.0 |
| 26 | 7 | 6 | 26.0 | 22.0 | 19.0 | 20.0 | 12.0 | 5.0 |
| 31 | 8 | 6 | 24.0 | 21.0 | 16.0 | 13.0 | 8.0 | 0.0 |
| 35 | 9 | 6 | 28.0 | 9.5 | 13.0 | 16.0 | 16.0 | 0.8 |
| 39 | 10 | 6 | 25.0 | 18.0 | 17.0 | 15.0 | 12.0 | 4.1 |
| 44 | 11 | 6 | 24.0 | 19.0 | 10.0 | 15.0 | 10.0 | 6.0 |
| 51 | 12 | 6 | 23.0 | 17.0 | 10.0 | 15.0 | 10.0 | 5.0 |
| 58 | 13 | 6 | 23.0 | 14.0 | 15.0 | 15.0 | 14.0 | 4.9 |
| 65 | 14 | 6 | 22.0 | 11.0 | 6.4 | 14.0 | 7.7 | 7.1 |
| 72 | 15 | 6 | 19.0 | 11.0 | 15.0 | 13.0 | 7.8 | 7.1 |
| 78 | 16 | 6 | 20.0 | 5.9 | 9.4 | 13.0 | 6.3 | 0.9 |
| 86 | 17 | 6 | 18.0 | 2.4 | 10.0 | 5.6 | 7.2 | 11.0 |
| 91 | 18 | 6 | 16.0 | 11.0 | 12.0 | 2.1 | 6.5 | 6.3 |
| 93 | 19 | 6 | 20.0 | 13.0 | 8.1 | 8.6 | 7.4 | 6.7 |
| 3 | 1 | 7 | 76.0 | 25.0 | 14.0 | 18.0 | 23.0 | 3.8 |
| 9 | 2 | 7 | 67.0 | 22.0 | 15.0 | 27.0 | 20.0 | 5.0 |
| 20 | 3 | 7 | 77.0 | 39.0 | 37.0 | 37.0 | 26.0 | 9.0 |
| 26 | 4 | 7 | 66.0 | 45.0 | 32.0 | 28.0 | 28.0 | 6.1 |
| 31 | 5 | 7 | 60.0 | 32.0 | 16.0 | 15.0 | 12.0 | 1.7 |
| 35 | 6 | 7 | 67.0 | 29.0 | 10.0 | 20.0 | 24.0 | 3.9 |
| 39 | 7 | 7 | 70.0 | 24.0 | 26.0 | 24.0 | 18.0 | 6.6 |
| 44 | 8 | 7 | 52.0 | 29.0 | 21.0 | 20.0 | 21.0 | 4.7 |
| 3 | 1 | 8 | 51.0 | 23.0 | 10.0 | 13.0 | 8.0 | 3.9 |
| 9 | 2 | 8 | 47.0 | 33.0 | 25.0 | 18.0 | 10.0 | 0.9 |
| 20 | 3 | 8 | 55.0 | 45.0 | 32.0 | 30.0 | 24.0 | 5.2 |
| 26 | 4 | 8 | 47.0 | 38.0 | 20.0 | 29.0 | 23.0 | 4.2 |
| 31 | 5 | 8 | 43.0 | 25.0 | 13.0 | 9.0 | 4.4 | 0.8 |
| 35 | 6 | 8 | 49.0 | 40.0 | 23.0 | 22.0 | 21.0 | 8.0 |
| 39 | 7 | 8 | 50.0 | 26.0 | 15.0 | 16.0 | 3.1 | 0.0 |
| 44 | 8 | 8 | 40.0 | 21.0 | 19.0 | 14.0 | 6.0 | 4.2 |
| 3 | 1 | 9 | 25.0 | 16.0 | 12.0 | 7.9 | 7.5 | 5.8 |
| 6 | 2 | 9 | 24.0 | 21.0 | 3.5 | 5.8 | 0.0 | 0.0 |
| 9 | 3 | 9 | 25.0 | 18.0 | 20.0 | 14.0 | 17.0 | 5.8 |
| 13 | 4 | 9 | 25.0 | 33.0 | 12.0 | 22.0 | 14.0 | 2.2 |
| 16 | 5 | 9 | 25.0 | 19.0 | 8.0 | 4.2 | 3.0 | 0.0 |
| 20 | 6 | 9 | 30.0 | 32.0 | 21.0 | 18.0 | 14.0 | 7.6 |
| 26 | 7 | 9 | 26.0 | 19.0 | 14.0 | 9.9 | 6.9 | 4.3 |
| 31 | 8 | 9 | 24.0 | 13.0 | 5.8 | 5.5 | 5.4 | 1.5 |
| 35 | 9 | 9 | 28.0 | 17.0 | 11.0 | 12.0 | 11.0 | 12.0 |
| 39 | 10 | 9 | 25.0 | 12.0 | 12.0 | 8.6 | 6.6 | 2.8 |
| 44 | 11 | 9 | 24.0 | 13.0 | 10.0 | 12.0 | 2.9 | 0.0 |
| 51 | 12 | 9 | 23.0 | 17.0 | 12.0 | 5.1 | 2.6 | 4.7 |
| 58 | 13 | 9 | 23.0 | 18.0 | 16.0 | 7.1 | 17.0 | 8.5 |
| 65 | 14 | 9 | 22.0 | 15.0 | 7.6 | 2.8 | 3.0 | 5.0 |
| 72 | 15 | 9 | 19.0 | 14.0 | 5.5 | 4.7 | 4.9 | 6.2 |
| 78 | 16 | 9 | 20.0 | 3.1 | 3.4 | 6.1 | 6.3 | 7.5 |
| 86 | 17 | 9 | 18.0 | 8.1 | 6.9 | 3.8 | 4.8 | 13.0 |
| 91 | 18 | 9 | 16.0 | 15.0 | 10.0 | 7.4 | 7.6 | 9.0 |
| 93 | 19 | 9 | 20.0 | 13.0 | 14.0 | 8.9 | 8.5 | 4.9 |

Table 36. Continued.

Table 37. VSS data for influent and effluent; mg/ℓ.

| DAY | EPI | COL | INF | EFF |
|---|---|---|---|---|
| 1 | 1 | 1 | 69. | 7.3 |
| 3 | 2 | 1 | 76. | 7. |
| 6 | 3 | 1 | 70. | 2.9 |
| 7 | 4 | 1 | 67. | 5.7 |
| 9 | 5 | 1 | 67. | 4.2 |
| 13 | 6 | 1 | 67. | 4. |
| 16 | 7 | 1 | 67. | 2.5 |
| 20 | 8 | 1 | 77. | 8.5 |
| 1 | 1 | 2 | 46. | 1.7 |

Table 37. Continued.

| DAY | EPI | COL | INF | EFF |
|---|---|---|---|---|
| 3 | 2 | 2 | 51. | .8 |
| 6 | 3 | 2 | 47. | 0. |
| 7 | 4 | 2 | 47. | 9.6 |
| 9 | 5 | 2 | 47. | .8 |
| 13 | 6 | 2 | 47. | 0. |
| 16 | 7 | 2 | 47. | 5. |
| 20 | 8 | 2 | 55. | 1.4 |
| 26 | 9 | 2 | 47. | 1.9 |
| 31 | 10 | 2 | 43. | 0. |
| 35 | 11 | 2 | 49. | 5.6 |
| 1 | 1 | 3 | 23. | 4. |
| 3 | 2 | 3 | 25. | 5.7 |
| 6 | 3 | 3 | 24. | 5. |
| 9 | 4 | 3 | 25. | 6.1 |
| 13 | 5 | 3 | 25. | 12. |
| 16 | 6 | 3 | 25. | 3.5 |
| 20 | 7 | 3 | 30. | 8.3 |
| 26 | 8 | 3 | 26. | 3.5 |
| 31 | 9 | 3 | 24. | 2.9 |
| 35 | 10 | 3 | 28. | 4.1 |
| 39 | 11 | 3 | 25. | 2.1 |
| 44 | 12 | 3 | 24. | 1.5 |
| 51 | 13 | 3 | 23. | 1.4 |
| 58 | 14 | 3 | 23. | 7. |
| 1 | 1 | 4 | 60. | 10. |
| 3 | 2 | 4 | 76. | 7. |
| 6 | 3 | 4 | 70. | 6.3 |
| 7 | 4 | 4 | 67. | 11. |
| 9 | 5 | 4 | 67. | 1.7 |
| 13 | 6 | 4 | 67. | 3.1 |
| 16 | 7 | 4 | 67. | 0. |
| 20 | 8 | 4 | 77. | 2.8 |
| 26 | 9 | 4 | 66. | .9 |
| 31 | 10 | 4 | 60. | 10. |
| 35 | 11 | 4 | 67. | 5.6 |
| 39 | 12 | 4 | 70. | 3.1 |
| 44 | 13 | 4 | 52. | .8 |
| 1 | 1 | 5 | 46. | 11. |
| 3 | 2 | 5 | 51. | 7. |
| 6 | 3 | 5 | 47. | 17. |
| 9 | 4 | 5 | 47. | 2.6 |
| 13 | 5 | 5 | 47. | .8 |
| 16 | 6 | 5 | 47. | 0. |
| 20 | 7 | 5 | 55. | 5.1 |
| 26 | 8 | 5 | 47. | 7.5 |
| 31 | 9 | 5 | 43. | 0. |
| 35 | 10 | 5 | 49. | 7. |
| 39 | 11 | 5 | 50. | 13. |
| 44 | 12 | 5 | 40. | 0. |
| 1 | 1 | 6 | 23. | 12. |
| 3 | 2 | 6 | 25. | 9.2 |
| 6 | 3 | 6 | 24. | 3.5 |
| 9 | 4 | 6 | 25. | 3.9 |
| 13 | 5 | 6 | 25. | 11. |
| 16 | 6 | 6 | 25. | 5.6 |
| 20 | 7 | 6 | 30. | 13. |
| 26 | 8 | 6 | 26. | 5. |
| 31 | 9 | 6 | 24. | 0. |
| 35 | 10 | 6 | 28. | .8 |
| 39 | 11 | 6 | 25. | 4.1 |
| 44 | 12 | 6 | 24. | 6. |
| 51 | 13 | 6 | 23. | 5. |
| 58 | 14 | 6 | 23. | 4.9 |
| 65 | 15 | 6 | 22. | 7.1 |
| 72 | 16 | 6 | 19. | 7.1 |
| 78 | 17 | 6 | 20. | .9 |

Table 37. Continued.

| DAY | EPI | COL | INF | EFF |
|---|---|---|---|---|
| 86 | 18 | 6 | 18. | 11. |
| 91 | 19 | 6 | 16. | 6.3 |
| 93 | 20 | 6 | 20. | 6.7 |
| 1 | 1 | 7 | 60. | 11. |
| 3 | 2 | 7 | 76. | 3.8 |
| 6 | 3 | 7 | 70. | 0. |
| 7 | 4 | 7 | 67. | 8.3 |
| 9 | 5 | 7 | 67. | 5. |
| 13 | 6 | 7 | 67. | 5.1 |
| 16 | 7 | 7 | 67. | 1.4 |
| 20 | 8 | 7 | 77. | 9. |
| 26 | 9 | 7 | 66. | 6.1 |
| 31 | 10 | 7 | 60. | 1.7 |
| 35 | 11 | 7 | 67. | 3.9 |
| 39 | 12 | 7 | 70. | 6.6 |
| 44 | 13 | 7 | 52. | 4.7 |
| 1 | 1 | 8 | 46. | 7.5 |
| 3 | 2 | 8 | 51. | 3.9 |
| 6 | 3 | 8 | 47. | 7.6 |
| 9 | 4 | 8 | 47. | .9 |
| 13 | 5 | 8 | 47. | 0. |
| 16 | 6 | 8 | 47. | 0. |
| 20 | 7 | 8 | 55. | 6.2 |
| 26 | 8 | 8 | 47. | 4.2 |
| 31 | 9 | 8 | 43. | .8 |
| 35 | 10 | 8 | 49. | 8. |
| 39 | 11 | 8 | 50. | 0. |
| 44 | 12 | 8 | 40. | 4.2 |
| 1 | 1 | 9 | 23. | 12. |
| 3 | 2 | 9 | 25. | 5.8 |
| 6 | 3 | 9 | 24. | 0. |
| 9 | 4 | 9 | 25. | 5.8 |
| 13 | 5 | 9 | 25. | 2.2 |
| 16 | 6 | 9 | 25. | 0. |
| 20 | 7 | 9 | 30. | 7.6 |
| 26 | 8 | 9 | 26. | 4.3 |
| 31 | 9 | 9 | 24. | 1.5 |
| 35 | 10 | 9 | 28. | 1.2 |
| 39 | 11 | 9 | 25. | 2.8 |
| 44 | 12 | 9 | 24. | 0. |
| 51 | 13 | 9 | 23. | 4.7 |
| 58 | 14 | 9 | 23. | 8.5 |
| 65 | 15 | 9 | 22. | 5. |
| 72 | 16 | 9 | 19. | 6.2 |
| 78 | 17 | 9 | 20. | 7.5 |
| 86 | 18 | 9 | 18. | 13. |
| 91 | 19 | 9 | 16. | 9. |
| 93 | 20 | 9 | 20. | 4.9 |

Table 38. Approach velocity$^{-1}$; sec/inch.

| DAY | COL 1 | COL 2 | COL 3 | COL 4 | COL 5 | COL 6 | COL 7 | COL 8 | COL 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 101 | 93 | 85 | 93 | 97 | 76 | 65 | 64 | 91 |
| 2 | 172 | 129 | 109 | 102 | 123 | 111 | 139 | 143 | 127 |
| 3 | 243 | 167 | 117 | 163 | 132 | 132 | 196 | 133 | 134 |
| 4 | 314 | 340 | 122 | 110 | 173 | 133 | 188 | 142 | 147 |
| 5 | 340 | 345 | 127 | 648 | 188 | 112 | 58 | 137 | 150 |
| 6 | 501 | 350 | 117 | 497 | 145 | 123 | 455 | 134 | 128 |
| 7 | 661 | 355 | 116 | 345 | 147 | 133 | 356 | 136 | 133 |
| 8 | 1302 | 360 | 118 | 463 | 248 | 144 | 257 | 167 | 143 |
| 9 | 1943 | 365 | 115 | 580 | 335 | 155 | 1047 | 120 | 146 |
| 10 | 2587 | 370 | 128 | 699 | 362 | 165 | 943 | 444 | 149 |
| 11 | 3225 | 375 | 147 | 817 | 388 | 145 | 989 | 325 | 152 |
| 12 | 3256 | 380 | 155 | 935 | 384 | 150 | 695 | 340 | 156 |
| 13 | 4597 | 385 | 169 | 1053 | 358 | 162 | 527 | 350 | 167 |
| 14 | 5148 | 390 | 192 | 1174 | 387 | 169 | 770 | 373 | 157 |
| 15 | 5789 | 395 | 207 | 1182 | 423 | 177 | 742 | 379 | 165 |
| 16 | 6430 | 400 | 229 | 1197 | 460 | 185 | 785 | 401 | 199 |
| 17 | 7071 | 405 | 229 | 1239 | 447 | 190 | 789 | 497 | 198 |
| 18 | 7712 | 410 | 252 | 871 | 468 | 200 | 816 | 439 | 215 |
| 19 | 8353 | 415 | 212 | 503 | 389 | 170 | 611 | 394 | 182 |
| 20 | 8994 | 420 | 172 | 135 | 309 | 139 | 206 | 350 | 148 |
| 21 | 9635 | 425 | 132 | 220 | 329 | 153 | 92 | 346 | 163 |
| 22 | 10276 | 876 | 159 | 205 | 242 | 146 | 174 | 334 | 138 |
| 23 | 10917 | 1197 | 172 | 216 | 257 | 156 | 177 | 363 | 137 |
| 24 | | 1568 | 125 | 205 | 154 | 158 | 195 | 232 | 139 |
| 25 | | 1949 | 127 | 204 | 230 | 145 | 185 | 273 | 142 |
| 26 | | 2330 | 122 | 216 | 296 | 151 | 190 | 210 | 150 |
| 27 | | 2671 | 122 | 170 | 194 | 144 | 163 | 230 | 140 |
| 28 | | 2175 | 113 | 172 | 184 | 140 | 191 | 224 | 153 |
| 29 | | 1789 | 123 | 192 | 203 | 163 | 178 | 216 | 170 |
| 30 | | 2375 | 124 | 167 | 213 | 163 | 222 | 225 | 170 |
| 31 | | 2358 | 124 | 186 | 215 | 161 | 132 | 235 | 155 |
| 32 | | 2703 | 133 | 203 | 113 | 95 | 112 | 245 | 184 |
| 33 | | 3038 | 140 | 196 | 123 | 103 | 120 | 263 | 195 |
| 34 | | 3374 | 146 | 219 | 214 | 170 | 220 | 259 | 170 |
| 35 | | 5616 | 117 | 176 | 231 | 150 | 200 | 189 | 174 |
| 36 | | 9699 | 133 | 222 | 195 | 154 | 224 | 187 | 175 |
| 37 | | | 184 | 185 | 176 | 157 | 182 | 194 | 160 |
| 38 | | | 108 | 189 | 212 | 143 | 171 | 167 | 166 |
| 39 | | | 123 | 193 | 245 | 155 | 201 | 194 | 150 |
| 40 | | | 120 | 182 | 214 | 147 | 185 | 176 | 162 |
| 41 | | | 115 | 200 | 235 | 150 | 190 | 189 | 90 |
| 42 | | | 113 | 208 | 210 | 148 | 245 | 174 | 155 |
| 43 | | | 150 | 197 | 205 | 153 | 153 | 177 | 162 |
| 44 | | | 140 | 216 | 198 | 159 | 256 | 176 | 157 |
| 45 | | | 131 | 200 | 257 | 165 | 637 | 257 | 178 |
| 46 | | | 136 | 266 | 282 | 155 | 469 | 255 | 185 |
| 47 | | | 87 | 334 | 172 | 106 | 282 | 168 | 134 |
| 48 | | | 197 | 492 | 290 | 129 | 1943 | 216 | 166 |
| 49 | | | 139 | 2063 | 530 | 126 | 3634 | 487 | 147 |
| 50 | | | 138 | 3724 | 961 | 145 | 5255 | 918 | 164 |
| 51 | | | 153 | | 1292 | 119 | | 1140 | 139 |
| 52 | | | 188 | | | 146 | | 1480 | 164 |
| 53 | | | 212 | | | 144 | | 1811 | 175 |
| 54 | | | 308 | | | 143 | | 2142 | 186 |
| 55 | | | 1030 | | | 194 | | 2473 | 190 |

Table 38. Continued.

| DAY | COL 1 | COL 2 | COL 3 | COL 4 | COL 5 | COL 6 | COL 7 | COL 8 | COL 9 |
|---|---|---|---|---|---|---|---|---|---|
| 56 | | | 1456 | | | 245 | | | 209 |
| 57 | | | 1882 | | | 158 | | | 263 |
| 58 | | | 2662 | | | 225 | | | 149 |
| 59 | | | 5325 | | | 146 | | | 152 |
| 60 | | | 9304 | | | 180 | | | 188 |
| 61 | | | | | | 196 | | | 223 |
| 62 | | | | | | 182 | | | 169 |
| 63 | | | | | | 156 | | | 182 |
| 64 | | | | | | 185 | | | 223 |
| 65 | | | | | | 203 | | | 210 |
| 66 | | | | | | 220 | | | 213 |
| 67 | | | | | | 203 | | | 229 |
| 68 | | | | | | 221 | | | 219 |
| 69 | | | | | | 214 | | | 219 |
| 70 | | | | | | 186 | | | 227 |
| 71 | | | | | | 178 | | | 215 |
| 72 | | | | | | 170 | | | 210 |
| 73 | | | | | | 205 | | | 239 |
| 74 | | | | | | 239 | | | 257 |
| 75 | | | | | | 216 | | | 234 |
| 76 | | | | | | 244 | | | 235 |
| 77 | | | | | | 223 | | | 239 |
| 78 | | | | | | 250 | | | 225 |
| 79 | | | | | | 214 | | | 230 |
| 80 | | | | | | 210 | | | 212 |
| 81 | | | | | | 219 | | | 228 |
| 82 | | | | | | 228 | | | 225 |
| 83 | | | | | | 227 | | | 228 |
| 84 | | | | | | 207 | | | 230 |
| 85 | | | | | | 237 | | | 238 |
| 86 | | | | | | 319 | | | 254 |
| 87 | | | | | | 215 | | | 249 |
| 88 | | | | | | 244 | | | 237 |
| 89 | | | | | | 206 | | | 222 |
| 90 | | | | | | 207 | | | 265 |
| 91 | | | | | | 244 | | | 242 |
| 92 | | | | | | 244 | | | 242 |
| 93 | | | | | | 244 | | | 242 |

Table 39. Carbon data for influent, 1 inch, 2 inch, 3 inch, 6 inch (depth ports) and effluent; mg/ℓ. Data are in sets of two: First line is total organic carbon (TOC); second line is soluble organic carbon (SOC).

| DAY | EPI | COL | INF | 1 IN | 2 IN | 3 IN | 6 IN | EFF |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 24.4 | 20.7 | 16.3 | 15.5 | 14.4 | 12.4 |
| 1 | 1 | 1 | 18.2 | 12.0 | 10.9 | 10.5 | 10.1 | 10.0 |
| 9 | 2 | 1 | 26.3 | 23.7 | 19.9 | 17.1 | 14.3 | 11.4 |
| 9 | 2 | 1 | 19.6 | 19.6 | 16.7 | 14.3 | 12.0 | 9.5 |
| 1 | 1 | 2 | 20.5 | 15.6 | 15.2 | 14.5 | 12.9 | 10.9 |
| 1 | 1 | 2 | 10.6 | 11.8 | 11.7 | 11.5 | 10.1 | 8.5 |
| 9 | 2 | 2 | 19.9 | 17.4 | 15.2 | 14.7 | 12.7 | 10.8 |
| 9 | 2 | 2 | 14.8 | 14.8 | 13.9 | 13.3 | 11.8 | 9.8 |
| 20 | 3 | 2 | 17.2 | 13.9 | 12.7 | 12.5 | 10.9 | 6.9 |
| 20 | 3 | 2 | 8.7 | 7.5 | 6.9 | 6.3 | 5.4 | 5.0 |
| 26 | 4 | 2 | 13.9 | 12.7 | 11.7 | 10.5 | 7.9 | 5.9 |
| 26 | 4 | 2 | 6.2 | 6.7 | 6.0 | 5.6 | 4.5 | 4.2 |
| 1 | 1 | 3 | 12.8 | 10.4 | 10.1 | 9.5 | 8.8 | 7.9 |
| 1 | 1 | 3 | 6.4 | 9.8 | 9.5 | 8.9 | 8.6 | 7.7 |
| 9 | 2 | 3 | 16.8 | 14.2 | 13.0 | 12.4 | 11.8 | 10.7 |
| 9 | 2 | 3 | 8.2 | 13.4 | 12.5 | 11.9 | 11.5 | 10.5 |
| 20 | 3 | 3 | 13.5 | 11.0 | 9.9 | 9.4 | 8.2 | 5.2 |
| 20 | 3 | 3 | 6.5 | 9.9 | 8.5 | 8.0 | 5.7 | 3.9 |
| 26 | 4 | 3 | 11.3 | 10.2 | 9.7 | 9.4 | 7.8 | 4.6 |
| 26 | 4 | 3 | 4.7 | 7.1 | 6.7 | 5.4 | 4.5 | 3.4 |
| 35 | 5 | 3 | 9.4 | 10.9 | 10.0 | 9.0 | 8.2 | 5.2 |
| 35 | 5 | 3 | 6.3 | 5.6 | 5.1 | 5.0 | 4.7 | 4.1 |
| 44 | 6 | 3 | 9.9 | 9.1 | 7.9 | 7.3 | 6.5 | 4.0 |
| 44 | 6 | 3 | 5.1 | 4.2 | 3.8 | 3.7 | 3.7 | 3.1 |
| 51 | 7 | 3 | 10.7 | 8.8 | 8.1 | 7.5 | 5.9 | 4.2 |
| 51 | 7 | 3 | 5.0 | 4.1 | 3.9 | 3.5 | 3.1 | 2.0 |
| 1 | 1 | 4 | 24.2 | 20.7 | 16.6 | 15.6 | 14.8 | 13.0 |
| 1 | 1 | 4 | 18.2 | 13.4 | 12.4 | 12.1 | 12.0 | 12.5 |
| 9 | 2 | 4 | 26.3 | 22.2 | 19.1 | 17.6 | 15.0 | 11.9 |
| 9 | 2 | 4 | 19.6 | 20.2 | 18.1 | 17.1 | 14.5 | 11.6 |
| 20 | 3 | 4 | 21.0 | 16.9 | 16.2 | 14.9 | 12.8 | 8.2 |
| 20 | 3 | 4 | 10.6 | 9.9 | 9.6 | 9.7 | 9.3 | 6.6 |
| 26 | 4 | 4 | 16.3 | 13.9 | 12.5 | 11.9 | 10.0 | 6.0 |
| 26 | 4 | 4 | 7.5 | 7.7 | 6.9 | 7.9 | 6.5 | 5.0 |
| 35 | 5 | 4 | 16.2 | 14.0 | 12.5 | 11.9 | 10.7 | 6.1 |
| 35 | 5 | 4 | 10.1 | 8.5 | 7.7 | 7.1 | 6.7 | 4.1 |
| 44 | 6 | 4 | 16.1 | 13.7 | 11.9 | 11.0 | 10.2 | 5.6 |
| 44 | 6 | 4 | 7.5 | 7.1 | 6.5 | 6.2 | 6.0 | 4.6 |
| 1 | 1 | 5 | 20.5 | 17.7 | 13.5 | 12.7 | 9.9 | 8.4 |
| 1 | 1 | 5 | 10.6 | 10.6 | 9.2 | 9.1 | 8.9 | 8.0 |
| 9 | 2 | 5 | 19.9 | 18.0 | 15.7 | 15.1 | 13.0 | 10.6 |
| 9 | 2 | 5 | 14.8 | 16.4 | 15.1 | 14.5 | 12.9 | 10.4 |
| 20 | 3 | 5 | 17.2 | 13.5 | 12.0 | 11.7 | 10.4 | 5.4 |
| 20 | 3 | 5 | 8.7 | 7.7 | 6.7 | 6.2 | 5.6 | 4.6 |
| 26 | 4 | 5 | 13.9 | 12.6 | 10.2 | 9.8 | 8.7 | 6.6 |
| 26 | 4 | 5 | 6.2 | 7.9 | 6.8 | 6.3 | 5.6 | 4.7 |
| 35 | 5 | 5 | 14.1 | 12.0 | 11.1 | 10.5 | 9.8 | 7.2 |
| 35 | 5 | 5 | 8.6 | 6.9 | 6.2 | 5.8 | 5.4 | 5.0 |
| 44 | 6 | 5 | 13.8 | 13.3 | 11.1 | 10.2 | 8.3 | 4.1 |
| 44 | 6 | 5 | 6.8 | 7.7 | 5.7 | 4.6 | 4.3 | 3.5 |
| 1 | 1 | 6 | 12.8 | 10.7 | 10.1 | 10.0 | 9.5 | 8.6 |
| 1 | 1 | 6 | 6.4 | 10.1 | 9.8 | 9.6 | 9.2 | 8.6 |
| 9 | 2 | 6 | 16.8 | 14.4 | 14.1 | 14.0 | 13.4 | 9.9 |
| 9 | 2 | 6 | 8.2 | 13.9 | 13.4 | 13.2 | 12.7 | 9.7 |
| 20 | 3 | 6 | 13.6 | 10.9 | 10.4 | 10.0 | 8.8 | 5.9 |
| 20 | 3 | 6 | 6.6 | 7.0 | 6.0 | 6.1 | 5.7 | 5.2 |
| 26 | 4 | 6 | 11.3 | 8.1 | 7.7 | 7.0 | 6.9 | 5.5 |
| 26 | 4 | 6 | 4.7 | 7.0 | 5.8 | 5.5 | 4.7 | 4.6 |
| 35 | 5 | 6 | 9.4 | 9.8 | 9.5 | 9.1 | 8.1 | 4.9 |
| 35 | 5 | 6 | 6.3 | 5.0 | 4.8 | 4.6 | 4.1 | 3.7 |
| 44 | 6 | 6 | 9.9 | 8.9 | 8.4 | 8.1 | 6.1 | 4.0 |

Table 39. Continued.

| DAY | EPI | COL | INF | 1 IN | 2 IN | 3 IN | 6 IN | EFF |
|---|---|---|---|---|---|---|---|---|
| 44 | 6 | 6 | 5.1 | 4.7 | 3.7 | 3.4 | 2.8 | 2.2 |
| 51 | 7 | 6 | 10.7 | 7.9 | 7.4 | 7.1 | 5.9 | 3.9 |
| 51 | 7 | 6 | 5.0 | 3.7 | 3.4 | 3.2 | 2.8 | 2.2 |
| 58 | 8 | 6 | 11.7 | 10.6 | 9.9 | 9.7 | 8.4 | 3.5 |
| 58 | 8 | 6 | 5.2 | 4.8 | 4.5 | 4.3 | 3.9 | 2.4 |
| 65 | 9 | 6 | 13.3 | 12.7 | 12.3 | 11.9 | 10.4 | 5.4 |
| 65 | 9 | 6 | 11.4 | 9.5 | 9.1 | 8.2 | 7.1 | 4.4 |
| 72 | 10 | 6 | 15.5 | 14.7 | 13.9 | 12.9 | 11.4 | 5.9 |
| 72 | 10 | 6 | 12.6 | 9.9 | 8.2 | 7.6 | 7.2 | 3.9 |
| 78 | 11 | 6 | 12.3 | 12.0 | 11.6 | 11.2 | 8.5 | 4.6 |
| 78 | 11 | 6 | 7.1 | 5.9 | 5.6 | 5.3 | 4.5 | 3.6 |
| 86 | 12 | 6 | 11.5 | 11.3 | 10.6 | 10.0 | 7.1 | 3.8 |
| 86 | 12 | 6 | 6.2 | 5.9 | 5.0 | 4.6 | 4.4 | 2.9 |
| 93 | 13 | 6 | 12.0 | 11.7 | 11.3 | 10.9 | 9.5 | 4.9 |
| 93 | 13 | 6 | 6.7 | 5.6 | 5.0 | 4.7 | 4.4 | 3.2 |
| 1 | 1 | 7 | 24.4 | 21.8 | 16.8 | 16.0 | 14.8 | 13.5 |
| 1 | 1 | 7 | 18.2 | 17.0 | 16.3 | 15.6 | 14.4 | 12.0 |
| 9 | 2 | 7 | 26.3 | 21.1 | 18.6 | 17.2 | 15.0 | 11.2 |
| 9 | 2 | 7 | 19.6 | 19.4 | 17.3 | 16.5 | 14.3 | 10.5 |
| 20 | 3 | 7 | 21.0 | 17.5 | 16.7 | 16.0 | 14.0 | 8.4 |
| 20 | 3 | 7 | 10.6 | 10.0 | 8.4 | 7.3 | 6.8 | 6.2 |
| 26 | 4 | 7 | 16.3 | 10.8 | 9.6 | 8.3 | 8.0 | 6.8 |
| 26 | 4 | 7 | 7.5 | 9.4 | 8.1 | 7.4 | 6.9 | 5.5 |
| 35 | 5 | 7 | 16.2 | 13.2 | 12.0 | 11.7 | 11.6 | 4.8 |
| 35 | 5 | 7 | 10.1 | 8.2 | 8.1 | 7.9 | 7.5 | 3.9 |
| 44 | 6 | 7 | 16.1 | 13.2 | 12.2 | 11.8 | 9.9 | 5.1 |
| 44 | 6 | 7 | 7.5 | 7.2 | 6.2 | 5.9 | 4.5 | 3.3 |
| 1 | 1 | 8 | 20.5 | 18.7 | 13.9 | 13.6 | 12.2 | 10.4 |
| 1 | 1 | 8 | 12.3 | 14.1 | 13.6 | 12.2 | 11.4 | 10.2 |
| 9 | 2 | 8 | 19.8 | 17.2 | 15.2 | 14.6 | 12.7 | 10.3 |
| 9 | 2 | 8 | 14.8 | 14.4 | 14.0 | 13.8 | 12.1 | 9.6 |
| 20 | 3 | 8 | 17.2 | 16.8 | 16.1 | 14.5 | 12.7 | 7.0 |
| 20 | 3 | 8 | 8.7 | 9.9 | 9.5 | 8.3 | 7.7 | 6.0 |
| 26 | 4 | 8 | 13.9 | 10.5 | 10.0 | 8.8 | 8.3 | 7.0 |
| 26 | 4 | 8 | 6.2 | 9.2 | 8.5 | 8.0 | 7.2 | 5.7 |
| 35 | 5 | 8 | 14.1 | 13.0 | 12.0 | 10.7 | 10.1 | 6.8 |
| 35 | 5 | 8 | 8.6 | 8.3 | 6.2 | 5.6 | 5.1 | 4.9 |
| 44 | 6 | 8 | 13.8 | 13.1 | 11.5 | 11.1 | 8.6 | 4.6 |
| 44 | 6 | 8 | 6.8 | 7.7 | 6.1 | 5.2 | 4.6 | 3.6 |
| 1 | 1 | 9 | 12.8 | 11.2 | 10.7 | 10.4 | 9.3 | 8.8 |
| 1 | 1 | 9 | 6.4 | 10.3 | 10.1 | 9.9 | 9.0 | 8.6 |
| 9 | 2 | 9 | 16.8 | 14.0 | 13.8 | 13.4 | 12.9 | 9.8 |
| 9 | 2 | 9 | 8.2 | 12.7 | 12.3 | 12.1 | 12.0 | 9.3 |
| 20 | 3 | 9 | 13.6 | 12.6 | 11.3 | 10.5 | 9.3 | 5.5 |
| 20 | 3 | 9 | 6.6 | 7.1 | 7.6 | 6.7 | 5.5 | 4.6 |
| 26 | 4 | 9 | 11.3 | 8.1 | 7.3 | 6.9 | 6.0 | 4.6 |
| 26 | 4 | 9 | 4.7 | 4.6 | 4.3 | 4.7 | 4.7 | 4.3 |
| 35 | 5 | 9 | 9.4 | 10.0 | 9.5 | 8.9 | 7.7 | 5.4 |
| 35 | 5 | 9 | 6.3 | 5.1 | 4.7 | 4.1 | 3.7 | 3.5 |
| 44 | 6 | 9 | 9.9 | 8.9 | 8.4 | 8.0 | 6.3 | 4.6 |
| 44 | 6 | 9 | 5.1 | 4.4 | 4.0 | 4.5 | 3.1 | 2.9 |
| 51 | 7 | 9 | 10.7 | 8.0 | 7.1 | 6.8 | 5.4 | 3.3 |
| 51 | 7 | 9 | 5.0 | 3.8 | 3.6 | 3.4 | 3.1 | 2.2 |
| 58 | 8 | 9 | 11.7 | 10.5 | 9.8 | 9.5 | 8.3 | 3.5 |
| 58 | 8 | 9 | 5.2 | 5.0 | 4.6 | 4.4 | 3.5 | 2.3 |
| 65 | 9 | 9 | 13.3 | 12.6 | 12.0 | 11.5 | 10.1 | 6.0 |
| 65 | 9 | 9 | 11.4 | 9.4 | 8.1 | 5.9 | 4.7 | 4.5 |
| 72 | 10 | 9 | 15.6 | 14.5 | 14.2 | 13.1 | 11.5 | 5.5 |
| 72 | 10 | 9 | 12.6 | 9.6 | 8.7 | 7.6 | 6.1 | 3.8 |
| 78 | 11 | 9 | 12.3 | 11.8 | 11.5 | 11.1 | 9.7 | 4.5 |
| 78 | 11 | 9 | 7.1 | 6.0 | 5.7 | 5.6 | 4.5 | 3.5 |
| 86 | 12 | 9 | 11.6 | 10.7 | 9.8 | 9.2 | 8.1 | 3.4 |
| 86 | 12 | 9 | 6.2 | 5.6 | 5.4 | 4.8 | 3.8 | 3.0 |
| 93 | 13 | 9 | 12.0 | 11.7 | 11.3 | 10.7 | 9.4 | 4.6 |
| 93 | 13 | 9 | 6.7 | 4.8 | 4.6 | 4.6 | 3.7 | 2.9 |

APPENDIX C

FIELD DATA FROM HARRIS (1977) UTILIZED TO VALIDATE THE ISF, THE MODIFIED ISF AND THE SIMPLIFIED ISF MODELS

Experiment number, day sample was taken (episode), episode number, filter number, influent VSS concentration (mg/ℓ), effluent VSS concentration (mg/ℓ), hydraulic loading (mgad), influent water temperature (°C).

Table 40. Field data from Harris (1977) utilized to validate the ISF, the modified ISF and the simplified ISF models.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 2.6 | 0.1 | 0.5 | 21.0 |
| 1 | 11 | 2 | 1 | 17.1 | 2.5 | 0.4 | 21.0 |
| 1 | 16 | 3 | 1 | 4.2 | 0.1 | 0.4 | 24.5 |
| 1 | 23 | 4 | 1 | 6.4 | 1.1 | 0.4 | 24.5 |
| 1 | 30 | 5 | 1 | 11.5 | 0.9 | 0.4 | 23.7 |
| 1 | 37 | 6 | 1 | 31.5 | 2.3 | 0.4 | 22.9 |
| | | | | | | | |
| 1 | 1 | 1 | 2 | 2.5 | 0.8 | 0.8 | 21.0 |
| 1 | 11 | 2 | 2 | 17.1 | 3.6 | 0.6 | 21.0 |
| 1 | 16 | 3 | 2 | 4.2 | 0.7 | 0.6 | 24.5 |
| 1 | 23 | 4 | 2 | 6.4 | 0.5 | 0.6 | 24.5 |
| 1 | 30 | 5 | 2 | 11.5 | 0.5 | 0.6 | 23.7 |
| | | | | | | | |
| 1 | 1 | 1 | 3 | 2.6 | 0.5 | 1.0 | 21.0 |
| 1 | 11 | 2 | 3 | 17.1 | 1.3 | 0.8 | 21.0 |
| 1 | 16 | 3 | 3 | 4.2 | 0.8 | 0.8 | 24.5 |
| 1 | 23 | 4 | 3 | 6.4 | 0.6 | 0.8 | 24.5 |
| 1 | 30 | 5 | 3 | 11.5 | 1.1 | 0.8 | 23.7 |
| | | | | | | | |
| 1 | 1 | 1 | 4 | 2.6 | 1.1 | 1.3 | 21.0 |
| 1 | 11 | 2 | 4 | 17.1 | 1.3 | 1.0 | 21.0 |
| 1 | 16 | 3 | 4 | 4.2 | 1.1 | 1.0 | 24.5 |
| 1 | 23 | 4 | 4 | 6.4 | 0.6 | 1.0 | 24.5 |
| | | | | | | | |
| 1 | 1 | 1 | 5 | 2.6 | 0.7 | 1.5 | 21.0 |
| 1 | 11 | 2 | 5 | 17.1 | 1.7 | 1.2 | 21.0 |
| 1 | 16 | 3 | 5 | 4.2 | 0.4 | 1.2 | 24.5 |
| 1 | 23 | 4 | 5 | 6.4 | 0.1 | 1.2 | 24.5 |
| | | | | | | | |
| 2 | 1 | 1 | 1 | 39.1 | 3.0 | 0.4 | 19.2 |
| 2 | 3 | 2 | 1 | 27.2 | 1.4 | 0.4 | 19.1 |
| 2 | 6 | 3 | 1 | 26.2 | 0.1 | 0.4 | 19.1 |
| 2 | 8 | 4 | 1 | 20.8 | 1.6 | 0.4 | 19.0 |
| 2 | 15 | 5 | 1 | 8.6 | 0.6 | 0.4 | 17.1 |
| 2 | 17 | 6 | 1 | 7.8 | 0.2 | 0.4 | 17.0 |
| 2 | 22 | 7 | 1 | 11.5 | 0.2 | 0.4 | 16.8 |
| | | | | | | | |
| 2 | 1 | 1 | 6 | 17.1 | 2.0 | 0.2 | 21.1 |
| 2 | 6 | 2 | 6 | 4.2 | 0.1 | 0.2 | 24.5 |
| 2 | 13 | 3 | 6 | 6.4 | 0.1 | 0.2 | 24.5 |
| 2 | 27 | 4 | 6 | 31.5 | 2.9 | 0.2 | 22.9 |
| 2 | 39 | 5 | 6 | 40.8 | 0.9 | 0.2 | 19.4 |
| 2 | 41 | 6 | 6 | 36.5 | 1.2 | 0.2 | 19.0 |

Table 40. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 1 | 6.0 | 0.1 | 0.4 | 15.1 |
| 3 | 9 | 2 | 1 | 11.4 | 0.6 | 0.4 | 13.9 |
| 3 | 16 | 3 | 1 | 8.9 | 0.7 | 0.4 | 11.9 |
| 3 | 23 | 4 | 1 | 33.5 | 0.2 | 0.4 | 9.5 |
| 3 | 30 | 5 | 1 | 25.3 | 0.6 | 0.4 | 7.1 |
| | | | | | | | |
| 3 | 1 | 1 | 6 | 39.1 | 2.2 | 0.2 | 19.2 |
| 3 | 3 | 2 | 6 | 27.2 | 0.4 | 0.2 | 19.1 |
| 3 | 6 | 3 | 6 | 26.2 | 1.5 | 0.2 | 19.1 |
| 3 | 8 | 4 | 6 | 20.8 | 0.6 | 0.2 | 19.0 |
| 3 | 15 | 5 | 6 | 8.6 | 0.6 | 0.2 | 17.1 |
| 3 | 17 | 6 | 6 | 7.8 | 0.2 | 0.2 | 17.0 |
| 3 | 23 | 7 | 6 | 11.5 | 0.4 | 0.2 | 16.8 |
| 3 | 30 | 8 | 6 | 6.0 | 0.4 | 0.2 | 15.1 |
| 3 | 37 | 9 | 6 | 11.4 | 0.6 | 0.2 | 13.9 |
| 3 | 44 | 10 | 6 | 8.9 | 0.3 | 0.2 | 11.9 |
| 3 | 51 | 11 | 6 | 33.5 | 0.5 | 0.2 | 11.9 |
| 3 | 58 | 12 | 6 | 25.3 | 0.4 | 0.2 | 9.5 |
| 3 | 65 | 13 | 6 | 18.2 | 0.5 | 0.2 | 7.1 |
| 3 | 72 | 14 | 6 | 29.5 | 0.6 | 0.2 | 6.8 |
| 3 | 79 | 15 | 6 | 11.5 | 0.2 | 0.2 | 5.1 |
| 3 | 84 | 16 | 6 | 18.2 | 0.4 | 0.2 | 4.1 |
| 3 | 93 | 17 | 6 | 18.1 | 0.6 | 0.2 | 3.7 |
| 3 | 100 | 18 | 6 | 26.9 | 1.0 | 0.2 | 2.7 |
| 3 | 107 | 19 | 6 | 11.9 | 1.0 | 0.2 | 3.4 |
| 3 | 114 | 20 | 6 | 16.6 | 0.8 | 0.2 | 2.1 |
| 3 | 121 | 21 | 6 | 6.8 | 0.9 | 0.2 | 2.8 |
| 3 | 128 | 22 | 5 | 4.0 | 1.0 | 0.2 | 3.0 |
| 3 | 135 | 23 | 6 | 6.0 | 0.5 | 0.2 | 3.0 |
| 3 | 142 | 24 | 6 | 11.6 | 2.1 | 0.2 | 2.0 |
| 3 | 149 | 25 | 6 | 22.3 | 3.0 | 0.2 | 2.0 |
| 3 | 156 | 26 | 6 | 27.2 | 3.1 | 0.2 | 2.0 |
| 3 | 163 | 27 | 6 | 39.4 | 3.9 | 0.2 | 2.5 |
| 3 | 170 | 28 | 6 | 40.2 | 6.0 | 0.2 | 3.6 |
| 3 | 177 | 29 | 6 | 35.7 | 5.4 | 0.2 | 3.5 |
| 3 | 184 | 30 | 6 | 40.4 | 3.9 | 0.2 | 4.5 |
| 4 | 2 | 1 | 1 | 29.5 | 1.0 | 0.4 | 6.8 |
| 4 | 9 | 2 | 1 | 11.5 | 0.6 | 0.4 | 5.1 |
| 4 | 14 | 3 | 1 | 18.2 | 0.8 | 0.4 | 4.1 |
| 4 | 23 | 4 | 1 | 18.1 | 1.0 | 0.4 | 3.7 |
| 4 | 30 | 5 | 1 | 26.9 | 1.6 | 0.4 | 2.7 |
| 4 | 37 | 6 | 1 | 11.9 | 1.5 | 0.4 | 3.4 |
| 4 | 44 | 7 | 1 | 16.6 | 0.9 | 0.4 | 2.1 |
| 4 | 51 | 8 | 1 | 6.8 | 0.8 | 0.4 | 2.8 |
| 4 | 58 | 9 | 1 | 4.0 | 1.1 | 0.4 | 3.0 |

Table 40. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 4 | 65 | 10 | 1 | 6.0 | 0.3 | 0.4 | 3.0 |
| 4 | 72 | 11 | 1 | 11.6 | 2.0 | 0.4 | 2.0 |
| 4 | 79 | 12 | 1 | 22.3 | 2.5 | 0.4 | 2.0 |
| 4 | 86 | 13 | 1 | 27.2 | 3.8 | 0.4 | 2.0 |
| 4 | 93 | 14 | 1 | 39.4 | 5.4 | 0.4 | 2.5 |
| 4 | 100 | 15 | 1 | 40.2 | 3.3 | 0.4 | 3.6 |
| 4 | 107 | 16 | 1 | 36.7 | 6.0 | 0.4 | 3.5 |
| 4 | 114 | 17 | 1 | 40.4 | 6.1 | 0.4 | 4.5 |
| 4 | 121 | 18 | 1 | 36.0 | 4.9 | 0.4 | 4.9 |
| 4 | 128 | 19 | 1 | 45.9 | 4.7 | 0.4 | 6.7 |
| 4 | 3 | 1 | 6 | 38.4 | 1.6 | 0.2 | 4.7 |
| 4 | 10 | 2 | 6 | 18.6 | 1.2 | 0.2 | 6.1 |
| 4 | 17 | 3 | 6 | 11.1 | 0.6 | 0.2 | 6.7 |
| 4 | 24 | 4 | 6 | 12.2 | 0.5 | 0.2 | 10.1 |
| 4 | 31 | 5 | 6 | 22.3 | 0.5 | 0.2 | 10.5 |
| 4 | 38 | 6 | 6 | 27.6 | 0.5 | 0.2 | 10.0 |
| 4 | 45 | 7 | 6 | 14.2 | 0.7 | 0.2 | 13.5 |
| 4 | 52 | 8 | 6 | 4.6 | 0.5 | 0.2 | 12.1 |
| 4 | 59 | 9 | 6 | 69.0 | 1.1 | 0.2 | 15.1 |
| 4 | 66 | 10 | 6 | 109.1 | 0.5 | 0.2 | 17.7 |
| 4 | 73 | 11 | 6 | 15.6 | 0.6 | 0.2 | 18.0 |
| 4 | 80 | 12 | 6 | 5.6 | 0.4 | 0.2 | 17.2 |
| 4 | 87 | 13 | 6 | 16.9 | 0.5 | 0.2 | 16.5 |
| 5 | 6 | 1 | 1 | 18.6 | 2.5 | 0.4 | 6.1 |
| 5 | 13 | 2 | 1 | 11.1 | 0.8 | 0.4 | 6.7 |
| 5 | 20 | 3 | 1 | 12.2 | 0.5 | 0.4 | 10.1 |
| 5 | 27 | 4 | 1 | 22.3 | 0.8 | 0.4 | 10.5 |
| 5 | 34 | 5 | 1 | 27.6 | 0.6 | 0.4 | 10.0 |
| 6 | 6 | 1 | 1 | 4.6 | 0.6 | 0.4 | 12.1 |
| 6 | 13 | 2 | 1 | 69.0 | 0.6 | 0.4 | 15.1 |
| 6 | 20 | 3 | 1 | 109.1 | 0.5 | 0.4 | 17.7 |
| 6 | 27 | 4 | 1 | 15.6 | 0.7 | 0.4 | 18.0 |
| 6 | 34 | 5 | 1 | 5.6 | 0.5 | 0.4 | 17.2 |
| 6 | 41 | 6 | 1 | 16.9 | 0.6 | 0.4 | 16.5 |
| 7 | 2 | 1 | 2 | 6.8 | 3.5 | 0.4 | 2.8 |
| 7 | 9 | 2 | 2 | 4.0 | 1.2 | 0.4 | 3.0 |
| 7 | 16 | 3 | 2 | 6.0 | 0.7 | 0.4 | 3.0 |
| 7 | 23 | 4 | 2 | 11.6 | 3.5 | 0.4 | 2.0 |
| 7 | 30 | 5 | 2 | 22.3 | 8.1 | 0.4 | 2.0 |
| 7 | 37 | 6 | 2 | 27.2 | 7.1 | 0.4 | 2.0 |
| 7 | 44 | 7 | 2 | 39.4 | 14.8 | 0.4 | 2.5 |
| 7 | 51 | 8 | 2 | 40.2 | 10.8 | 0.4 | 3.6 |
| 7 | 58 | 9 | 2 | 36.7 | 10.5 | 0.4 | 3.5 |
| 7 | 65 | 10 | 2 | 40.4 | 9.8 | 0.4 | 4.5 |
| 7 | 72 | 11 | 2 | 36.0 | 8.3 | 0.4 | 4.9 |
| 7 | 79 | 12 | 2 | 45.9 | 13.2 | 0.4 | 6.7 |
| 9 | 2 | 1 | 2 | 14.2 | 1.9 | 0.6 | 13.5 |
| 9 | 9 | 2 | 2 | 4.6 | 0.5 | 0.6 | 12.1 |
| 9 | 16 | 3 | 2 | 69.0 | 1.0 | 0.6 | 15.1 |
| 9 | 23 | 4 | 2 | 109.1 | 1.6 | 0.6 | 17.7 |
| 9 | 4 | 1 | 4 | 16.6 | 0.9 | 0.4 | 2.1 |
| 9 | 11 | 2 | 4 | 6.8 | 1.1 | 0.4 | 2.8 |
| 9 | 18 | 3 | 4 | 4.0 | 1.0 | 0.4 | 3.0 |
| 9 | 25 | 4 | 4 | 6.0 | 0.1 | 0.4 | 3.0 |
| 9 | 32 | 5 | 4 | 11.6 | 1.7 | 0.4 | 2.0 |
| 9 | 39 | 6 | 4 | 22.3 | 7.2 | 0.4 | 2.0 |
| 9 | 46 | 7 | 4 | 27.2 | 9.0 | 0.4 | 2.0 |
| 9 | 53 | 8 | 4 | 39.4 | 4.8 | 0.4 | 2.5 |
| 9 | 60 | 9 | 4 | 40.2 | 4.1 | 0.4 | 3.6 |

Table 40. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 9 | 67 | 10 | 4 | 36.7 | 4.6 | 0.4 | 3.5 |
| 9 | 74 | 11 | 4 | 40.4 | 3.3 | 0.4 | 4.5 |
| 9 | 81 | 12 | 4 | 36.0 | 5.8 | 0.4 | 4.9 |
| 9 | 88 | 13 | 4 | 45.9 | 7.3 | 0.4 | 6.7 |
| 9 | 95 | 14 | 4 | 42.1 | 6.7 | 0.4 | 2.5 |
| 9 | 102 | 15 | 4 | 38.4 | 3.5 | 0.4 | 4.7 |
| 9 | 109 | 16 | 4 | 18.6 | 2.5 | 0.4 | 6.1 |
| 9 | 116 | 17 | 4 | 11.1 | 2.0 | 0.4 | 6.7 |
| 9 | 123 | 18 | 4 | 12.2 | 1.7 | 0.4 | 10.1 |
| 9 | 130 | 19 | 4 | 22.3 | 1.8 | 0.4 | 10.5 |
| 9 | 137 | 20 | 4 | 27.6 | 2.3 | 0.4 | 10.0 |
| 9 | 4 | 1 | 5 | 16.6 | 0.9 | 0.4 | 2.1 |
| 9 | 11 | 2 | 5 | 6.8 | 0.7 | 0.4 | 2.8 |
| 9 | 18 | 3 | 5 | 4.0 | 1.2 | 0.4 | 3.0 |
| 9 | 25 | 4 | 5 | 6.0 | 0.5 | 0.4 | 3.0 |
| 9 | 32 | 5 | 5 | 11.6 | 1.5 | 0.4 | 2.0 |
| 9 | 39 | 6 | 5 | 22.3 | 3.3 | 0.4 | 2.0 |
| 9 | 46 | 7 | 5 | 27.2 | 3.8 | 0.4 | 2.0 |
| 9 | 53 | 8 | 5 | 39.4 | 5.6 | 0.4 | 2.5 |

## APPENDIX D

### FIELD DATA FROM Tupyi (1977) UTILIZED TO VALIDATE THE ISF, THE MODIFIED ISF AND THE SIMPLIFIED ISF MODELS

Experiment number, day sample was taken (episode), episode number, filter number, influent VSS concentration (mg/ℓ), effluent VSS concentration (mg/ℓ), hydraulic loading (mgad), influent water temperature (°C).

Table 41. Field data from Tupyi (1977) utilized to validate the ISF, the modified ISF and the simplified ISF models.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 2 | 1 | 1 | 1 | 22.5 | 10.1 | 0.4 | 19.2 |
| 2 | 8 | 2 | 1 | 21.4 | 1.2 | 0.4 | 19.0 |
| 2 | 10 | 3 | 1 | 44.6 | 1.5 | 0.4 | 19.2 |
| 2 | 15 | 4 | 1 | 23.4 | 0.9 | 0.4 | 20.0 |
| 2 | 18 | 5 | 1 | 24.0 | 2.5 | 0.4 | 17.9 |
| 2 | 24 | 6 | 1 | 15.4 | 4.5 | 0.4 | 17.2 |
| 2 | 29 | 7 | 1 | 9.2 | 1.3 | 0.4 | 16.0 |
| 3 | 1 | 1 | 1 | 3.2 | 1.1 | 0.4 | 4.0 |
| 3 | 8 | 2 | 1 | 2.4 | 1.0 | 0.4 | 5.0 |
| 3 | 15 | 3 | 1 | 3.0 | 1.1 | 0.4 | 4.9 |
| 3 | 22 | 4 | 1 | 7.2 | 0.9 | 0.4 | 5.5 |
| 3 | 29 | 5 | 1 | 9.3 | 0.8 | 0.4 | 3.0 |
| 3 | 34 | 6 | 1 | 10.5 | 0.9 | 0.4 | 2.5 |
| 3 | 41 | 7 | 1 | 4.2 | 0.8 | 0.4 | 4.1 |
| 3 | 50 | 8 | 1 | 14.9 | 1.2 | 0.4 | 4.0 |
| 3 | 57 | 9 | 1 | 19.8 | 1.3 | 0.4 | 4.5 |
| 3 | 64 | 10 | 1 | 16.0 | 1.3 | 0.4 | 1.5 |
| 3 | 71 | 11 | 1 | 6.5 | 1.5 | 0.4 | 2.0 |
| 3 | 78 | 12 | 1 | 7.0 | 0.2 | 0.4 | 2.0 |
| 3 | 85 | 13 | 1 | 11.3 | 4.1 | 0.4 | 2.0 |
| 3 | 92 | 14 | 1 | 8.6 | 3.1 | 0.4 | 2.0 |
| 3 | 100 | 15 | 1 | 8.8 | 2.7 | 0.4 | 2.0 |
| 3 | 105 | 16 | 1 | 6.4 | 3.4 | 0.4 | 2.0 |
| 3 | 112 | 17 | 1 | 6.7 | 3.0 | 0.4 | 3.0 |
| 3 | 119 | 18 | 1 | 7.0 | 2.7 | 0.4 | 2.5 |
| 3 | 125 | 19 | 1 | 7.5 | 2.0 | 0.4 | 2.5 |
| 3 | 134 | 20 | 1 | 11.8 | 2.8 | 0.4 | 3.8 |
| 3 | 141 | 21 | 1 | 21.9 | 3.0 | 0.4 | 5.1 |
| 3 | 147 | 22 | 1 | 16.3 | 2.5 | 0.4 | 9.7 |
| 3 | 154 | 23 | 1 | 32.3 | 9.4 | 0.4 | 9.9 |
| 3 | 161 | 24 | 1 | 46.5 | 1.6 | 0.4 | 10.4 |
| 4 | 1 | 1 | 1 | 11.9 | 2.0 | 0.4 | 19.0 |
| 4 | 8 | 2 | 1 | 20.1 | 1.6 | 0.4 | 18.0 |
| 4 | 15 | 3 | 1 | 67.6 | 1.4 | 0.4 | 20.0 |
| 4 | 22 | 4 | 1 | 15.6 | 1.9 | 0.4 | 20.0 |
| 4 | 29 | 5 | 1 | 5.5 | 1.5 | 0.4 | 17.0 |
| 4 | 36 | 6 | 1 | 19.6 | 1.0 | 0.4 | 16.2 |
| 4 | 43 | 7 | 1 | 13.9 | 0.9 | 0.4 | 23.1 |
| 4 | 50 | 8 | 1 | 62.4 | 1.9 | 0.4 | 23.9 |
| 4 | 57 | 9 | 1 | 18.2 | 2.3 | 0.4 | 23.0 |
| 4 | 64 | 10 | 1 | 18.3 | 3.4 | 0.4 | 23.0 |
| 4 | 71 | 11 | 1 | 31.9 | 5.5 | 0.4 | 23.0 |
| 4 | 78 | 12 | 1 | 6.7 | 0.2 | 0.4 | 22.5 |

Table 41. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 4 | 85 | 13 | 1 | 10.9 | 0.6 | 0.4 | 23.0 |
| 4 | 92 | 14 | 1 | 13.0 | 0.6 | 0.4 | 20.5 |
| 4 | 99 | 15 | 1 | 16.1 | 0.6 | 0.4 | 20.0 |
| 1 | 1 | 1 | 3 | 35.8 | 4.8 | 1.5 | 19.0 |
| 1 | 4 | 2 | 3 | 35.3 | 10.2 | 1.5 | 19.0 |
| 1 | 9 | 3 | 3 | 22.5 | 6.9 | 1.5 | 19.2 |
| 1 | 16 | 4 | 3 | 21.4 | 7.0 | 1.5 | 19.0 |
| 1 | 18 | 5 | 3 | 44.6 | 12.5 | 1.5 | 19.2 |
| 1 | 22 | 6 | 3 | 23.4 | 6.5 | 1.5 | 20.0 |
| 1 | 25 | 7 | 3 | 24.0 | 7.1 | 1.5 | 17.9 |
| 1 | 31 | 8 | 3 | 15.4 | 4.9 | 1.5 | 17.2 |
| 1 | 36 | 9 | 3 | 9.2 | 2.5 | 1.5 | 16.0 |
| 1 | 43 | 12 | 3 | 22.9 | 4.2 | 1.5 | 22.2 |
| 2 | 1 | 1 | 3 | 6.5 | 1.4 | 1.0 | 9.0 |
| 2 | 10 | 2 | 3 | 4.0 | 1.9 | 1.0 | 5.2 |
| 2 | 17 | 3 | 3 | 3.2 | 1.6 | 1.0 | 4.0 |
| 2 | 24 | 4 | 3 | 2.4 | 1.5 | 1.0 | 5.0 |
| 2 | 31 | 5 | 3 | 3.0 | 3.0 | 1.0 | 4.9 |
| 2 | 38 | 6 | 3 | 7.2 | 3.7 | 1.0 | 5.5 |
| 2 | 45 | 7 | 3 | 9.3 | 2.3 | 1.0 | 3.0 |
| 2 | 50 | 8 | 3 | 10.5 | 5.8 | 1.0 | 2.5 |
| 2 | 57 | 9 | 3 | 4.2 | 2.3 | 1.0 | 4.1 |
| 2 | 66 | 10 | 3 | 14.9 | 6.9 | 1.0 | 4.0 |
| 2 | 73 | 11 | 3 | 19.8 | 17.5 | 1.0 | 4.5 |
| 2 | 80 | 12 | 3 | 16.0 | 12.4 | 1.0 | 1.5 |
| 2 | 87 | 13 | 3 | 6.5 | 4.6 | 1.0 | 2.0 |
| 2 | 94 | 14 | 3 | 7.0 | 5.6 | 1.0 | 2.0 |
| 2 | 101 | 15 | 3 | 11.3 | 10.7 | 1.0 | 2.0 |
| 2 | 108 | 16 | 3 | 8.6 | 7.3 | 1.0 | 2.0 |
| 2 | 116 | 17 | 3 | 8.8 | 5.6 | 1.0 | 2.0 |
| 2 | 121 | 18 | 3 | 6.4 | 6.9 | 1.0 | 2.0 |
| 2 | 128 | 19 | 3 | 6.7 | 6.3 | 1.0 | 3.0 |
| 2 | 135 | 20 | 3 | 7.0 | 5.7 | 1.0 | 2.5 |
| 2 | 141 | 21 | 3 | 7.5 | 5.2 | 1.0 | 2.5 |
| 2 | 150 | 22 | 3 | 11.8 | 6.8 | 1.0 | 3.8 |
| 2 | 157 | 23 | 3 | 21.9 | 12.2 | 1.0 | 5.1 |
| 2 | 163 | 24 | 3 | 16.3 | 10.0 | 1.0 | 9.7 |
| 2 | 170 | 25 | 3 | 32.3 | 21.5 | 1.0 | 9.9 |
| 2 | 177 | 26 | 3 | 46.5 | 22.6 | 1.0 | 10.4 |
| 2 | 184 | 27 | 3 | 11.7 | 2.4 | 1.0 | 14.5 |
| 2 | 191 | 28 | 3 | 9.2 | 2.2 | 1.0 | 16.0 |
| 2 | 212 | 29 | 3 | 67.6 | 56.3 | 1.0 | 20.0 |
| 2 | 219 | 30 | 3 | 15.6 | 4.8 | 1.0 | 20.0 |

Table 41. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 35.3 | 8.7 | 1.0 | 19.0 |
| 2 | 6 | 2 | 2 | 22.5 | 7.4 | 1.0 | 19.2 |
| 2 | 13 | 3 | 2 | 21.4 | 5.3 | 1.0 | 19.0 |
| 2 | 15 | 4 | 2 | 44.6 | 10.4 | 1.0 | 19.2 |
| 2 | 19 | 5 | 2 | 23.4 | 7.1 | 1.0 | 20.0 |
| 2 | 22 | 6 | 2 | 24.0 | 7.1 | 1.0 | 17.9 |
| 2 | 28 | 7 | 2 | 15.4 | 4.6 | 1.0 | 17.2 |
| 2 | 33 | 8 | 2 | 9.2 | 2.8 | 1.0 | 16.0 |
| 2 | 40 | 9 | 2 | 22.9 | 2.4 | 1.0 | 22.2 |
| 3 | 1 | 1 | 2 | 6.2 | 1.5 | 1.0 | 7.8 |
| 3 | 6 | 2 | 2 | 6.3 | 1.8 | 1.0 | 5.5 |
| 3 | 12 | 3 | 2 | 6.5 | 2.5 | 1.0 | 9.0 |
| 3 | 21 | 4 | 2 | 4.0 | 1.5 | 1.0 | 5.2 |
| 3 | 28 | 5 | 2 | 3.2 | 1.2 | 1.0 | 4.0 |
| 3 | 35 | 6 | 2 | 2.4 | 1.3 | 1.0 | 5.0 |
| 3 | 42 | 7 | 2 | 3.0 | 1.5 | 1.0 | 4.9 |
| 3 | 49 | 8 | 2 | 7.2 | 4.2 | 1.0 | 5.5 |
| 3 | 56 | 9 | 2 | 9.3 | 3.2 | 1.0 | 3.0 |
| 3 | 61 | 10 | 2 | 10.5 | 4.8 | 1.0 | 2.5 |
| 3 | 68 | 11 | 2 | 4.2 | 2.4 | 1.0 | 4.1 |
| 3 | 77 | 12 | 2 | 14.9 | 10.9 | 1.0 | 4.0 |
| 3 | 84 | 13 | 2 | 19.8 | 9.2 | 1.0 | 4.5 |
| 3 | 91 | 14 | 2 | 16.0 | 6.4 | 1.0 | 1.5 |
| 3 | 98 | 15 | 2 | 6.5 | 4.5 | 1.0 | 2.0 |
| 3 | 105 | 16 | 2 | 7.0 | 5.6 | 1.0 | 2.0 |
| 3 | 112 | 17 | 2 | 11.3 | 7.7 | 1.0 | 2.0 |
| 3 | 119 | 18 | 2 | 8.6 | 5.7 | 1.0 | 2.0 |
| 3 | 127 | 19 | 2 | 8.8 | 5.7 | 1.0 | 2.0 |
| 3 | 132 | 20 | 2 | 6.4 | 4.5 | 1.0 | 2.0 |
| 3 | 139 | 21 | 2 | 6.7 | 4.3 | 1.0 | 3.0 |
| 3 | 146 | 22 | 2 | 7.0 | 4.1 | 1.0 | 2.5 |
| 3 | 153 | 23 | 2 | 7.5 | 4.5 | 1.0 | 2.5 |
| 3 | 162 | 24 | 2 | 11.8 | 4.3 | 1.0 | 3.8 |
| 3 | 169 | 25 | 2 | 21.9 | 8.9 | 1.0 | 5.1 |
| 3 | 175 | 26 | 2 | 16.3 | 11.9 | 1.0 | 9.7 |
| 5 | 1 | 1 | 5 | 4.0 | 2.9 | 2.0 | 5.2 |
| 5 | 8 | 2 | 5 | 3.2 | 1.2 | 2.0 | 4.0 |

Table 41. Continued.

| RUN NO. | DAY NO. | EPI NO. | FILT NO. | INF MG/L | EFF MG/L | LOAD MGAD | TEMP C |
|---|---|---|---|---|---|---|---|
| 5 | 15 | 3 | 5 | 2.4 | 1.7 | 2.0 | 5.0 |
| 5 | 22 | 4 | 5 | 3.0 | 1.9 | 2.0 | 4.9 |
| 5 | 29 | 5 | 5 | 7.2 | 6.2 | 2.0 | 5.5 |
| 5 | 36 | 6 | 5 | 9.3 | 5.1 | 2.0 | 3.0 |
| 5 | 41 | 7 | 5 | 10.5 | 7.5 | 2.0 | 2.5 |
| 5 | 48 | 8 | 5 | 4.2 | 1.9 | 2.0 | 4.1 |
| 5 | 57 | 9 | 5 | 14.9 | 11.5 | 2.0 | 4.0 |
| 5 | 64 | 10 | 5 | 19.8 | 7.8 | 2.0 | 4.5 |
| 5 | 71 | 11 | 5 | 16.0 | 6.3 | 2.0 | 1.5 |
| 5 | 78 | 12 | 5 | 6.5 | 4.6 | 2.0 | 2.0 |
| 5 | 85 | 13 | 5 | 7.0 | 6.1 | 2.0 | 2.0 |
| 5 | 92 | 14 | 5 | 11.3 | 10.0 | 2.0 | 2.0 |
| 5 | 99 | 15 | 5 | 8.8 | 7.2 | 2.0 | 2.0 |
| 5 | 106 | 16 | 5 | 8.8 | 4.4 | 2.0 | 2.0 |
| 5 | 111 | 17 | 5 | 6.4 | 5.2 | 2.0 | 2.0 |
| 5 | 118 | 18 | 5 | 6.7 | 5.2 | 2.0 | 3.0 |
| 5 | 125 | 19 | 5 | 7.0 | 5.1 | 2.0 | 2.5 |
| 5 | 131 | 20 | 5 | 7.5 | 4.6 | 2.0 | 2.5 |
| 5 | 140 | 21 | 5 | 11.8 | 10.7 | 2.0 | 3.8 |
| 6 | 1 | 1 | 5 | 16.3 | 11.0 | 2.0 | 9.7 |
| 6 | 8 | 2 | 5 | 32.3 | 21.9 | 2.0 | 9.9 |
| 6 | 15 | 3 | 5 | 46.5 | 27.7 | 2.0 | 10.4 |
| 6 | 22 | 4 | 5 | 11.7 | 2.5 | 2.0 | 14.5 |
| 6 | 29 | 5 | 5 | 9.2 | 2.0 | 2.0 | 16.0 |
| 6 | 36 | 6 | 5 | 11.9 | 2.8 | 2.0 | 19.0 |
| 6 | 43 | 7 | 5 | 20.1 | 11.2 | 2.0 | 18.0 |
| 7 | 1 | 1 | 5 | 5.5 | 1.2 | 2.0 | 17.0 |
| 7 | 8 | 2 | 5 | 19.6 | 3.3 | 2.0 | 16.2 |
| 7 | 15 | 3 | 5 | 13.9 | 2.3 | 2.0 | 23.1 |
| 7 | 22 | 4 | 5 | 62.4 | 31.9 | 2.0 | 23.9 |
| 8 | 1 | 1 | 5 | 18.3 | 5.6 | 1.0 | 23.0 |
| 8 | 8 | 2 | 5 | 31.9 | 14.9 | 1.0 | 23.0 |
| 8 | 15 | 3 | 5 | 21.0 | 8.0 | 1.0 | 23.0 |
| 8 | 22 | 4 | 5 | 10.0 | 1.2 | 1.0 | 23.0 |
| 8 | 29 | 5 | 5 | 16.9 | 2.1 | 1.0 | 20.5 |
| 8 | 36 | 6 | 5 | 16.1 | 3.1 | 1.0 | 20.0 |

APPENDIX E

THE COMPUTER PROGRAM CONTAINING THE ISF MODEL UTILIZED TO VALIDATE THE FIELD DATA FROM HARRIS (1977)

```
      DIMENSION DECAY(17,260),TEMP(17,50),TTEMP(17,260)
      DIMENSION DHL(17,260),DLOAD(17,260)
      DIMENSION DLAYER(4)
      DIMENSION HL(17,50)
      DIMENSION DML(17,260)
      DIMENSION DMLL(17,4),PCSD(5,17,260),A(260),B(260),C(260)
      INTEGER IT(17,50),NN(17),NON(17),ITUM(50)
      DIMENSION AML(17,260),SLOPM(17,260)
      DIMENSION SALC(17,260),COUTF(17,260)
      DIMENSION SALM(17,260),SALMG(17,260),CIN(17,260),COUT(17,260)
      REAL CLVL(5),CSS(5,17,50),CS(5,17),DUM(50),DZ(4),CSSD(5,17,260)
      INTEGER TMAX,TIM,DELT
      DIMENSION CD(6)
      DATA CD/.3900E-01,.3201E-01,.2561E-01,.1388E-01,.3618E-01,0.0/
      DATA DZ/5.08,2.54,7.62,60.96/
      DATA NON/37,35,30,28,23,25,42,33,189,130,88,36,42,80,26,143,58/
      DATA NN/6,5,5,4,4,7,6,5,30,19,13,5,6,12,4,20,8/
      DATA DLAYER/0.778,0.389,1.168,9.344/
C
C     DEN=DENSITY OF ALGAE,MG DRY WT/L WET VOLUME
C     RHO=DENSITY OF ALGAE,MG DRY WT/CM*03. WET VOLUME
C     AREA=AREA OF FILTER,CM**2.
C     DEP=DEPTH OF THE FILTER,CM
C     EE=BASE OF THE NATURAL LOGARITHM SYSTEM
C
      DEN=7.137E05
      RHO=7.137E02
      AREA=153.2790
      DEP=30.*2.54
      EE=2.718281828
C
C     TIM=INPUT VARIABLE TO FUN1 FOR DAILY VALUES
C     IDY=DAY NUMBER
C     IE=EPISODE NUMBER WHERE AN EPISODE IS A SAMPLING
C
C     IC=COLUMN NUMBER              NC=NUMBER OF COLUMNS
C
C     ID=DAILY MASS LOADING RANGE NUMBER     ND=NUMBER OF DML RANGES
C
C     DELT=DELTA TIME,DAYS          NZM=NUMBER OF LAYERS
C
C     IZ=PORT DEPTH NUMBER          NZ=NUMBER OF PORTS
      NC=17
      ND=5
      NZ=5
      NZM=NZ-1
      NZI=31
      NZIM=NZI-1
      DELT=1
C
C
C     IZ DEPTH
C     1  INFLUENT
```

```
C      2  2 IN
C      3  3 IN
C      4  6 IN
C      5  EFFLUENT
C
C
C   CLVL(IZ)=ARRAY(TEMPORARY)TO HOLD VSS VALUES IN MG/L
C
C   HL(IC,IE)=ARRAY TO HOLD THE HYDRAULIC LOADING,MGAD,
C   ON THE DAY OF SAMPLING.
C
C   TEMP(IC,IE)=ARRAY TO HOLD INFLUENT TEMPERATURE,DEG.C.,
C   ON THE DAY OF SAMPLING.
C
C   IT(IC,IE)=ARRAY(TEMPORARY)TO HOLD DAY NO. FOR A PARTICULAR EPISODE
C
C   CSS(IZ,IC,IE)=ARRAY TO HOLD VSS VALUES...
C   L WET VOL/L FILTRATE FOR EPISODES
C
C   READ IN AND WRITE OUT RAW VSS DATA FOR INF AND EFF.
C
C   WRITE TABLE HEADING FOR RAW DATA
C
      WRITE(6,98)
   98 FORMAT('1',33X,'VSS,MG/L')
C
      WRITE(6,97)
   97 FORMAT('0',1X,'DAY',1X,'EPISODE',1X,'COLUMN',3X,'INF',6X,'EFF',4X,
     1'LOADING',3X,'TEMP'/1X,'NO.',3X,'NO.',4X,'NO.',4X,'MG/L',5X,'MG/L'
     2,5X,'MGAD',4X,'DEG.C')
C
   91 READ(5,103)IDY,IE,IC,CLVL(1),CLVL(5),HL(IC,IE),TEMP(IC,IE)
C
      IF(IDY.EQ.199)GO TO 12
C
      WRITE(6,104)IDY,IE,IC,CLVL(1),CLVL(5),HL(IC,IE),TEMP(IC,IE)
C
      IT(IC,IE)=IDY
      CSS(1,IC,IE)=CLVL(1)/DEN
      IF(CLVL(5).LE.0.0)GO TO 13
      CSS(5,IC,IE)=CLVL(5)/DEN
      GO TO 15
   13 CSS(5,IC,IE)=0.1/DEN
   15 CONTINUE
      GO TO 91
  103 FORMAT(1X,I4,2I5,4F5.1)
  104 FORMAT(' ',1X,I3,3X,I3,4X,I2,4F9.1)
C
   12 CONTINUE
C
C
C   WRITE OUT V/V DATA FOR INF AND EFF    EPISODE.
C
      WRITE(6,102)
  102 FORMAT('1',10X,'VSS,VOLUME OF ALGAE/VOLUME OF FILTRATE   EPISODE')
C
      DO 16 IC=1,NC
      NMAX=NN(IC)
      WRITE(6,403)IC
   16 WRITE(6,502)(IT(IC,IE),CSS(1,IC,IE),CSS(5,IC,IE),IE=1,NMAX)
  403 FORMAT('0','COLUMN NO.'/3X,I4/1X,'DAY NO.',4X,'INFLUENT',5X,'EFFLU
     1ENT')
  502 FORMAT(' ',3X,I3,2X,2E13.4)
C
C
C   INITIALIZE COUNTER AND ARRAYS
C
```

```
      KK=0
      DO 20 IC=1,NC
      AML(IC,1)=0.
   20 SALM(IC,1)=0.
C
 1000 KK=KK+1
      KP=KK+1
      KM=KK-1
      TIM=KK*DELT
C
C    TMAX IS THE NUMBER OF DAYS FOR THE IC'TH COLUMN
C
C    NON(IC)=ARRAY TO HOLD THE TOTAL NO. OF DAYS FOR EACH COLUMN
C
      DO 30 IC=1,NC
C
      TMAX=NON(IC)*DELT
      IF(TIM.GT.TMAX)GO TO 30
C
C
C    ITUM(J)=ARRAY TO HOLD ALL VALUES OF EPISODE TIME
C    IN DAYS.....FUNCTION GENERATOR.
C
C    DUM(K)=ARRAY(TEMPORARY)TO HOLD ALL VALUES OF CSS FOR A GIVEN
C    COLUMN AT A GIVEN DEPTH---FUNCTION GENERATOR
C
      DO 30 IZ=1,NZ,4
      NMAX=NN(IC)
      DO 31 J=1,NMAX
   31 ITUM(J)=IT(IC,J)
C
      DO 40 K=1,NMAX
   40 DUM(K)=CSS(IZ,IC,K)
C
C    CS(IZ,IC)=ARRAY(TEMPORARY)VSS GENERATED BY FUN1
C
      CS(IZ,IC)=FUN1(TIM,NMAX,ITUM,DUM)
C
C    CSSD(IZ,IC,KK)=ARRAY TO HOLD VSS VALUES(MG/L),DAILY.
C
      CSSD(IZ,IC,KK)=CS(IZ,IC)*DEN
   30 CONTINUE
C
C    DAILY VALUES OF CSSD DETERMINED,PROCEED WITH CALCULATIONS
C
      DO 50 IC=1,NC
C
      TMAX=NON(IC)*DELT
      IF(TIM.GT.TMAX)GO TO 50
C
      DO 50 IZ=1,NZM,3
C
      IF(IZ.EQ.1)GO TO 48
C
      GO TO 49
C
C    DLOAD(IC,KK)=ARRAY TO HOLD THE VOLUME OF SEWAGE LOADED(IN TERMS
C    OF THE LAB COLUMNS) IN L.
C
C    DHL(IC,KK)=ARRAY TO HOLD DAILY HYDRAULIC LOAD(IN TERMS
C    OF THE LAB COLUMNS) IN CM/DAY.
C
C    DML(IC,KK)=ARRAY TO HOLD DAILY MASS LOADED(IN TERMS
C    OF THE LAB COLUMNS) IN MG/DAY.
C
   48 IF(IC.GT.5)GO TO 21
      IF(KK.LT.IT(IC,2))DLOAD(IC,KK)=HL(IC,1)*14.368
```

```
      IF(KK.GE.IT(IC,2))DLOAD(IC,KK)=HL(IC,2)*14.388
      GO TO 22
   21 DLOAD(IC,KK)=HL(IC,2)*14.388
   22 CONTINUE
      DHL(IC,KK)=DLOAD(IC,KK)*1.0E03/AREA
      DML(IC,KK)=DLOAD(IC,KK)*CSSD(1,IC,KK)
C
C
      IF(DML(IC,KK).LE.165.)GO TO 334
C
      ACON=0.9985
      BCON=0.7478
C
C
      SK1=34.5
      SK2=9190.
C
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
C
      IF(TIM.EQ.TMAX)GO TO 336
      AML(IC,KP)=AML(IC,KK)
  336 XXX=AML(IC,KK)
C
      IF(KK.EQ.1)SALC(IC,KK)=(SK1*XXX)/(SK2+XXX)
C
      SLOPM(IC,KK)=(SK1*SK2)/(SK2+XXX)**2.
C
      IF(KK.EQ.1)GO TO 341
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
  341 CONTINUE
C
      GO TO 335
C
C
  333 IF(KK.EQ.1)SALC(IC,KK)=1.6032E-01
C
      SLOPM(IC,KK)=8.007E-04
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
      IF(TIM.EQ.TMAX)GO TO 337
      AML(IC,KP)=AML(IC,KK)
  337 CONTINUE
C
      IF(KK.EQ.1)GO TO 342
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
  342 CONTINUE
C
      ACON=1.5038E-05
      BCON=7.2566
C
      GO TO 335
C
  334 IF(KK.EQ.1)SALC(IC,KK)=4.871E-02
C
      SLOPM(IC,KK)=4.085E-04
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
      IF(TIM.EQ.TMAX)GO TO 338
      AML(IC,KP)=AML(IC,KK)
  338 CONTINUE
C
      IF(KK.EQ.1)GO TO 343
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
```

```
  343 CONTINUE
C
      ACON=2.737E-07
      BCON=0.8969
C
  335 CONTINUE
C
      IF(KK.EQ.1)GO TO 46
      SALMG(IC,KK)=(SALC(IC,KK)-SALC(IC,KM))*AREA
C
      GO TO 52
C
   46 SALMG(IC,KK)=SALC(IC,KK)*AREA
C
   52 CONTINUE
C
      SALM(IC,KK)=SALM(IC,KK)+SALMG(IC,KK)
C
      IF(TIM.EQ.TMAX)GO TO 53
      SALM(IC,KP)=SALM(IC,KK)
   49 CONTINUE
   53 CONTINUE
   50 CONTINUE
C
C
      IF(KK.GE.189)GO TO 55
      GO TO 1000
C
   55 CONTINUE
C
C
      KK=0
C
 2000 KK=KK+1
      TIM=KK*DELT
C
      DO 60 IC=1,NC
      TMAX=NON(IC)*DELT
      IF(TIM.GT.TMAX)GO TO 60
      NMAX=NN(IC)
C
      DO 61 J=1,NMAX
   61 ITUM(J)=IT(IC,J)
C
      DO 62 K=1,NMAX
   62 DUM(K)=TEMP(IC,K)
C
      TTEMP(IC,KK)=FUN1(TIM,NMAX,ITUM,DUM)
C
   60 CONTINUE
C
      IF(KK.GE.189)GO TO 63
      GO TO 2000
C
   63 CONTINUE
C
C
C   WRITE OUT VSS,MG/L    DAILY.
C
      WRITE(6,298)
  298 FORMAT('1',20X,'VSS,MG/L    DAILY')
C
      DO 54 IC=1,NC
      TMAX=NON(IC)
      WRITE(6,404)IC
C
      DO 56 K=1,TMAX
```

```
      IF(DML(IC,K).LE.165.)ID=5
      IF(DML(IC,K).LE.279.AND.DML(IC,K).GT.165.)ID=1
      IF(DML(IC,K).LE.408.AND.DML(IC,K).GT.279.)ID=2
      IF(DML(IC,K).LE.687.AND.DML(IC,K).GT.408.)ID=3
      IF(DML(IC,K).GT.687.)ID=6
C
   56 WRITE(6,503)K,CSSD(1,IC,K),CSSD(5,IC,K),DML(IC,K),DHL(IC,K),DLOAD(
     1IC,K),AML(IC,K),SALM(IC,K),ID
C
      J=TMAX
      ABC=AML(IC,J)/J
      WRITE(6,504)ABC
C
   54 CONTINUE
C
  404 FORMAT('0','COLUMN NO.'/3X,I4/1X,'DAY NO.',4X,'INFLUENT',5X,'EFFLU
     1ENT',8X,'DML',11X,'DHL',8X,'DLOAD',8X,'AML',10X,'SALM',10X,'DML'/1
     25X,'MG/L',9X,'MG/L',7X,'MG/DAY',8X,'CM/DAY',7X,'L/DAY',8X,'MG',12X
     3,'MG',10X,'RANGE')
  503 FORMAT(' ',3X,I3,2X,3E13.4,2F12.3,2E13.4,I10)
  504 FORMAT('0',5X,'AVERAGE DML FOR FILTER RUN=',F5.0)
C
C
C    DMLL REPRESENTED HERE ARE THE DAILY MASS LOADED LAMBDA VALUES
C    WHICH HAVE BEEN ADJUSTED IN THE PROCESS OF MODEL CALIBRATION.
C
C
      WRITE(6,792)
  792 FORMAT('1',24X,'ISF MODEL COEFFICIENTS'//3X,'DML',2X,'DECAY COEF.'
     1,1X,'LAYER(1)SLAM',1X,'LAYER(2)SLAM',1X,'LAYER(3)SLAM',1X,'LAYER(4
     2)SLAM'/2X,'RANGE',4X,'DAY-1',8X,'CM-1',9X,'CM-1',9X,'CM-1',9X,'CM-
     31')
C
      DO 790 ID=1,ND
      READ(5,791)CD(ID),(DMLL(ID,IZ),IZ=1,NZM)
      WRITE(6,793)ID,CD(ID),(DMLL(ID,IZ),IZ=1,NZM)
  790 CONTINUE
  791 FORMAT(5X,5E13.4)
  793 FORMAT('0',I5,5E13.4)
C
C
      DO 810 IC=1,NC
      TMAX=NON(IC)
C
      DO 814 K=1,TMAX
      IF(DML(IC,K).LE.165.)ID=5
      IF(DML(IC,K).LE.279.AND.DML(IC,K).GT.165.)ID=1
      IF(DML(IC,K).LE.408.AND.DML(IC,K).GT.279.)ID=2
      IF(DML(IC,K).LE.687.AND.DML(IC,K).GT.408.)ID=3
      IF(DML(IC,K).GT.687.)ID=6
      CD(6)=CD(3)
      KM=K-1
      CIN(IC,K)=CSSD(1,IC,K)
      DECAY(IC,K)=CD(ID)*(PSI**(TTEMP(IC,K)-20.))
C
      IF(K.EQ.1)GO TO 846
      COUTF(IC,K)=CIN(IC,K)*(1.-(SLOPM(IC,K)*AREA))-DECAY(IC,K)*SALC(IC,
     1KM)*1.0E03/DHL(IC,K)
C
      GO TO 847
C
  846 COUTF(IC,K)=CIN(IC,K)*(1.-(SLOPM(IC,K)*AREA))
C
  847 CONTINUE
C
  814 CONTINUE
C
```

```
  810 CONTINUE
C
C
C    WRITE OUT CIN,COUTF,SLOPM,SALC,DML RANGE,TEMPERATURE
C    AND DECAY COEFFICIENT DATA FOR EACH COLUMN.
C
      DO 816 IC=1,NC
      TMAX=NON(IC)
C
      WRITE(6,817)IC
C
      DO 816 K=1,TMAX
      IF(DML(IC,K).LE.165.)ID=5
      IF(DML(IC,K).LE.279.AND.DML(IC,K).GT.165.)ID=1
      IF(DML(IC,K).LE.408.AND.DML(IC,K).GT.279.)ID=2
      IF(DML(IC,K).LE.687.AND.DML(IC,K).GT.408.)ID=3
      IF(DML(IC,K).GT.687.)ID=6
C
  816 WRITE(6,818)K,CIN(IC,K),COUTF(IC,K),SLOPM(IC,K),SALC(IC,K),ID,TTEM
     1P(IC,K),DECAY(IC,K)
  817 FORMAT('1',5X,'COLUMN NO.',I2//2X,'DAY',7X,'CIN',9X,'COUTF',8X,'SL
     1OPM',9X,'SALC',5X,'DML',3X,'TEMPERATURE',3X,'DECAY'/11X,'MG/L',10X
     2,'MG/L',5X,'MG/CM**2/MG',4X,'MG/CM**2',2X,'RANGE',3X,'DEGREES,C',4
     3X,'DAY-1')
  818 FORMAT(' ',I5,4E13.4,I5,F11.1,E13.4)
C
C
C    THE CORRECT COUTF CONCENTRATIONS HAVE NOW BEEN DETERMINED.
C
C    BASIC MODEL FOR THE SAND PHASE....
C    DSP/DT = DHL*(-DCSS/DZ) + BETA*SP.
C    SP REPRESENTS SPECIFIC DEPOSIT.
C    DMLL*CIN = (-DCSS/DZ)..WHERE DMLL IS THE SAND FILTER COEF.,CM-1.
C
C    ANALYSIS OF THE IMPACT OF BETA(IC,KK), MEAN BETA(BMB(IC)),
C    MEAN BETA FROM SELECTED BETA VALUES...
C    RESULTED IN DELETION OF THE SAND BIOLOGICAL ACTIVITY TERM FROM
C    THE SAND PHASE MODEL....
C
C    THEREFORE...THE BASIC MODEL FOR THE SAND PHASE BECOMES....
C
C    DSP/DT = DHL*(-DCSS/DZ)
C
C    DMLL*CSSIN = (-DCSS/DZ)
C
C    IN TERMS OF AML....
C
C    DSP/DAML = (DHL/DML)*(-DCSS/DZ)
C
C    DMLL*CSSIN = (-DCSS/DZ)
C
C    MAKE COMPARISON OF VSS PREDICTED AND ACTUAL USING
C    THE 20 EMPIRICAL SAND FILTER TERM ISF MODEL.
C
      KK=0
 5000 KK=KK+1
      TIM=KK*DELT
C
      DO 870 IC=1,NC
C
      THAX=NON(IC)
      IF(TIM.GT.THAX)GO TO 870
C
      IF(DML(IC,KK).LE.165.)ID=5
      IF(DML(IC,KK).LE.279.AND.DML(IC,KK).GT.165.)ID=1
      IF(DML(IC,KK).LE.408.AND.DML(IC,KK).GT.279.)ID=2
      IF(DML(IC,KK).LE.687.AND.DML(IC,KK).GT.408.)ID=3
```

```
      IF(DML(IC,KK).GT.687.)ID=6
C
      DO 870 IZ=1,NZM
      IZP=IZ+1
C
      DMLL(6,IZ)=DMLL(3,IZ)
C
      IF(IZ.EQ.1)CSSD(1,IC,KK)=COUTF(IC,KK)
      IF(IZ.EQ.1)PCSD(1,IC,KK)=COUTF(IC,KK)
C
C   WHICH IS PREDICTED BY THE ISF MODEL.
C
C   PCSD REPRESENTS THE VSS EFFLUENT CONCENTRATION FROM THE SAND FILTER
      PCSD(IZP,IC,KK)=(PCSD(IZ,IC,KK))*(EE**(-(DMLL(ID,IZ))*(DZ(IZ))))
C
  870 CONTINUE
C
      IF(KK.GE.189)GO TO 874
C
      GO TO 5000
C
  874 CONTINUE
C
C
      DO 880 IC=1,NC
      TMAX=NON(IC)
      WRITE(6,871)IC
C
      IZ=4
      IZP=IZ+1
      IE=1
      WRITE(6,772)IZ
C
      DO 880 KK=1,TMAX
C
      IF(DML(IC,KK).LE.165.)ID=5
      IF(DML(IC,KK).LE.279.AND.DML(IC,KK).GT.165.)ID=1
      IF(DML(IC,KK).LE.408.AND.DML(IC,KK).GT.279.)ID=2
      IF(DML(IC,KK).LE.687.AND.DML(IC,KK).GT.408.)ID=3
      IF(DML(IC,KK).GT.687.)ID=6
C
      DMLL(6,IZ)=DMLL(3,IZ)
C
      WRITE(6,783)KK,PCSD(IZP,IC,KK),DMLL(ID,IZ),AML(IC,KK),ID
      WRITE(7,783)KK,PCSD(IZP,IC,KK),DMLL(ID,IZ),AML(IC,KK),ID
C
      GO TO 882
  881 WRITE(6,773)KK,CSSD(IZP,IC,KK),PCSD(IZP,IC,KK),DMLL(ID,IZ),AML(IC,
     1KK),ID
      WRITE(7,773)KK,CSSD(IZP,IC,KK),PCSD(IZP,IC,KK),DMLL(ID,IZ),AML(IC,
     1KK),ID
      IE=IE+1
  882 CONTINUE
C
  880 CONTINUE
C
  871 FORMAT('1',13X,'MODEL VALIDATION OF FIELD DATA FROM HARRIS,1977'/1
     1X,'COMPARISON OF PREDICTED AND ACTUAL EFF VSS CONCENTRATIONS FOR 2
     20 EMPIRICAL COEF. ISF MODEL'//27X,'COLUMN NO.',I3)
  772 FORMAT('0','LAYER NO.',I2/28X,'VSS',10X,'VSS'/25X,'ACTUAL EFF',1X,
     1'PREDICTED EFF',5X,'DMLL',10X,'AML',10X,'ID'/5X,'DAY',17X,'FROM LA
     2YER',2X,'FROM LAYER'/28X,'MG/L',9X,'MG/L',9X,'CM-1',10X,'MG')
  783 FORMAT(' ',5X,I3,26X,F13.1,F13.5,F13.0,I10)
  773 FORMAT(' ',5X,I3,13X,2F13.1,F13.5,F13.0,I10)
C
C
C   PLOT OUT PREDICTED AND ACTUAL VSS CONCENTRATIONS...
```

```
C    20 EMPIRICAL COEFFICIENT ISF MODEL.
C
       DO 920 IC=1,NC
       MAX=NN(IC)
       TMAX=NON(IC)
C
       IZ=4
       IZP=IZ+1
       IE=1
       WRITE(6,921)IC,IZ
C
C
       DO 922 KK=1,TMAX
       II=MAX+KK
C
       IF(KK.EQ.IT(IC,IE))A(IE)=AML(IC,KK)
       IF(KK.EQ.IT(IC,IE))B(IE)=CSSD(IZP,IC,KK)
       IF(KK.EQ.IT(IC,IE))C(IE)=0.
       IF(KK.EQ.IT(IC,IE))IE=IE+1
       A(II)=AML(IC,KK)
       B(II)=PCSD(IZP,IC,KK)
       C(II)=1.
  922 CONTINUE
C
       N=MAX+TMAX
C
       CALL PLOTER(N,A,B,DZ,C)
C
  920 CONTINUE
C
C
  921 FORMAT('1',35X,'MODEL VALIDATION OF FIELD DATA FROM HARRIS,1977'//
     1/27X,'COMPARISON OF PREDICTED(III) AND ACTUAL(STAR) FILTER EFF VSS
     2 CONCENTRATIONS'//28X,'FILTER NO.',I2,5X,'LAYER NO.',I2)
C
C
       STOP
       END
```

20 EMPIRICAL SAND FILTER COEFFICIENTS (ISF MODEL).

| ID | LAYER(1) | LAYER(2) | LAYER(3) | LAYER(4) |
|---|---|---|---|---|
| 3 | .5119E-01 | .5086E-01 | .1263E-01 | .2610E-01 |
| 2 | .4521E-01 | .1259E-01 | .5330E-01 | .1816E-01 |
| 1 | .3578E-01 | .3112E-01 | .1998E-01 | .2328E-01 |
| 4 | .4472E-01 | .3112E-01 | .1998E-01 | .1073E-01 |
| 5 | .7727E-01 | .4107E-01 | .2398E-01 | .1311E-01 |

ARBITRARY FUNCTION GENERATOR SUBROUTINE   VSS VS TIME

```
    ------------------------------------------------------------
    ------------------------------------------------------------

C      TIM=TIME,THE INPUT INDEPENDENT VARIABLE
C      NMAX=TOTAL NUMBER OF COORDINATE POINTS
C      ITUM=ARRAY OF THE INDEPENDENT VARIABLE,TIME
C      DUM=ARRAY OF THE DEPENDENT VARIABLE,VSS
C
       FUNCTION FUN1(TIM,NMAX,ITUM,DUM)
       REAL DUM(2)
       INTEGER ITUM(2)
       IF(TIM-ITUM(1))5,5,6
    6  IF(TIM-ITUM(NMAX))1,2,2
```

```
    2 FUN1=DUM(NMAX)
      RETURN
    5 FUN1=DUM(1)
      RETURN
    1 DO 3 I=2,NMAX
      IF(TIM.LT.ITUM(I))GO TO 4
    3 CONTINUE
    4 FUN1=DUM(I-1)+(TIM-ITUM(I-1))*(DUM(I)-DUM(I-1))/(ITUM(I)-ITUM(I-1
     1)
      RETURN
      END
C
    ---------------------------------------------------------------
    ---------------------------------------------------------------
    PLOTER SUBROUTINE.
    ---------------------------------------------------------------
    ---------------------------------------------------------------

C-----SUBROUTINE TO PLOT N POINTS  SPECIFIED BY ARRAYS A AND B .  T=TITLE
C-----INITIALIZE PLOT PAGE
C----------------------------------------------------------------------
      INTEGER STAR,TICK,DASH
      REAL IPAGE
      DIMENSION IM(10),C(1)
      DIMENSION IPAGE(50,120),R(10),D(10),A(1),B(1),T(10)
      DATA IM/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,1H0/
      DATA STAR,TICK,DASH/1H*,1HI,1H-/
      DATA IBLNK/1H /
      IPG=120
      DO 20 I=1,IPG
      DO 20 II=1,50
20    IPAGE(II,I)=IBLNK
      DO 1 I=1,IPG
      IPAGE(50,I)=DASH
      IF(MOD(I-1,IPG/10).EQ.0) IPAGE(50,I)=TICK
1     CONTINUE
      DO 2 I=1,50
      IPAGE(I,1)=TICK
      IF(MOD(I-1,5).EQ.0) IPAGE(I,1)=DASH
2     CONTINUE
C----------------------------------------------------------------------
C-----FIND MAX AND MIN OF X AND Y ARRAYS
C----------------------------------------------------------------------
      AMAX=A(1)
      AMIN=A(1)
      BMAX=B(1)
      BMIN=B(1)
      DO 3 I=2,N
      IF(AMAX.LT.A(I)) AMAX=A(I)
      IF(AMIN.GT.A(I)) AMIN=A(I)
      IF(BMAX.LT.B(I)) BMAX=B(I)
      IF(BMIN.GT.B(I)) BMIN=B(I)
3     CONTINUE
      AEXT=.1*(AMAX-AMIN)
        BEXT=.1*(BMAX-BMIN)
C----------------------------------------------------------------------
C-----EXTEND GRAPH TO FRAME DATA
C----------------------------------------------------------------------
      RANGE=AMAX-AMIN+2.*AEXT
      DOMAIN=BMAX-BMIN+2.*BEXT
      DO 4 I=1,10
      FLI=I
      II=11-I
      R(I )=AMIN-AEXT+FLI*RANGE/10.
    4 D(II)=BMIN-BEXT+FLI*DOMAIN/10.
C----------------------------------------------------------------------
C----- PLACE DATA POINTS INTO PLOT
C----------------------------------------------------------------------
```

```
      DO 5 I=1,N
      K=(AEXT+A(I)-AMIN)/RANGE*FLOAT(IPG)
      IF(K.LT.1) K=1
      L=(BEXT+B(I)-BMIN)/DOMAIN*50.
      IF(L.LT.1) L=1
      L=51-L
 5    IPAGE(L,K)=STAR
      K=1
      DO 6 I=1,50
      IF(MOD(I-1,5)) 7,8,7
    8 WRITE(6,101) D(K),(IPAGE(I,J),J=1,IPG)
      K=K+1
      GO TO 6
    7 WRITE(6,102)(IPAGE(I,J),J=1,IPG)
    6 CONTINUE
  101 FORMAT(1H ,F10.4,1X,120A1)
  102 FORMAT(12X,120A1)
      WRITE(6,103)(R(I),I=1,10)
  103 FORMAT(1H0,10X,10(F10.4,2X))
      RETURN
      END
C
    -------------------------------------------------------------------------
    -------------------------------------------------------------------------
```

## APPENDIX F

## THE COMPUTER PROGRAM CONTAINING THE SIMPLIFIED ISF MODEL UTILIZED TO VALIDATE FIELD DATA FROM TUPYI (1977)

```
IF PROGRAM IMPLIMENTED TO PREDICT EFFLUENT VSS VALUES AND EFS IS
0.40 OR 0.68 MM, UTILIZE THE GAMMA CORRECTION STEP.



      DIMENSION DHL(17,260),DLOAD(17,260),TEMP(17,260)
      DIMENSION DLAYER(4)
      DIMENSION HL(17,50)
      DIMENSION DML(17,260)
      DIMENSION DMLL(50),A(260),B(260),C(260)
      DIMENSION PCSDA(35,6,260),PCSDB(35,5,260)
      INTEGER IT(17,50),NN(11),NON(11),ITUM(50)
      DIMENSION AML(17,260),SLOPM(17,260)
      DIMENSION SALC(17,260)
      DIMENSION SALM(17,260),SALMG(17,260)
      REAL CLVL(5),CSS(5,17,50),CS(5,17),DUM(50),DZ(4),CSSD(5,17,260)
      INTEGER TMAX,TIM,DELT
      DATA DZ/5.08,2.54,7.62,60.96/
      DATA NON/36,166,103,40,177,148,43,23,37,46,219/
      DATA NN/7,24,15,9,26,21,7,4,6,10,30/
      DATA DLAYER/0.778,0.389,1.168,9.344/
C
C     DEN=DENSITY OF ALGAE,MG DRY WT/L WET VOLUME
C     RHO=DENSITY OF ALGAE,MG DRY WT/CM*03. WET VOLUME
C     AREA=AREA OF FILTER,CM**2.
C     DEP=DEPTH OF THE FILTER,CM
C     EE=BASE OF THE NATURAL LOGARITHM SYSTEM
C
      DEN=7.137E05
      RHO=7.137E02
      AREA=153.2790
      DEP=30.*2.54
      EE=2.718281828
C
C     TIM=INPUT VARIABLE TO FUN1 FOR DAILY VALUES
C     IDY=DAY NUMBER
C     IE=EPISODE NUMBER WHERE AN EPISODE IS A SAMPLING
C
C     IC=COLUMN NUMBER               NC=NUMBER OF COLUMNS
C
C     ID=DAILY MASS LOADING RANGE NUMBER     ND=NUMBER OF DML RANGES
C
C     DELT=DELTA TIME,DAYS           NZM=NUMBER OF LAYERS
C
C     IZ=PORT DEPTH NUMBER           NZ=NUMBER OF PORTS
      NC=11
      ND=5
      NZ=5
      NZM=NZ-1
      NZI=31
      NZIM=NZI-1
      DELT=1
C
C
C     IZ DEPTH
```

```
C       1  INFLUENT
C       2  2 IN
C       3  3 IN
C       4  6 IN
C       5  EFFLUENT
C
C
C    CLVL(IZ)=ARRAY(TEMPORARY)TO HOLD VSS VALUES IN MG/L
C
C    HL(IC,IE)=ARRAY TO HOLD THE HYDRAULIC LOADING,MGAD.
C    ON THE DAY OF SAMPLING.
C
C    TEMP(IC,IE)=ARRAY TO HOLD INFLUENT TEMPERATURE,DEG.C.,
C    ON THE DAY OF SAMPLING.
C
C    IT(IC,IE)=ARRAY(TEMPORARY)TO HOLD DAY NO. FOR A PARTICULAR EPISODE
C
C    CSS(IZ,IC,IE)=ARRAY TO HOLD VSS VALUES...
C    L WET VOL/L FILTRATE FOR EPISODES
C
C    READ IN AND WRITE OUT RAW VSS DATA FOR INF AND EFF.
C
C    WRITE TABLE HEADING FOR RAW DATA
C
      WRITE(6,98)
   98 FORMAT('1',33X,'VSS,MG/L')
C
      WRITE(6,97)
   97 FORMAT('0',1X,'DAY',1X,'EPISODE',1X,'COLUMN',3X,'INF',6X,'EFF',4X,
     1'LOADING',3X,'TEMP'/1X,'NO.',3X,'NO.',4X,'NO.',4X,'MG/L',5X,'MG/L'
     2,5X,'MGAD',4X,'DEG.C')
C
   91 READ(5,103)IDY,IE,IC,CLVL(1),CLVL(5),HL(IC,IE),TEMP(IC,IE)
C
      IF(IDY.EQ.222)GO TO 12
C
      WRITE(6,104)IDY,IE,IC,CLVL(1),CLVL(5),HL(IC,IE),TEMP(IC,IE)
C
      IT(IC,IE)=IDY
      CSS(1,IC,IE)=CLVL(1)/DEN
      IF(CLVL(5).LE.0.0)GO TO 13
      CSS(5,IC,IE)=CLVL(5)/DEN
      GO TO 15
   13 CSS(5,IC,IE)=0.1/DEN
   15 CONTINUE
      GO TO 91
  103 FORMAT(1X,I4,2I5,4F5.1)
  104 FORMAT(' ',1X,I3,3X,I3,4X,I2,4F9.1)
C
   12 CONTINUE
C
C
C    WRITE OUT V/V DATA FOR INF AND EFF    EPISODE.
C
      WRITE(6,102)
  102 FORMAT('1',18X,'VSS,VOLUME OF ALGAE/VOLUME OF FILTRATE   EPISODE')
C
      DO 16 IC=1,NC
      NMAX=NN(IC)
      WRITE(6,403)IC
   16 WRITE(6,502)(IT(IC,IE),CSS(1,IC,IE),CSS(5,IC,IE),IE=1,NMAX)
  403 FORMAT('0','COLUMN NO.'/3X,I4/1X,'DAY NO.',4X,'INFLUENT',5X,'EFFLU
     1ENT')
  502 FORMAT(' ',3X,I3,2X,2E13.4)
C
C
C    INITIALIZE COUNTER AND ARRAYS
C
```

```
      KK=0
      DO 20 IC=1,NC
      AML(IC,1)=0.
   20 SALM(IC,1)=0.
C
 1000 KK=KK+1
      KP=KK+1
      KM=KK-1
      TIM=KK*DELT
C
C
C   NON(IC)=ARRAY TO HOLD THE TOTAL NO. OF DAYS FOR EACH COLUMN
C
      DO 30 IC=1,NC
C
      TMAX=NON(IC)*DELT
      IF(TIM.GT.TMAX)GO TO 30
C
C
C   ITUM(J)=ARRAY TO HOLD ALL VALUES OF EPISODE TIME
C   IN DAYS.....FUNCTION GENERATOR.
C
C   DUM(K)=ARRAY(TEMPORARY)TO HOLD ALL VALUES OF CSS FOR A GIVEN
C   COLUMN AT A GIVEN DEPTH---FUNCTION GENERATOR
C
      DO 30 IZ=1,NZ,4
      NMAX=NN(IC)
      DO 31 J=1,NMAX
   31 ITUM(J)=IT(IC,J)
C
      DO 40 K=1,NMAX
   40 DUM(K)=CSS(IZ,IC,K)
C
C   CS(IZ,IC)=ARRAY(TEMPORARY)VSS GENERATED BY FUN1
C
      CS(IZ,IC)=FUN1(TIM,NMAX,ITUM,DUM)
C
C   CSSD(IZ,IC,KK)=ARRAY TO HOLD VSS VALUES(MG/L),DAILY.
C
      CSSD(IZ,IC,KK)=CS(IZ,IC)*DEN
   30 CONTINUE
C
C   DAILY VALUES OF CSSD DETERMINED,PROCEED WITH CALCULATIONS
C
      DO 50 IC=1,NC
C
C   TMAX IS THE NUMBER OF DAYS FOR THE IC'TH COLUMN
      TMAX=NON(IC)*DELT
      IF(TIM.GT.TMAX)GO TO 50
C
      DO 50 IZ=1,NZM,3
C
      IF(IZ.EQ.1)GO TO 48
C
      GO TO 49
C
C   DLOAD(IC,KK)=ARRAY TO HOLD THE VOLUME OF SEWAGE LOADED(IN TERMS
C   OF THE LAB COLUMNS) IN L.
C
C   DHL(IC,KK)=ARRAY TO HOLD DAILY HYDRAULIC LOAD(IN TERMS
C   OF THE LAB COLUMNS) IN CM/DAY.
C
C   DML(IC,KK)=ARRAY TO HOLD DAILY MASS LOADED(IN TERMS
C   OF THE LAB COLUMNS) IN MG/DAY.
C
   48 IF(IC.GT.5)GO TO 21
      IF(KK.LT.IT(IC,2))DLOAD(IC,KK)=HL(IC,1)*14.388
      IF(KK.GE.IT(IC,2))DLOAD(IC,KK)=HL(IC,2)*14.388
```

```
      GO TO 22
   21 DLOAD(IC,KK)=HL(IC,2)*14.388
   22 CONTINUE
      DHL(IC,KK)=DLOAD(IC,KK)*1.0E03/AREA
      DML(IC,KK)=DLOAD(IC,KK)*CSSD(1,IC,KK)
C
C
      IF(DML(IC,KK).LE.165.)GO TO 334
C
      ACON=0.9985
      BCON=0.7478
C
C
      SK1=34.5
      SK2=9190.
C
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
C
      IF(TIM.EQ.TMAX)GO TO 336
      AML(IC,KP)=AML(IC,KK)
  336 XXX=AML(IC,KK)
C
      IF(KK.EQ.1)SALC(IC,KK)=(SK1*XXX)/(SK2+XXX)
C
      SLOPM(IC,KK)=(SK1*SK2)/(SK2+XXX)**2.
C
      IF(KK.EQ.1)GO TO 341
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
  341 CONTINUE
C
      GO TO 335
C
C
  333 IF(KK.EQ.1)SALC(IC,KK)=1.6032E-01
C
      SLOPM(IC,KK)=8.007E-04
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
      IF(TIM.EQ.TMAX)GO TO 337
      AML(IC,KP)=AML(IC,KK)
  337 CONTINUE
C
      IF(KK.EQ.1)GO TO 342
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
  342 CONTINUE
C
      ACON=1.5038E-05
      BCON=7.2566
C
      GO TO 335
C
  334 IF(KK.EQ.1)SALC(IC,KK)=4.871E-02
C
      SLOPM(IC,KK)=4.085E-04
      AML(IC,KK)=AML(IC,KK)+DML(IC,KK)
      IF(TIM.EQ.TMAX)GO TO 338
      AML(IC,KP)=AML(IC,KK)
  338 CONTINUE
C
      IF(KK.EQ.1)GO TO 343
C
      SALC(IC,KK)=SLOPM(IC,KK)*DML(IC,KK)+SALC(IC,KM)
C
  343 CONTINUE
C
```

```
      ACON=2.737E-07
      BCON=8.8969
C
  335 CONTINUE
C
      IF(KK.EQ.1)GO TO 46
      SALMG(IC,KK)=(SALC(IC,KK)-SALC(IC,KM))*AREA
C
      GO TO 52
C
   46 SALMG(IC,KK)=SALC(IC,KK)*AREA
C
   52 CONTINUE
C
      SALM(IC,KK)=SALM(IC,KK)+SALMG(IC,KK)
C
      IF(TIM.EQ.TMAX)GO TO 53
      SALM(IC,KP)=SALM(IC,KK)
   49 CONTINUE
   53 CONTINUE
   50 CONTINUE
C
C
      IF(KK.GE.219)GO TO 55
      GO TO 1000
C
   55 CONTINUE
C
C
C    WRITE OUT VSS,MG/L    DAILY.
C
      WRITE(6,298)
  298 FORMAT('1',28X,'VSS,MG/L    DAILY')
C
      DO 54 IC=1,NC
      TMAX=NON(IC)
      WRITE(6,404)IC
C
      DO 56 K=1,TMAX
      IF(DML(IC,K).LE.165.)ID=5
      IF(DML(IC,K).LE.279.AND.DML(IC,K).GT.165.)ID=1
      IF(DML(IC,K).LE.408.AND.DML(IC,K).GT.279.)ID=2
      IF(DML(IC,K).LE.687.AND.DML(IC,K).GT.408.)ID=3
      IF(DML(IC,K).GT.687.)ID=6
C
   56 WRITE(6,503)K,CSSD(1,IC,K),CSSD(5,IC,K),DML(IC,K),DHL(IC,K),DLOAD(
     1IC,K),AML(IC,K),SALM(IC,K),ID
C
      J=TMAX
      ABC=AML(IC,J)/J
      WRITE(6,504)ABC
C
   54 CONTINUE
C
  404 FORMAT('0','COLUMN NO.'/3X,I4/1X,'DAY NO.',4X,'INFLUENT',5X,'EFFLU
     1ENT',8X,'DML',11X,'DHL',8X,'DLOAD',8X,'AML',10X,'SALM',10X,'DML'/1
     25X,'MG/L',9X,'MG/L',7X,'MG/DAY',8X,'CM/DAY',7X,'L/DAY',8X,'MG',12X
     3,'MG',10X,'RANGE')
  503 FORMAT(' ',3X,I3,2X,3E13.4,2F12.3,2E13.4,I10)
  504 FORMAT('0',5X,'AVERAGE DML FOR FILTER RUN=',F5.0)
C
C
C     THE SAND PORTION OF THE MODEL WILL BE RUN
C     IN ORDER TO OBSERVE EFFECTS OF SAL ON ISF MODEL.
C
C   THE DMLL UTILIZED HERE WAS DEVELOPED W/O SAL PORTION OF MODEL.
C
```

```
C
C   BASIC MODEL FOR THE SAND PHASE....
C   DSP/DT = DHL*(-DCSS/DZ) + BETA*SP.
C   SP REPRESENTS SPECIFIC DEPOSIT.
C   DMLL*CIN = (-DCSS/DZ)..WHERE DMLL IS THE SAND FILTER COEFF.,CM-1.
C
C
C   ANALYSIS OF THE IMPACT OF BETA(IC,KK), MEAN BETA(BMB(IC)),
C   MEAN BETA FROM SELECTED BETA VALUES...
C   RESULTED IN DELETION OF THE SAND BIOLOGICAL ACTIVITY TERM FROM
C   THE SAND PHASE MODEL....
C
C   THEREFORE...THE BASIC MODEL FOR THE SAND PHASE BECOMES....
C
C   DSP/DT = DHL*(-DCSS/DZ)
C
C   DMLL*CSSIN = (-DCSS/DZ)
C
C   IN TERMS OF AML....
C
C   DSP/DAML = (DHL/DML)*(-DCSS/DZ)
C
C   DMLL*CSSIN = (-DCSS/DZ)
C
C
C   DMLL IS CALCULATED FROM THE FUNCTIONAL RELATIONSHIP
C   BETWEEN GAMMA AND DEPTH,WHERE DEPTH IS IN CM.
C
C
C ****************************************
C *                                      *
C * DMLL = 0.1828*(DEPTH)**(-0.9934)     *
C *                                      *
C ****************************************
C
C
C   SINCE THE SAL MODEL IS NOT INCLUDED IN THE SIMPLIFIED ISF MODEL,
C   THERE IS NO TEMPERATURE DEPENDENCE.
C
C
C   LOAD THE DMLL ARRAY
C
      DO 5001 IZI=1,NZIM
 5001 DMLL(IZI)=0.1828*((IZI)**(-0.9934))
C
C
C   MAKE COMPARISON OF VSS PREDICTED AND ACTUAL USING
C   DMLL VALUES CALCULATED FROM THE FUNCTIONAL RELATIONSHIP
C   BETWEEN DMLL AND DEPTH.....WITHOUT SAL.
C
C
C
C
C   ***********************************************
C   CORRECTION OF GAMMA(DMLL)TERM IF EFS.NE.0.17.
C     IF(EFS.EQ.0.17)GO TO 7002
C
C     DO 7004 IZI=1,NZIM
C7004 DMLL(IZI)=0.3138*DMLL(IZI)
C
C7002 CONTINUE
C   ***********************************************
C
C
C
C
      KK=0
 5000 KK=KK+1
      TIM=KK*DELT
```

```
C
      DO 870 IC=1,NC
C
      TMAX=NON(IC)
      IF(TIM.GT.TMAX)GO TO 870
C
      IF(IC.LE.6)GO TO 901
      JK=IC-6
C
      DO 902 IZI=1,NZIM
      IZIP=IZI+1
C
      IF(IZI.EQ.1)PCSDB(1,JK,KK)=CSSD(1,IC,KK)
C
      PCSDB(IZIP,JK,KK)=(PCSDB(IZI,JK,KK))*(EE**(-(DMLL(IZI))*2.54))
C
  902 CONTINUE
C
      GO TO 870
C
  901 DO 911 IZI=1,NZIM
      IZIP=IZI+1
C
      IF(IZI.EQ.1)PCSDA(1,IC,KK)=CSSD(1,IC,KK)
C
      PCSDA(IZIP,IC,KK)=(PCSDA(IZI,IC,KK))*(EE**(-(DMLL(IZI))*2.54))
C
  911 CONTINUE
C
  870 CONTINUE
C
C
      IF(KK.GE.219)GO TO 874
C
      GO TO 5000
C
  874 CONTINUE
C
C
      DO 880 IC=1,NC
C
      TMAX=NON(IC)
      WRITE(6,871)IC
C
      IZ=4
      IE=1
      IZP=IZ+1
      IZI=30
      IZIP=IZI+1
      WRITE(6,772)IZ
C
C
      IF(IC.LE.6)GO TO 903
      JK=IC-6
C
      DO 904 KK=1,TMAX
      IF(KK.EQ.IT(IC,IE))GO TO 905
C
      WRITE(6,783)KK,PCSDB(IZIP,JK,KK),DMLL(IZI),AML(IC,KK)
      WRITE(7,783)KK,PCSDB(IZIP,JK,KK),DMLL(IZI),AML(IC,KK)
C
      GO TO 906
C
  905 WRITE(6,773)KK,CSSD(IZP,IC,KK),PCSDB(IZIP,JK,KK),DMLL(IZI),AML(IC,
     1KK)
      WRITE(7,773)KK,CSSD(IZP,IC,KK),PCSDB(IZIP,JK,KK),DMLL(IZI),AML(IC,
     1KK)
      IE=IE+1
```

```
C
  906 CONTINUE
C
  904 CONTINUE
C
      GO TO 880
C
  903 DO 912 KK=1,TMAX
C
      IF(KK.EQ.IT(IC,IE))GO TO 913
C
      WRITE(6,783)KK,PCSDA(IZIP,IC,KK),DMLL(IZI),AML(IC,KK)
      WRITE(7,783)KK,PCSDA(IZIP,IC,KK),DMLL(IZI),AML(IC,KK)
C
      GO TO 914
C
  913 WRITE(6,773)KK,CSSD(IZP,IC,KK),PCSDA(IZIP,IC,KK),DMLL(IZI),AML(IC,
     1KK)
      WRITE(7,773)KK,CSSD(IZP,IC,KK),PCSDA(IZIP,IC,KK),DMLL(IZI),AML(IC,
     1KK)
      IE=IE+1
C
  914 CONTINUE
C
  912 CONTINUE
C
  880 CONTINUE
C
C
C
  871 FORMAT('1',13X,'MODEL VALIDATION OF FIELD DATA (TUPYI,1977)'/1X,'C
     1OMPARISON OF PREDICTED VS ACTUAL EFF VSS CONCENTRATIONS FOR DMLL C
     2ALCULATED FROM DEPTH'//27X,'COLUMN NO.',I3)
  772 FORMAT('0','LAYER NO.',I2/28X,'VSS',10X,'VSS'/25X,'ACTUAL EFF',1X,
     1'PREDICTED EFF',5X,'DMLL',10X,'AML',10X,'ID'/5X,'DAY',17X,'FROM LA
     2YER',2X,'FROM LAYER'/28X,'MG/L',9X,'MG/L',9X,'CM-1',10X,'MG')
  783 FORMAT(' ',5X,I3,26X,F13.1,F13.5,F13.0)
  773 FORMAT(' ',5X,I3,13X,2F13.1,F13.5,F13.0)
C
C
      STOP
      END


C     TIM=TIME,THE INPUT INDEPENDENT VARIABLE
C     NMAX=TOTAL NUMBER OF COORDINATE POINTS
C     ITUM=ARRAY OF THE INDEPENDENT VARIABLE,TIME
C     DUM=ARRAY OF THE DEPENDENT VARIABLE,VSS
C
      FUNCTION FUN1(TIM,NMAX,ITUM,DUM)
      REAL DUM(2)
      INTEGER ITUM(2)
      IF(TIM-ITUM(1))5,5,6
    6 IF(TIM-ITUM(NMAX))1,2,2
    2 FUN1=DUM(NMAX)
      RETURN
    5 FUN1=DUM(1)
      RETURN
    1 DO 3 I=2,NMAX
      IF(TIM.LT.ITUM(I))GO TO 4
    3 CONTINUE
    4 FUN1=DUM(I-1)+(TIM-ITUM(I-1))*(DUM(I)-DUM(I-1))/(ITUM(I)-ITUM(I-1)
     1)
      RETURN
      END
```

## APPENDIX G

## ANALYTICAL METHODS

| Parameter | Method | Reference |
|---|---|---|
| Chlorophyll | Relative Fluorescence | Turner Fluorometer Manual, Model 110 |
| Phytoplankton | Sedgwick-Rafter Counting Cell | APHA, 1971, Standard Methods for the Examination of Water and Wastewater |
| Specific Conductance | Electrometric | |
| Suspended Solids | Glass Fiber Filter (103°C) | |
| Volatile Suspended Solids | Glass Fiber Filter (550°C) | |
| pH | Electrometric | Beckman Manual, Zeromatic II |
| Total Organic Carbon | Digestion, Ampule | Oceanographic International, Operating Procedures Manual, 0524 B Total Carbon System |
| Soluble Organic Carbon | Filtration, Digestion, Ampule | |

Computer programs were run on the Burroughs 6700 at the Computer Center, Utah State University, Logan, Utah.