January 1973

Effects of Baffles on the Performance of Anerobic Waste Stabilization Ponds

Stephen B. Nielson

E. Joe Middlebrooks

Donald B. Porcella

Recommended Citation

Nielson, Stephen B.; Middlebrooks, E. Joe; and Porcella, Donald B., "Effects of Baffles on the Performance of Anerobic Waste Stabilization Ponds" (1973). *Reports.* Paper 172.
https://digitalcommons.usu.edu/water_rep/172

EFFECTS OF BAFFLES ON THE PERFORMANCE OF ANAEROBIC WASTE STABILIZATION PONDS

by

Stephen B. Nielson
E. Joe Middlebrooks
Donald B. Porcella

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

April 1973

PRWR17-2

ABSTRACT

The performance of three baffled model ponds was monitored and compared to the performance of an unbaffled model pond utilizing four hydraulic and organic loading rates. All four ponds were operated simultaneously under the same environmental conditions using a synthetic wastewater.

Removal of organic carbon by the biological systems in the different pond configurations only varied from 94-98 percent at the longest detention time (15 days); however, a considerable effect of the baffling was observed at the lower detention times. At a hydraulic detention time of 1.5 days the percent carbon removal was 53, 60, 62, and 70 percent for the control, end-around, over-and-under, and longitudinal baffling systems, respectively.

The biological kinetics of the model ponds were determined using three mathematical models. Performance was evaluated by using the kinetic parameters and conventional stabilization pond operating parameters. Direct comparisons with the performance parameters of the model ponds appear valid for analysis of the three models studied. The performance of the baffled ponds was described by a completely mixed model incorporating attached biomass; however, the performance of the unbaffled control pond was not described by the completely mixed model.

Performance parameters of the baffled, model ponds were significantly better than the control pond.

ACKNOWLEDGMENTS

The work described herein was supported in part by the State of Utah through the Utah Water Research Laboratory, and by a traineeship granted by the Academic Training Branch, Manpower Development Staff, Office of Water Programs, Environmental Protection Agency. The authors express their appreciation for the assistance in financing this project.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

INTRODUCTION

Waste stabilization ponds are the most common method of wastewater treatment in areas where large parcels of inexpensive land are available and a high quality effluent is not required at all times (1). The major advantage of a stabilization pond is the relatively low cost associated with operation and maintenance of the system (17). However, there are several disadvantages associated with the performance characteristics of stabilization ponds; these include hydraulic short-circuiting, long hydraulic detention times, and high concentrations of effluent suspended solids (24).

Nature of the problem

Hydraulic short-circuiting occurs in a stabilization pond when the flow of influent raw sewage does not readily mix with the pond liquid. Mixing of the raw sewage and the pond liquid is dependent upon the relative density of each liquid; the density is generally inversely proportional to the temperature of the liquid. Therefore, if the influent waste stream has a temperature which is significantly different from the pond liquid, mixing may be seriously impaired (35).

The concentration of organisms in a waste stabilization pond liquid is low relative to other forms of biological treatment. Organisms provide the actual treatment of the wastewater by reducing organic matter which is dissolved or suspended in the water. Because the organisms are widely dispersed, the wastewater must be contained for a long period to provide adequate time for the organisms to reduce the organic matter (36).

High concentrations of suspended solids are often found in the effluent of a stabilization pond. The major cause of excessive concentrations of effluent suspended solids is large populations of algae (20,24). In stabilization ponds, growth of algae depends on direct radiation combined with a high concentration of nutrients available in the pond liquid.

Purpose and scope of the study

The purpose of this study was to determine if baffles could improve the performance of waste stabilization ponds.

Hydraulic short-circuiting can be reduced by installing baffles in a stabilization pond. Baffles provide physical restrictions to form a definite path which the influent wastewater must follow through the pond. By changing the direction of flow, the baffles would also promote hydraulic turbulence which would encourage mixing of the influent wastewater with the pond liquid (25).

The submerged surface provided by baffles encourages the growth of attached organisms. A large mass of attached organisms could increase the overall concentration of microorganisms in the pond exposed to the liquid which would decrease the time required to degrade the organic matter.

The attached organisms could affect the concentration of suspended organisms such as algae. Both the attached and suspended organisms would be dependent on a common nutrient source; therefore, the growth of any attached organisms would reduce the growth rate of suspended organisms by utilizing some of the available nutrients.

Attached organisms usually form a dense slime which sloughs periodically; but, unlike the bouyant suspended organisms, it is usually dense enough to settle out of the liquid under the influence of gravity. Consequently, the attached growth in a pond could lower the concentration of suspended solids discharged in the effluent.

The general objectives of this study were to determine the effects of baffles on the performance and biological kinetics of anaerobic waste stabilization ponds. To implement this objective, the performances of three baffled model ponds were monitored and compared to the performance of an unbaffled model pond.

The specific objectives of this study were as follows:

1. To describe and compare the biological kinetics of the systems using mathematical models.
2. To determine and compare the extent of mixing which occurred in the model ponds.
3. To determine and assess the advantages of each baffle configuration.
4. To assess the growth and influence of the attached biomass.
5. To assess the growth and influence of the suspended biomass.

6. To determine and compare the quality of the effluents of the model ponds.

7. To determine and compare the diurnal variations of pH, alkalinity, free carbon dioxide, and organic carbon in the effluent of the model ponds.

8. To determine the dominant algal genera present in each of the model ponds.

9. To determine the influence of a free liquid-air interface on the performance of the model ponds.

LITERATURE REVIEW

A waste stabilization pond, as defined by Marias (26), is a shallow man-made basin which utilizes natural biological processes to reduce organic matter and destroy pathogenic organisms. The actual basin is usually an earthen structure which is compacted and sealed to prevent excessive seepage (10).

The physical and biological performance of waste stabilization ponds is the major evaluation criteria used in this report. Therefore, brief discussions will be presented concerning the treatment capabilities of waste stabilization ponds, series operation of the ponds, effects of dissolved oxygen in the pond liquid, general effects of baffles on the performance of a pond, and previous baffled pond investigations.

Treatment capabilities of waste stabilization ponds

In most applications, waste stabilization ponds are employed to provide the only treatment given to a wastewater except for disinfection of the final effluent. In this capacity, waste stabilization ponds must provide primary and secondary treatment of the wastewater, digestion of volatile solids, and destruction of pathogenic organisms.

Primary treatment of wastewater is a process which removes much of the solid matter suspended in the wastewater by sedimentation. Primary treatment is usually accomplished by routing the wastewater through a basin to reduce its velocity. Reducing the velocity of the wastewater also reduces the hydraulic turbulence that tends to hold solid matter in suspension. As a result of the reduced hydraulic turbulence, gravity becomes the dominant force acting on the suspended solid matter; consequently, the solid matter will tend to settle to the pond bottom or float to the water surface, depending on its relative density.

Much of the solid matter removed during primary treatment can be biologically digested which reduces the volatile portion of the solid matter to respiratory end-products (7,19,36).

Secondary treatment of wastewater is a process which reduces the colloidal and soluble portion of the organic matter. Stabilization ponds employ a biological process to accomplish secondary treatment by encouraging the growth of organisms that can utilize organic matter as a source of nutrients. Much of the organic matter is converted into cell protoplasm and the remainder is used for respiration. Even though much of the organic matter is merely changed in form, the organisms can be separated from the liquid more easily than the original colloidal and soluble matter (1, 7, 8, 14, 16, 18, 27, 31, 32).

Many of the pathogenic organisms are destroyed during the treatment of wastewater in a pond because these organisms are enteric in origin and the ecosystem of a stabilization pond is not usually favorable for their growth (9,16,26,30,40).

Series operation of waste stabilization ponds

Waste stabilization ponds are usually comprised of a system of two or more individual ponds arranged in series. The individual ponds are generally designated as primary, secondary, or maturation, depending upon the type of treatment occurring in the pond (28,31,36,41).

Primary ponds provide primary treatment of the raw wastewater. Generally, these ponds also provide an environment for the digestion of volatile solid matter and storage for nonbiodegradable solid matter (20).

Effluent from the primary pond is usually discharged into a secondary pond where most of the secondary treatment occurs (18,32).

A maturation pond, sometimes called a tertiary or polishing pond, further treats the effluent discharged from the secondary pond. In a maturation pond oxygenation and improved biological quality of the wastewater usually occur (9,26,30,38). The treated effluent from a maturation pond is generally disinfected and then discharged into the receiving stream.

Pond classification according to oxygen concentration

The presence, or absence, of dissolved oxygen in the pond liquid will determine the type of biological population, end products of the reduced organic matter, kinetic rates of biodegradation, and will also indicate the rate of organic loading in the pond (8,43). Because of the importance of dissolved oxygen, stabilization ponds are often classified according to their dissolved oxygen content.

An anaerobic stabilization pond is completely devoid of any measurable dissolved oxygen (7,32). Anaerobic conditions usually prevail when a pond is subjected to a high organic loading rate. In an anaerobic environment, organisms usually utilize more of the organic matter for respiration than for synthesis of new cells. High respiration to synthesis ratios result in reduced suspended solids and more complete treatment. Another advantage of an anaerobic pond is the high surface loading rates which require less land area. The principal disadvantages of an anaerobic pond are low rates of biodegradation, effluent devoid of oxygen, and anaerobic respiration products which often include odorous gases (19,22,27,36).

An aerobic stabilization pond contains measurable dissolved oxygen throughout the entire depth of the liquid. In the absence of mechanical aeration devices, these ponds are generally very shallow and used only as maturation ponds (32).

A facultative waste stabilization pond contains both an aerobic zone and an anaerobic zone. Near the surface, the pond liquid contains dissolved oxygen which forms an aerobic zone. Near the bottom of the pond, the liquid is completely devoid of measurable dissolved oxygen. This anaerobic zone permits the anaerobic decomposition of solid organic matter. Because of the flexibility offered by a facultative-type stabilization pond, it is the most widely used (8,15,43).

Effects of baffles on waste stabilization pond performance

For the purposes of this report, a baffle will be considered as any physical restriction which directs the flow of wastewater through a pond.

The major functions performed by baffles are to reduce hydraulic short-circuiting and to provide a submerged surface which can encourage the growth of attached biomass. Attached biomass growing on the surface of the baffles could increase the total mass of organisms in the pond and thus improve the treatment efficiency. Hydraulic short-circuiting could be reduced because the flow of wastewater through the pond would follow a path determined by the configuration of the baffles, depending upon the baffle configuration, hydraulic turbulence could be promoted which would encourage mixing of the liquid.

By convention, an arrangement of baffles is usually designated by the type of hydraulic characteristics which results. The three baffle configurations considered in this report are the over-and-under, the end-around, and the longitudinal.

An over-and-under baffle configuration forces the wastewater to move from the bottom to the surface in an up and down fashion as the flow proceeds through the pond. This baffle configuration forces the liquid under a baffle and then directs the flow over the following baffle. Thus, the vertical direction of flow is reversed at each baffle. The mean flow path through a pond with over-and-under baffles would be longer than in an unbaffled pond and the velocity of the wastewater would increase as a result. Also baffles would increase the friction and the hydraulic turbulence in the pond which would result in a larger hydraulic head loss through the pond (3,4,5).

An end-around baffle configuration forces the wastewater to follow a snake-like path, in the horizontal plane, through the pond. This baffle configuration forces the liquid to flow through multiple channels which are arranged in series. The flow leaves one channel and then is forced around the end of the baffle into another channel. Thus, the horizontal direction of flow is reversed at the end of each baffle. The mean flow path through a pond with end-around baffles would be longer than in an unbaffled pond and the velocity of the wastewater would increase as a result. Also, the baffles would increase the friction and the hydraulic turbulence in the pond which would result in a larger hydraulic head loss through the pond (3,4,5).

A longitudinal baffle configuration does not alter the direction of flow, rather the wastewater is forced to flow through multiple, parallel channels. The flow path through a pond with longitudinal baffles would be equal to an unbaffled pond and the velocity would be approximately the same. However, the baffles would increase the friction which would increase the hydraulic head loss through the pond.

Previous baffled pond investigations

Most of the literature pertaining to the effects of baffles on the performance of waste stabilization ponds are vague. Several investigators (12,18,19,22,23,25,35,37) have used baffles in waste stabilization ponds and indicated that the performance of the pond was affected.

Nemerow (35) installed over-and-under baffles in an anaerobic stabilization pond which was used to treat wastewater from a poultry processing plant located near Millsboro, Delaware. These ponds had an average organic loading rate of 935 lbs BOD/acre/day and a hydraulic detention time of 7.35 days. The baffled pond was able to remove 72.5 percent of the applied BOD.[1] Nemerow indicated that the baffles improved sedimentation of heavy solids, flotation of grease and feathers, and the submerged surface encouraged the growth of attached biomass. No detailed information was included which could be used to determine the effects resulting directly from the baffles.

---

[1] Biochemical oxygen demand, 5-day.

Howe et al. (22) performed a pilot-plant study using an end-around baffle configuration in an anaerobic waste stabilization pond, treating a chemical waste which contained an influent suspended solids concentration of 30,000 ppm. The primary purpose of the baffles was to improve sedimentation of the suspended solids. They indicated that the removal of suspended solids was satisfactory, but no amounts or percentages were reported. This pilot study resulted in the construction of a similar, full-scale pond located in Indiana.

Reynolds (37) investigated the performance of three, anaerobic, model ponds, each with a different baffle configuration; over-and-under, end-around, and longitudinal. A scum baffle was installed in the model ponds to retain floating materials. The scum baffle promoted the development of a dense layer of scum which almost covered the entire liquid surface of the model ponds. The results from Reynolds' study indicated that none of the baffle configurations significantly improved the performance of the model ponds.

Some investigators (12,18) used baffles to improve the performance of model ponds, but they did not include baffles in corresponding pilot or full-scale operations. The exclusion of baffles in full-scale ponds may have been due to economic restrictions.

EQUIPMENT AND PROCEDURES

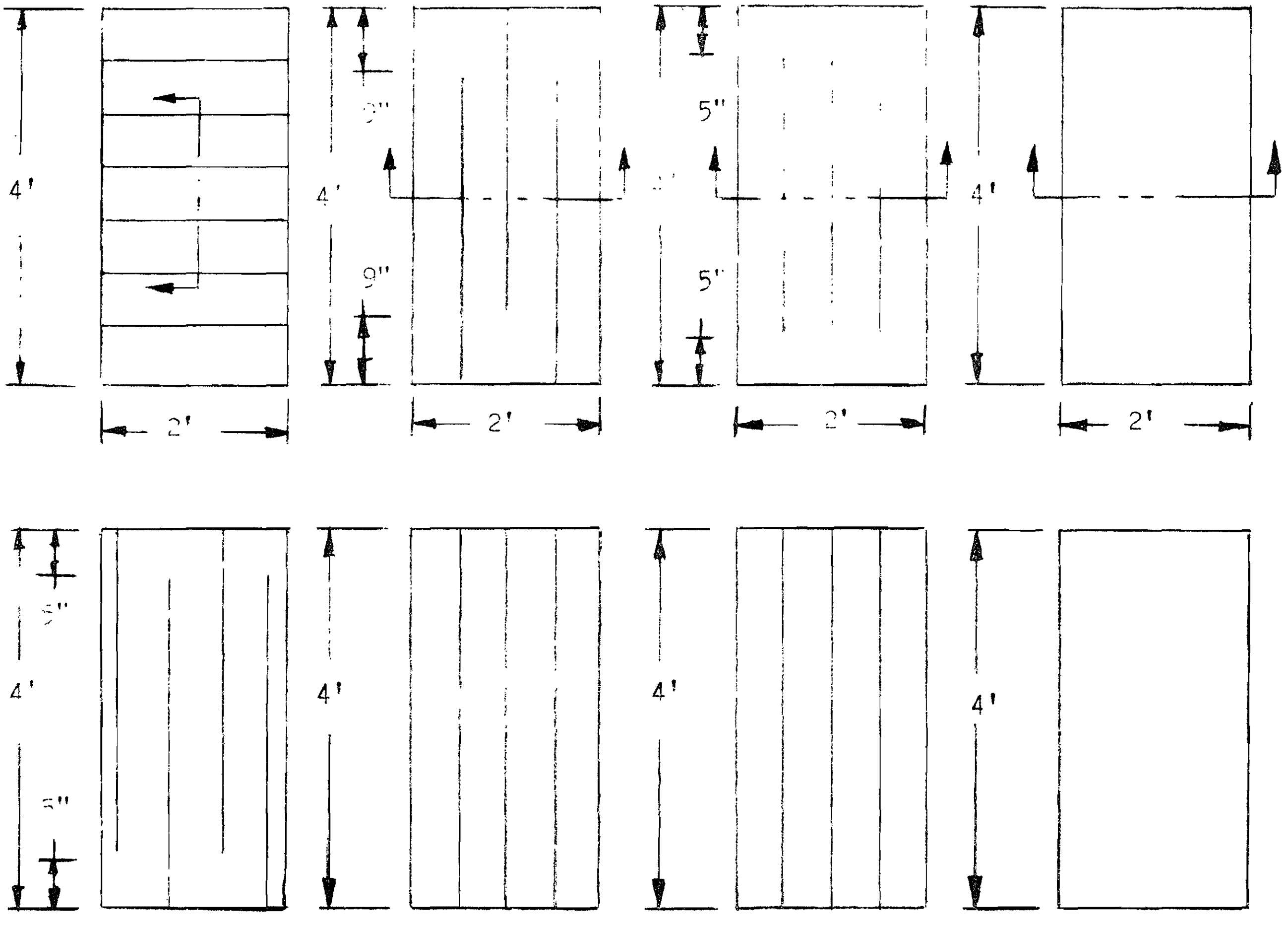
Four individual model ponds consisting of a longitudinally baffled pond, an over-and-under baffled pond, an end-around baffled pond, and an unbaffled pond were used in this study. The model ponds were designed and constructed by Reynolds (37).

Model ponds

Schematics of all four model ponds and their respective baffle configurations are shown in Figure 1. Each pond was 2 feet wide, 4 feet long, and 4 feet deep. A liquid depth of approximately 3.75 feet provided an operating volume of approximately 200 gallons in each pond.

The ponds were constructed from 3/4 inch plywood which was covered with fiberglass and resin to prevent leakage. After the fiberglass coating, the ponds were lined with pine lumber. The baffles were also constructed from pine lumber which provided a material homogeneity between the pond liner and the baffles.

When the ponds were filled with water, each baffle configuration supplied a total submerged surface area of



Over-and-under End-around Longitudinal Control

Figure 1. Schematic of model pond designs, top shows plan view and bottom shows section as indicated (dimensions approximate).

approximately 10,000 square inches and the walls supplied a submerged surface area of approximately 5,000 square inches. It was felt that the submerged surface area of the baffles was significantly larger than the walls; therefore, the effects resulting directly from the baffles could be detected and measured.

Because each baffle configuration supplied the same submerged surface area, the performances resulting from each baffle configuration could be directly compared to assess the relative effectiveness of each configuration.

Experimental apparatus

A synthetic waste was supplied to the model ponds through a combination of both an organic loading system and a hydraulic loading system. Each system was operated independently. The entire system is shown schematically in Figure 2.

During storage, the organic portion of the synthetic waste was highly concentrated. The concentrated mixture was kept in a refrigerator which provided an average liquid temperature of 4 C. Consequently, no excessive organic matter reduction was realized in storage.

The concentrated, synthetic waste, stored in the refrigerator, was continuously mixed to maintain a homogeneous liquid. Concurrently, this mixture was continuously metered into a storage loop by a peristaltic pump[1] which provided an average flow rate of 200 ml/hr.

Once every hour, a submersible pump,[2] which was located in a tank filled with tap water, was actuated by a percentage timer.[3] The pump forced tap water through the storage loop and flushed the synthetic waste into the pond. The tap water also served as a diluent to provide the desired concentration of organic carbon.

Average daily flow rates through the ponds were controlled by setting the pump timer to operate the pumps for a specified period of time each hour. The pump operating times during the various runs are listed in Table 1.

Table 1. Operating time of the hydraulic dilution pumps (sec/hr).

Hydraulic detention time (days)	Pump operating time per hour (seconds)
15.0	28
5.0	81
2.5	155
1.5	230

Fine adjustment of the average daily flow rates through the ponds was accomplished using an adjustable valve that was installed in the hydraulic line.

To prevent back-siphoning of pond liquid into the tap water storage tank, a siphon break was installed in the discharge line at the highest elevation.

The mixture of concentrated synthetic waste and tap water entered the model pond through a diffuser which tended to distribute the influent equally across the width.

A light fixture[4] was mounted above each model pond and adjusted to provide a light intensity of approximately 600 foot-candles at the water surface. This intensity was recommended by Aquirre and Gloyna (1) for successful growth of algae. An automatic timer[5] was used to provide alternating light and dark periods. Light was supplied to the ponds for 14 hours a day.

Synthetic waste

A synthetic waste was used to supply substrate and nutrients to the model ponds. The main ingredients of the waste were powdered nonfat milk[6] and dry dog food.[7] Additional nitrogen and phosphorus were added in the form of NH_4Cl and Na_3PO_4, respectively, to assure that organic carbon was the limiting nutrient. Table 2 contains the proportional quantities and characteristics of the ingredients used in the synthetic waste.

Table 2. Characteristics of the concentrated synthetic waste and the diluted influent to the model ponds.

Ingredient	Quantity
Waste Concentration	
TOC[a] of milk	400 mg/g
TOC of dfs[b]	4,300 mg/l
Ratio milk/dfs	100 g/l
pH	7.0
Temperature	4C
Influent to ponds	
TOC	200 mg/l
BOD/TOC	2.41
NH_4Cl as N	10 mg/l
Na_3PO_4 as P	2 mg/l

[a] Total organic carbon.

[b] Dog food supernatant.

---

[1] Polystaltic pump, Buchler Instruments.

[2] Little Giant Submersible Pump, Model 4.

[3] General Electric Percentage Timer, TSA-14.

[4] Western Lighting Corp. Four Tube High Intensity Light Bank, Issue B.

[5] Sears and Roebuck Light Timer, Model 6170.

[6] Pet Instant Nonfat Dry Milk.

[7] Gaines Gravy Train.

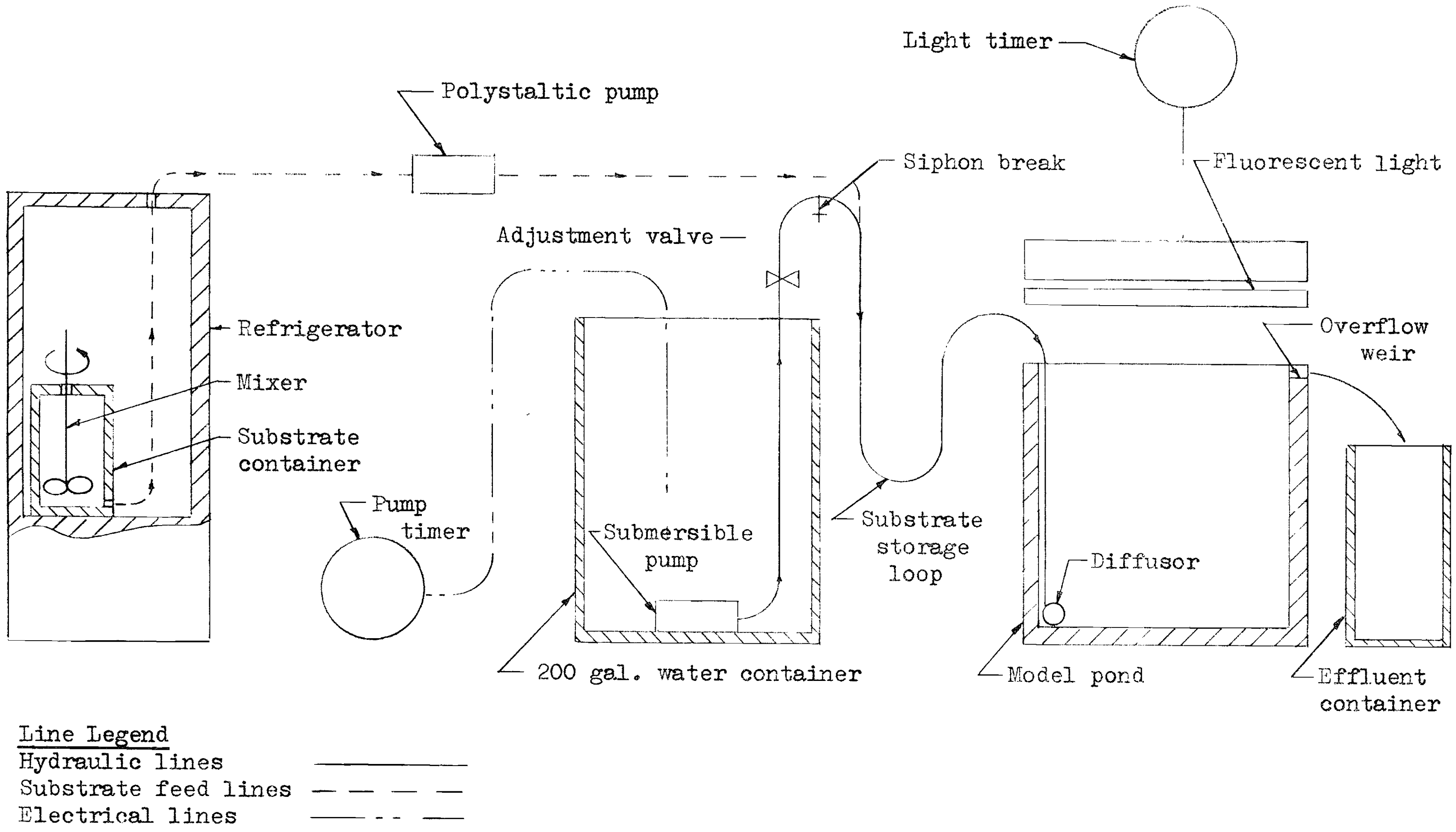


Figure 2. Schematic diagram of the experimental apparatus.

The dog food was prepared by adding 90 grams of dry dog food to 500 ml of tap water and blending the mixture for 60 seconds at the highest setting of a household-type food blender.[8] The blended mixture was diluted two liters with tap water and allowed to settle for 24 hours in a refrigerator maintained at 3 C. After settling, the supernatant was decanted off and used as the synthetic waste. This method of preparation provided an average organic carbon concentration in the dog food supernatant of 4,300 mg/l.

Powdered, nonfat milk supplied most of the organic carbon to the ponds. The dry milk had an approximate organic carbon (TOC) content of 400 mg per gram of milk.

Sampling procedures

During normal operation, the total volume of effluent from each pond was collected for a period of 24 hours. Samples of the collected effluent were analyzed for total organic carbon, soluble organic carbon, and suspended solids.

To determine diurnal variations effluent samples were collected hourly and analyzed for pH, alkalinity, and temperature. Free carbon dioxide samples were collected every 2 hours. Samples to be analyzed for total organic carbon, soluble organic carbon, and suspended solids were collected every 4 hours.

The concentrated synthetic wastewater and tap water were analyzed for total and soluble organic carbon each day prior to being placed into the influent feed bottle.

Floating biomass which was trapped between the baffles of the over-and-under pond were removed daily. Two or three samples of the floating material were analyzed for total solids at steady-state operation during each run. The average mass of floating material removed from the units at various detention times is given in Table 3.

Table 3. Average daily removal of floating materials from the over-and-under pond (mg).

Hydraulic detention time (days)	Mass (mg)
15.0	6,500
5.0	900
2.5	1,900
1.5	--

A vacuum-powered scraper was used to obtain samples of the attached biomass at the conclusion of each run (37). As the scraper was pulled up the submerged surface, attached biomass was loosened and drawn into a collection bottle. The locations of the sampling sites used to obtain these samples are shown in Figure 3.

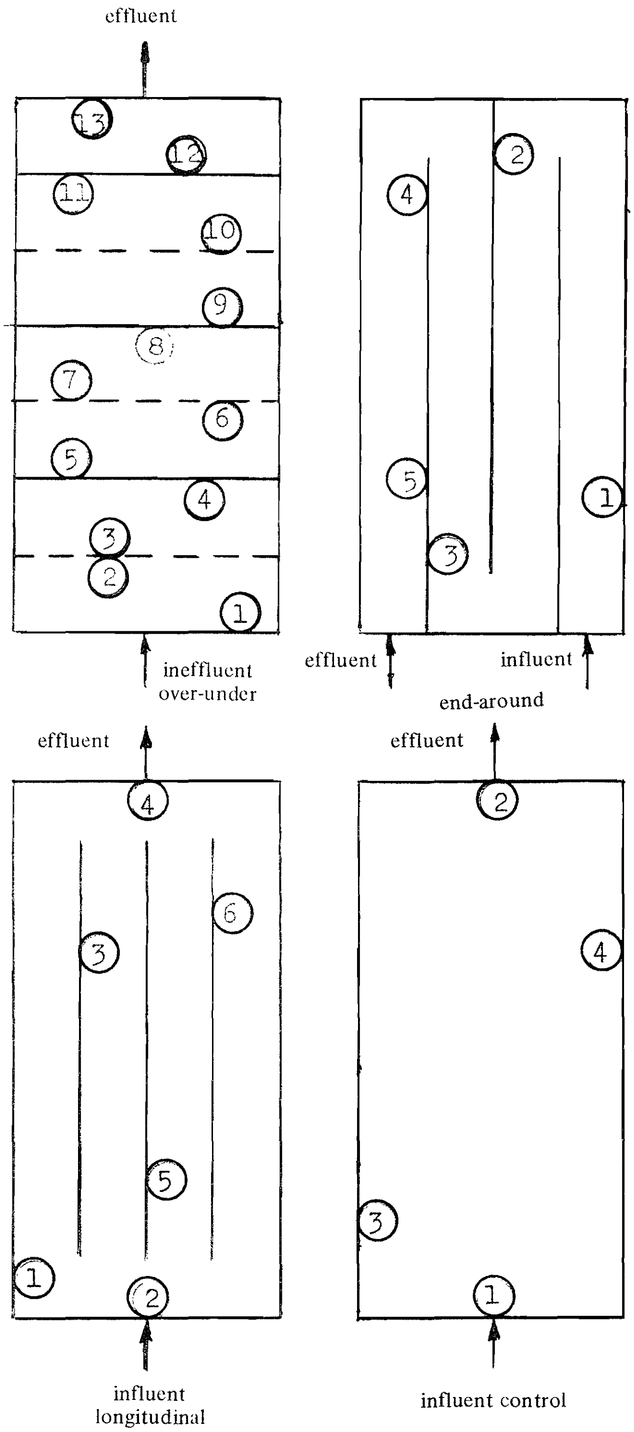


Figure 3. Attached biomass sampling sites in the model ponds.

---

[8] Waring Blender.

During the 15-day run, samples were taken from each pond and the genera and percent composition of the algae were determined.

Analytical techniques

All analyses were made in duplicate and the average values were used for computations and are reported in the Appendix.

Total and soluble organic carbon concentrations were determined using a total organic carbon analyzer[9] (6). Soluble organic carbon was determined after filtering the sample through a glass fiber filter.[10]

Suspended solids were determined using the technique presented by Strickland and Parsons (42).

Alkalinity, total solids, BOD, COD,[11] and free carbon dioxide were determined using the procedures outlined in Standard Methods (2). An electrochemical device[12] was used to measure pH. Dissolved oxygen and temperature measurements were measured using an electronic dissolved oxygen probe[13] in conjunction with a thermistor.

During the 1.5-day run, a mechanical failure in the organic carbon analyzer necessitated the substitution of an alternate method for determination of organic carbon; COD determinations were substituted for organic carbon determinations. Fortunately, the COD organic carbon characteristics of both the influent and effluent had been previously established. Characterization parameters for the effluent are given in Table 4 and the parameters of the influent were given earlier in Table 3.

Table 4. Relationship between organic carbon, BOD, and COD determined on the effluent of the control pond during the 5-day run.

Characteristic	Quantity
Organic carbon measurement of the same sample	
TOC	94 mg/l
SOC[a] (filtered)	67 mg/l
BOD_5	267 mg/l
BOD_5 (filtered)	197 mg/l
COD	279 mg/l
Ratio of parameters	
COD/TOC	2.95
BOD_5/TOC	2.84
BOD_5 (f)/SOC	2.94

[a] Soluble organic carbon.

Model pond operation

During the initial start-up, each pond was seeded with 20 gallons of municipal sewage (37). Seed was obtained from the primary waste stabilization pond which was owned and operated by Logan City Corporation, located near Logan, Utah.

The model ponds remained completely anaerobic throughout the entire experiment as a result of the high organic loading rate that ranged from 291 pounds BOD/acre/day to 2,910 pounds BOD/acre/day, during the 15 and 1.5-day runs, respectively. The organic loading rates resulted from maintaining an influent organic carbon concentration of 200 mg/l in the raw wastewater and varying the hydraulic detention time. Figure 4 illustrates the variation of organic loading rate as a function of detention time in a 200 gallon pond with an influent wastewater strength of 200 mg/l.

The hydraulic detention time of the wastewater in the model ponds was determined by weighing the effluent. After weighing, the effluent containers were emptied, cleaned, and placed back in service. Any adjustment then required to change the flow rate was performed by adjusting the pump rate.

To insure proper flow rates of concentrated synthetic waste, a flow measurement was performed daily. At lower hydraulic detention times, precipitate was observed in the feed lines; when this condition appeared the lines were cleaned with hot water.

The constancy of the organic carbon content of the concentrated, synthetic waste was maintained by preparing fresh substrate daily.

Floating matter which accumulated between the baffles in the over-and-under pond was removed daily. This action insured good light penetration and effective gas transfer.

Occasionally, the light intensity on the water surface was measured and, if necessary, adjusted to maintain approximately 600 foot-candles.

Calculations

Organic carbon concentrations in the concentrated, synthetic waste were determined and regulated by utilizing a carbon budget measured at the substrate storage loop (Figure 2). The equation used to determine the

---

[9] Beckman Instruments, Inc., Model 915.

[10] Whatman Glass Fiber Filter GF/C.

[11] Chemical oxygen demand.

[12] Orion Specific Ion Meter, Model 407.

[13] Electronic Instruments Limited Dissolved Oxygen Meter, Model 15A.

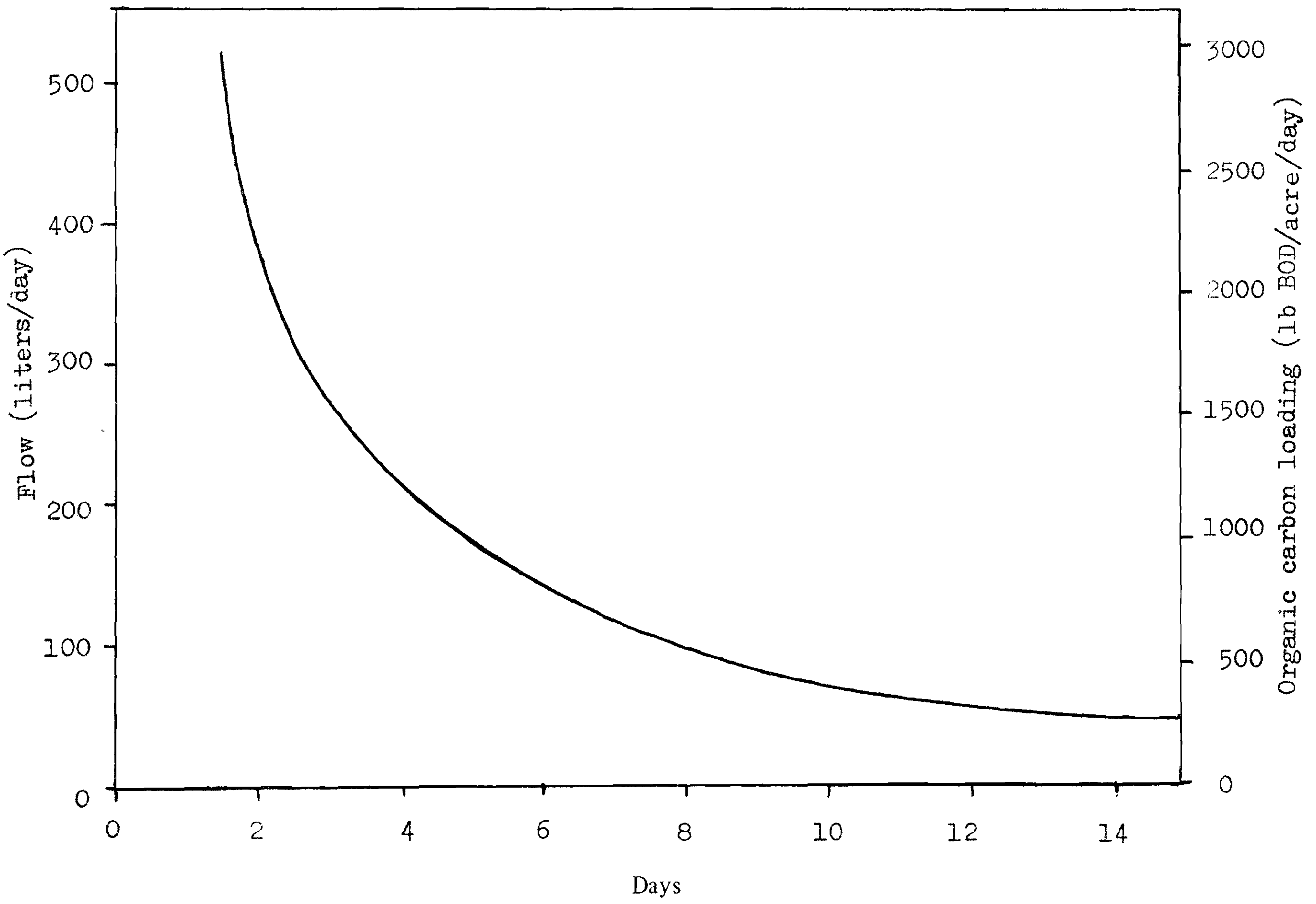


Figure 4. Flow and organic carbon loading vs. theoretical detention time for pond volume of 200 gallons and waste strength of 200 mg/l as TOC.

desired organic carbon concentration of the concentrated, synthetic waste was:

$$TOC_c = \frac{(TOC_p)F_p - (TOC_t)F_t}{F_c} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

in which

TOC = total organic carbon, mass/volume
F = flow, volume/time

Subscripts:

c = concentrated, synthetic waste
t = tap water
p = pond liquid

Statistical analyses of data obtained from this study were performed using procedures outlined by Dixon and Massey (11).

MATHEMATICAL MODELS

Most stabilization pond designs, particularly early designs, have been based upon organic and hydraulic loading parameters established by individual state boards of health (43). Most of these loading parameters have been determined empirically to establish design criteria that would insure satisfactory treatment of wastewater within specific geographical regions.

Empirically established loading parameters have provided reasonably good pond designs. Generally, however, these parameters have not contained provisions that would relate the rate or extent of biological growth to removal of organic matter.

A more rational approach to pond design has been approached through the use of kinetic models. Kinetic models provide a mathematical description of the ponds which can relate biological reaction rates to the physical parameters of the pond and the strength of the wastewater.

Three kinetic models will be developed in this section: 1) the Marias-Shaw kinetic model (a first order completely mixed flow model); 2) the Monod kinetic model (in conjunction with materials, balances, and completely mixed flow); 3) a first order growth model with a plug-flow reactor configuration.

Marias-Shaw kinetic model

Two investigators, Marias and Shaw (26), proposed and developed a kinetic model to describe the reduction of soluble organic matter occurring in a stabilization pond. Their model is a variation of the original concepts presented by Herbert (21).

Marias and Shaw have reported that the change of the limiting nutrient concentration due to biological growth follows first-order reaction kinetics for a particular substrate, biological population, and environmental conditions. This relationship can be expressed as a differential equation which is:

$$\frac{dS}{dt} = KS \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

in which

S = concentration of the limiting nutrient, mass/volume

K = first-order degradation constant, time^{-1}

t = time

The following development is presented to provide an in-depth comparison of the Marias-Shaw kinetic model and the other kinetic models developed in this section. The original development has been slightly modified to conform with the symbols and terminology used in this report.

The following assumptions were used by Marias and Shaw to simplify the mathematics:

i. Complete and instantaneous mixing of influent, soluble organic matter with the reactor contents.

ii. Equation 2 is valid.

iii. None of the reactor contents is lost by seepage or evaporation.

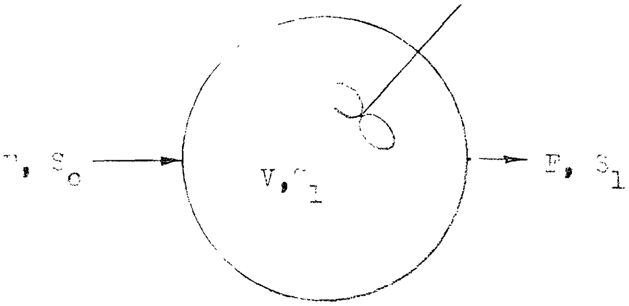


Figure 5. Schematic of a biological reactor which contains a homogeneous mixture of soluble organic matter.

Figure 5 shows a schematic of a biological reactor which satisfies the assumptions made above. The materials balance for the substrate in the reactor is:

$$\left[\begin{array}{c}\text{Net change of substrate}\\ \text{in the reactor}\end{array}\right] = \left[\begin{array}{c}\text{Substrate entering}\\ \text{in influent}\end{array}\right. - \begin{array}{c}\text{Substrate leaving}\\ \text{in effluent}\end{array} - \left.\begin{array}{c}\text{Substrate utilized}\\ \text{by the organisms}\end{array}\right] \quad . \; . \; . \; (3)$$

Using the designations given in Figure 5, Equation 3 becomes:

$$V(dS_1)\text{net} = S_oFdt - S_1Fdt - V(dS_1)g \quad . \; . \; . \; . \; (4)$$

in which

V = reactor volume

$(dS_1)net$ = net change of substrate concentration in reactor, mass/volume
S_o = substrate concentration in the influent, mass/volume
S_1 = substrate concentration in the effluent and the reactor, mass/volume
F = flow rate through the reactor, volume/time
$(dS_1)g$ = change substrate concentration due to biological growth, mass/volume

Dividing Equation 4 by V and dt gives:

$$\frac{(dS_1)net}{dt} = \frac{S_oF}{V} - \frac{S_1F}{V} - \frac{(dS_1)g}{dt} \quad . \; . \; . \; . \; . \; (5)$$

At steady-state conditions the net change of substrate concentration in the reactor will be zero, or $(dS_1)net/dt = 0$. Also, the change of substrate concentration will follow first-order reaction kinetics, or $(dS_1)g/dt = KS_1$. Incorporating these criteria, Equation 5 now becomes:

$$0 = \frac{S_oF}{V} - \frac{S_1F}{V} - KS_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; (6)$$

The mean hydraulic detention time in the reactor can be expressed as a ratio of reactor volume and flow as follows:

$$\theta = \frac{V}{F} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (7)$$

in which
θ = mean hydraulic detention time

When the above expression is substituted into Equation 6 and rearranged, the linear form of Equation 6 becomes:

$$\frac{S_o - S_1}{\theta} = KS_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (8)$$

Equation 8 can be used to predict the concentration of substrate in the pond effluent for any given hydraulic detention time or influent substrate concentration after determining the value of the constant K.

Monod kinetic model

The purpose of the Monod kinetic model is to establish a mathematical relationship between the growth of biological organisms and the change of substrate concentration in the wastewater. To develop this kinetic model, two basic relationships that were established by Monod (33,34) are employed.

An empirical relationship between growth rate and the concentration of a limiting nutrient was established by Monod (33) and has been successfully applied to the biological reactions which occur in the treatment of wastewater (12,32). The relationship is:

$$\mu = \frac{\hat{\mu}S}{K_s + S} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (9)$$

in which
μ = specific growth rate, time^{-1}
$\hat{\mu}$ = maximum growth rate, time^{-1}
S = concentration of limiting nutrient, mass/volume
K_s = concentration limiting nutrient at one-half the maximum growth rate, mass/volume

The maximum growth rate and the substrate concentration at half the maximum growth rate are essentially constants for a given culture and limiting nutrient (33).

Monod (34) also determined that the weight of organisms grown per weight substrate utilized is a constant for a given organism, substrate, and set of environmental conditions. This relationship can be expressed as:

$$Y = \frac{\text{Weight of organisms grown}}{\text{Weight of substrate utilized}} \quad . \; . \; . \; . \; . (10)$$

in which
Y = yield constant, dimensionless

The following assumptions were used to simplify the development of the model utilizing Monod's kinetic equation:

i. Complete and instantaneous mixing of influent, soluble organic matter with the reactor contents.
ii. None of the reactor contents are lost by seepage or evaporation.
iii. Equations 9 and 10 are valid.
iv. Organism growth rate follows first-order reaction kinetics; for suspended organisms $dX/dt = \mu X$.
v. Both the attached and suspended organisms have similar growth and decay rates.
vi. Both the attached and suspended organisms are distributed homogeneously in the horizontal plane of the reactor.
vii. Vertical distribution of both the attached and suspended organism is constant in the reactor.

Figure 6 is a schematic of a biological reactor which satisfies the assumptions made above.

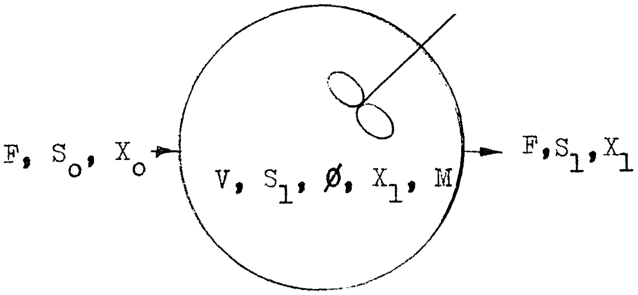


Figure 6. Schematic of a biological reactor which contains suspended and attached organisms and a homogeneous mixture of soluble organic matter.

The materials balance for the organisms in the reactor is:

$$\left[\begin{matrix}\text{Net change of}\\ \text{organisms in}\\ \text{the reactor}\end{matrix}\right] = \left[\begin{matrix}\text{Organisms entering}\\ \text{in influent}\end{matrix}\right.$$

$$- \begin{matrix}\text{Organisms leaving}\\ \text{in effluent}\end{matrix} + \begin{matrix}\text{Growth of suspended}\\ \text{and attached organ-}\\ \text{isms in the reactor}\end{matrix}$$

$$\left. - \begin{matrix}\text{Decay of suspended}\\ \text{and attached organ-}\\ \text{isms in the reactor}\end{matrix}\right] \quad \ldots\ldots\ldots\ldots (11)$$

Using the designations given in Figure 6, Equation 11 becomes:

$$V(dX_1)net + \phi(dM)net = FX_o dt - FX_1 dt + V(dX_1)g$$

$$- k_d VX_1 dt + \phi(dM)g - k_d \phi M dt \quad \ldots\ldots (12)$$

in which

V = reactor volume

ϕ = submerged surface area

$(dX_1)net$ = net change of suspended organism concentration in the reactor, mass/volume

$(dM)net$ = net change of attached organism density, mass/area

X_o = organism concentration in the influent, mass/volume

X_1 = suspended organism concentration in the effluent, mass/volume

$(dX_1)g$ = change of suspended organism concentration due to growth, mass/volume

$(dM)g$ = change of attached organism density due to growth, mass/area

F = flow rate through the reactor, volume/time

k_d = specific decay rate which accounts for all cellular losses, time^{-1}

The concentration of organisms in the influent is negligible when compared with the concentration of organisms in the reactor. Therefore, dividing Equation 12 by V and dt and neglecting the organisms in the influent gives:

$$\frac{(dX_1)net}{dt} + \frac{\phi(dM)net}{V\,dt} = \frac{-F}{V}X_1 + \frac{(dX_1)g}{dt} - k_d X_1$$

$$+ \frac{\phi}{V}\frac{(dM)g}{dt} - \frac{\phi}{V}k_d M \quad \ldots\ldots\ldots\ldots (13)$$

The growth rate of organisms in the reactor was assumed to follow first-order reaction kinetics. Therefore, the following relationship can be used to determine the rate at which the suspended organisms concentration in the reactor changes as a result of growth

$$\frac{(dX_1)g}{dt} = \mu X_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

And the change due to growth in the attached organisms is:

$$\frac{(dM)g}{dt} = \mu M \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

At steady-state conditions the net change of organisms in the reactor will be zero, or $(dX_1)net/dt = (dM)net/dt = 0$. Using the expressions for growth given by Equations 14 and 15, at steady-state conditions Equation 13 becomes:

$$0 = \frac{-FX_1}{V} + \mu X_1 - k_d X_1 + \frac{\phi}{V}\mu M - \frac{\phi}{V}k_d M \quad \ldots (16)$$

Rearranging the above equation and solving for the dilution rate, 1/θ, yields:

$$\frac{1}{\theta} = (\mu - k_d) \quad 1 + \frac{\theta}{V}\frac{M}{X_1} \quad \ldots\ldots\ldots\ldots (17)$$

Referring again to Figure 6, a materials balance for the substrate in the reactor is:

$$\left[\begin{matrix}\text{Net change of}\\ \text{substrate in}\\ \text{the reactor}\end{matrix}\right] = \left[\begin{matrix}\text{Substrate entering}\\ \text{in the influent}\end{matrix}\right.$$

$$\left. + \begin{matrix}\text{Substrate leaving}\\ \text{in the effluent}\end{matrix} - \begin{matrix}\text{Substrate utilized}\\ \text{by the organisms}\end{matrix}\right] \quad \ldots (18)$$

Using the designations given in Figure 6, Equation 18 becomes:

$$V(dS_1)net = FS_o dt - FS_1 dt - V(dS_1)g \quad \ldots (19)$$

Including both attached and suspended organisms, Equation 10, Monod's expression for yield becomes:

$$Y = \frac{(dX_1)g + \frac{\phi}{V}(dM)g}{(dS_1)g} \quad \ldots\ldots\ldots\ldots (20)$$

Substituting Equations 14 and 15 into Equation 20 and solving the resulting expression for $(dS_1)g$ gives:

$$(dS_1)g = \frac{\mu}{Y}(X_1 + \frac{\phi}{V}M)\, dt \quad \ldots\ldots\ldots (21)$$

Dividing Equation 19 by V and dt and substituting Equation 21 for $(dS_1)g$. Equation 19 now becomes:

$$\frac{(dS_1)net}{dt} = \frac{FS_o}{V} - \frac{FS_1}{V} - \frac{\mu}{Y}(X_1 + \frac{\phi}{V}M) \quad \ldots (22)$$

At steady-state conditions the net change of substrate concentration in the reactor is zero, or $(dS_1)net/dt = 0$. When steady-state conditions are imposed and rearranged, Equation 22 becomes:

$$\frac{S_o - S_1}{\theta} = \frac{\mu}{Y}\left[X_1 + \frac{\phi}{V}M\right] \quad \ldots\ldots\ldots (23)$$

By solving Equation 17 for specific growth rate and substituting the resulting expression into Equation 23, the following relationship is obtained:

$$\frac{(S_o - S_1)}{\theta} = \frac{1}{Y}\left[\frac{1}{\theta \quad 1 + \frac{\phi}{V}\frac{M}{X_1}} + k_d\right]\left[X_1 + \frac{\phi}{V}M\right]$$

Simplifying and rearranging the above equation into a linear form gives:

$$\frac{S_o - S_1}{X_1} = \frac{k_d}{Y}\theta\left[1 + \frac{\phi M}{VX_1}\right] + \frac{1}{Y} \quad \ldots\ldots (24)$$

By solving Equation 17 for specific growth rate, the resulting expression can be equated to Equation 9 for specific growth rate. The following relationship is obtained:

$$\frac{\hat{\mu}S_1}{K_s + S_1} = \frac{1}{\theta\left[1 + \frac{\phi}{V}\frac{M}{X_1}\right]} + k_d$$

The above equation can be manipulated into the linear form as follows:

$$\frac{\theta\left[1 + \frac{\phi M}{VX_1}\right]}{1 + \theta\left[1 + \frac{\phi M}{VX_1}\right]k_d} = \left(\frac{K_s}{\hat{\mu}}\right)\frac{1}{S_1}\ \frac{1}{\hat{\mu}} \quad \ldots\ldots (25)$$

Equations 24 and 25 can be used to predict the mass of suspended and attached organisms in a pond for any given influent substrate concentration, effluent substrate concentration, hydraulic detention time, or submerged surface area after determining the constants Y, k_d, $\hat{\mu}$, and K_s.

Plug-flow kinetic model

Theoretically, a plug-flow condition will exist in a biological reactor when a completely mixed, infinitesimally wide volume of liquid passes through the reactor without mixing with any other similar infinitesimal volumes. An infinitesimal volume of liquid in a plug-flow reactor would behave as shown in Figure 7.

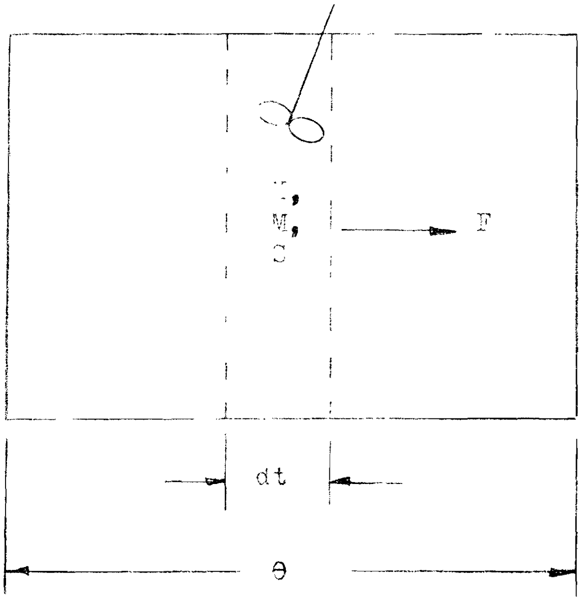


Figure 7. Schematic of a biological reactor which contains suspended and attached organisms and plug-flow hydraulic characteristics.

The following assumptions were used to develop the plug-flow kinetic model:

- i. Plug-flow movement of the soluble organic matter through the reactor.
- ii. None of reactor contents are lost by seepage or evaporation.
- iii. Equation 2 is valid.
- iv. The rate of change in substrate concentration is a function of both attached and suspended organisms.

v. Both the attached and suspended organisms are distributed homogeneously in the horizontal plane of the reactor.
vi. Vertical distribution of both the attached and suspended organisms is constant in the reactor.
vii. The reactor has a constant cross-section and flow rate.

The rate of change of substrate concentration can be a first-order kinetic reaction which is:

$$\begin{bmatrix}\text{Change of substrate}\\ \text{concentration in}\\ \text{the reactor}\end{bmatrix}$$

$$= f\left\{\begin{matrix}\text{(Substrate concentration),}\\ \text{(Suspended organism concen-}\\ \text{tration + attached organism}\\ \text{density)}\end{matrix}\right\} \quad . . . . (26)$$

Using the designations given in Figure 7, Equation 26 can be expressed as a differential equation which is:

$$\frac{dS}{dt} = - kS\ (X_1 + \frac{\phi}{V} M) \quad . . . . (27)$$

Equation 27 can be rearranged and integrated as follows:

$$- \int_{S_o}^{S_1} \frac{dS}{S} = \int_0^{\theta} k(X_1 + \frac{\phi}{V} M)\ dt$$

or

$$\ln \frac{S_o}{S_1} = k\theta\ (X_1 + \frac{\phi}{V} M) \quad . . . . (28)$$

in which

k = degradation constant, volume/mass-time

Equation 28 can be employed to predict the retention time and wetted surface area required to produce a designated effluent concentration when S_o and k are known and the division between suspended and attached biomass is selected.

RESULTS AND DISCUSSION

Data were collected from four model ponds to determine the effects of baffles on the performance of anaerobic stabilization ponds. The effects on performance resulting directly from the baffles were isolated from overall performance by establishing the control pond as the datum to which the baffled ponds were referenced. In addition, the relative effectiveness of each baffle configuration was determined by making a comparison between the baffled ponds.

Throughout this study, major emphasis was placed on collecting data that would allow an analysis of the performance of the treatment ponds using the mathematical models. However, conventional operating data removal, suspended solids, attached solids, algae, pH, alkalinity, free carbon dioxide, odor, effects of surface scum, and sedimentation of solids in the over-and-under pond, were also monitored and reported.

The results for each parameter and model analysis are presented and discussed separately in the following sections. Data are summarized in Tables A-1 through A-22 in the Appendix.

Organic carbon removal

Removal of soluble organic carbon at various detention times in the model ponds is shown in Figure 8. Reduction of soluble organic carbon during the 15-day run was approximately equal in all the model ponds. Below a hydraulic detention time of 5 days, removal of soluble organic carbon decreased sharply and different removal percentages were observed in the various ponds.

Percentages of soluble organic carbon removed from the wastewater by the model ponds were higher than those normally encountered for anaerobic wastewater lagoons. At a detention time as low as 1.5 days, organic carbon removal was 68 percent in the longitudinal baffled pond which had a soluble organic carbon loading rate of 3,000 lb BOD/acre/day. The characteristics of the synthetic waste and the physical dimensions of the model ponds were presumed to be the principal reasons for the high percentage of organic carbon removal and also the high biological degradation rates observed during this study.

The principal source of organic carbon in the synthetic waste was the dry powdered milk. Dry milk has a high organic carbon content, approximately 40 percent by dry weight, and is biologically degraded with relative ease. Therefore, the organic carbon in the wastewater was present in a form easily degraded by the microorganisms and thus the organic carbon was utilized at a rapid rate. Thus, the synthetic waste is expected to result in higher removal than would be expected for a typical waste.

The physical dimensions of the model pond were 2 feet wide by 4 feet long by 4 feet deep. The walls of the models provided a surface upon which biological growth could occur, and the system probably closely approximated a trickling filter or a bio-disc treatment device. The boundary effects which were induced by the containing walls of the model probably would not be apparent in a full-scale pond unless the surfaces were placed very close together.

The differences in biological degradation rate between the baffling configuration was a result of the attached growth on the walk and the improvement in flow characteristics. However, the cause of the unusually high biological degradation rates observed in this experiment was probably the characteristics of the synthetic waste.

Suspended solids

The variations of average, effluent suspended solids at various detention times are shown in Figure 9. Generally, effluent suspended solids increased in the baffled ponds as the hydraulic detention time decreased; however, the amount of suspended solids in the control pond effluent decreased with decreasing detention time.

Microscopic observations of effluent samples indicated that most of the suspended solids were comprised of algae.

During the 15-day run, the effluent from the baffled ponds contained a lower concentration of solids than did the control pond. This was attributed to the increased utilization of substrate and nutrients by attached biomass found in the baffled ponds. Attached biomass competition apparently competed more successfully for substrates and nutrients than suspended biomass and thus reduced the quantity of effluent solids.

Below a hydraulic detention time of about 5 days, the quantity of suspended solids did not appear to be affected by the attached biomass. The increased hydraulic turbulence could have caused a change in the attached

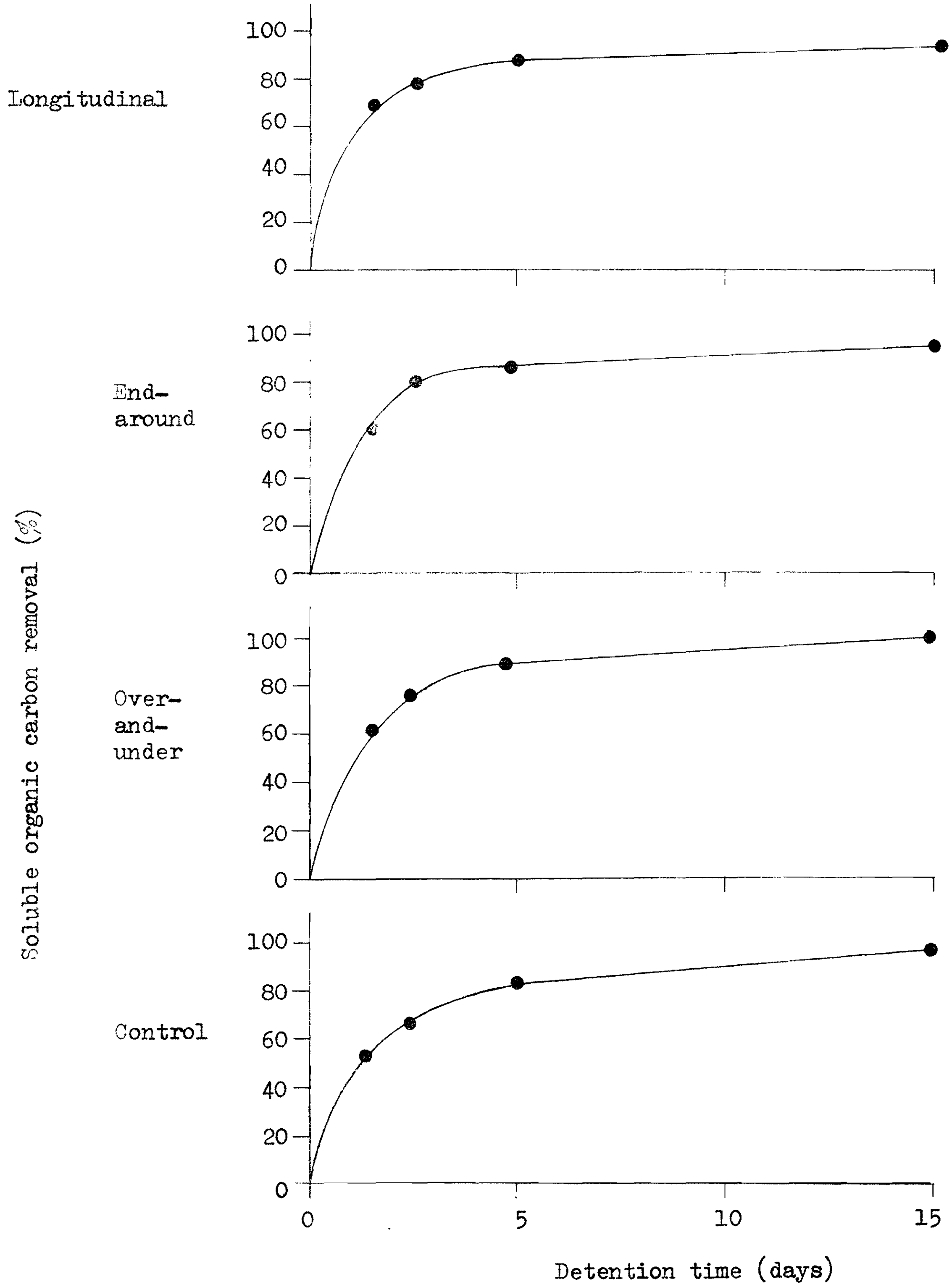


Figure 8. Percent removal of soluble organic carbon at various detention times.

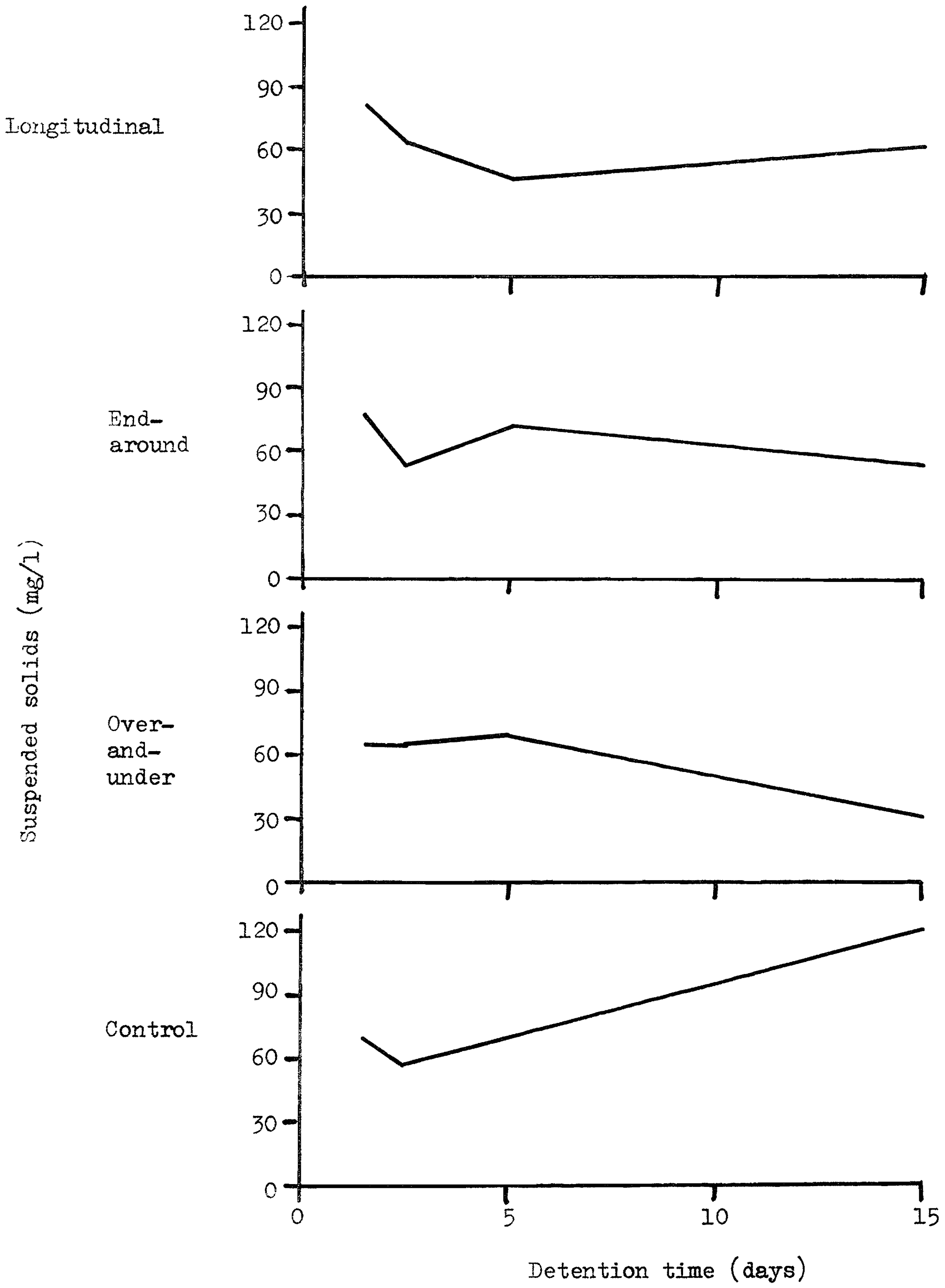


Figure 9. Effluent suspended solids concentration of the model ponds for various hydraulic detention times.

mass. Also, lower percentages of nutrient removal could have eliminated some of the competition between the attached and suspended organisms.

Diurnal variations in concentrations of effluent suspended solids were not as pronounced as those usually reported in the literature for facultative ponds (8,10,13). The general lack of diurnal variation was attributed to the relatively low light intensity of 500 foot-candles as compared to natural sunlight. At this intensity, algae could reside in a stratified layer close to the water surface during the periods when the lights were operated. Consequently, after the lights were out, the algae were already close to the surface and the quantity leaving in the effluent was not seriously affected by the absence or presence of light. Figure 10 shows the diurnal fluctuations of effluent suspended solids during both the 15 and 5-day runs.

Attached solids

Each of the baffled ponds contained a larger mass of attached solids than the control pond for the detention times tested. The growth of attached solids and type of organisms was apparently related to the submerged surface area and hydraulic characteristics of the pond.

Figure 11 shows the variation in the mass of attached solids measured in the model ponds for the various detention times. In general, the mass of attached solids increased in all of the ponds as the hydraulic detention times were decreased. This relationship resulted from increasing the organic loading rate by maintaining a constant organic carbon concentration in the influent substrate throughout the experiment.

Presence of attached biomass upon the submerged surfaces of the model ponds allowed biological degradation of the wastewater to proceed in a manner similar to a biological filter. In both a baffled pond and a biological filter, wastewater is passed over microorganisms that are attached to a solid surface. The surface area:volume ratio in the model ponds was much smaller than that normally found in biological filters, and because of this it is unlikely that the effect of the attached biomass was as significant as the improvement of the mixing pattern provided by the baffles.

At the conclusion of this study, the baffles were removed from the model ponds and two separate biological populations were observed on the baffles. From the water surface to a depth of about 2 feet, a slimy, dark-green growth was dominant. Below the dark-green growth, a fuzzy appearing, light-brown culture was the dominant culture. The transition zone between the two populations was only a few inches. It was believed that the dark-green growth coincided with the algal distribution in the pond liquid.

A dark-pink coloration was observed at the interface of the baffle surface and the attached biomass. Similar observations were reported by Gloyna and Aquirre (18) during a model study of ponds, and they indicated the pink coloration was probably a result of purple-sulfur bacteria. Gloyna and Aquirre (18) attributed the presence of purple-sulfur bacteria to high organic loading rates and cold (about 12 C) temperatures. A temperature of 20 ± 2 C was maintained throughout this study which would indicate that high organic loading rates can stimulate the growth of purple-sulfur bacteria without cold temperatures. However, similar effects could also be produced by temperature changes.

Algae

During the 15-day run, liquid samples were taken from the model ponds and examined microscopically to determine the dominant genera of algae. The genera observed and the approximate percentage of the total algal population are reported in Table 5.

Table 5. Algal genera present during the 15-day run and the approximate percentage composition of the total population.

Pond	Genera	Percent Composition
Longitudinal	Oscillatoria	75
	Euglena	20
	Chlamydomonas	1
End-around	Euglena	40
	Chlamydomonas	40
	Oscillatoria	2
Control	Chlamydomonas	90
	Euglena	1
Over-and-under	Chlamydomonas	50
	Euglena	50
Over-and-under (floating on surface)	Euglena	99

The predominant genera in each of the model ponds varied, but the genera found in all of the model ponds were Oscillatoria, Euglena, and Chlamydomonas. These genera are all commonly found in municipal waste stabilization ponds (13,15,29). Qualities common to all three genera include phototaxis and the ability to assimilate acetate anaerobically (13,36).

Phototaxis is the ability of the algae to move with light as the stimulant. The algal genera identified in the model ponds would tend to reside in stratified layers to optimize the amount of radiation which they received. It was noted in an earlier section of this report that stratified layers were visually apparent.

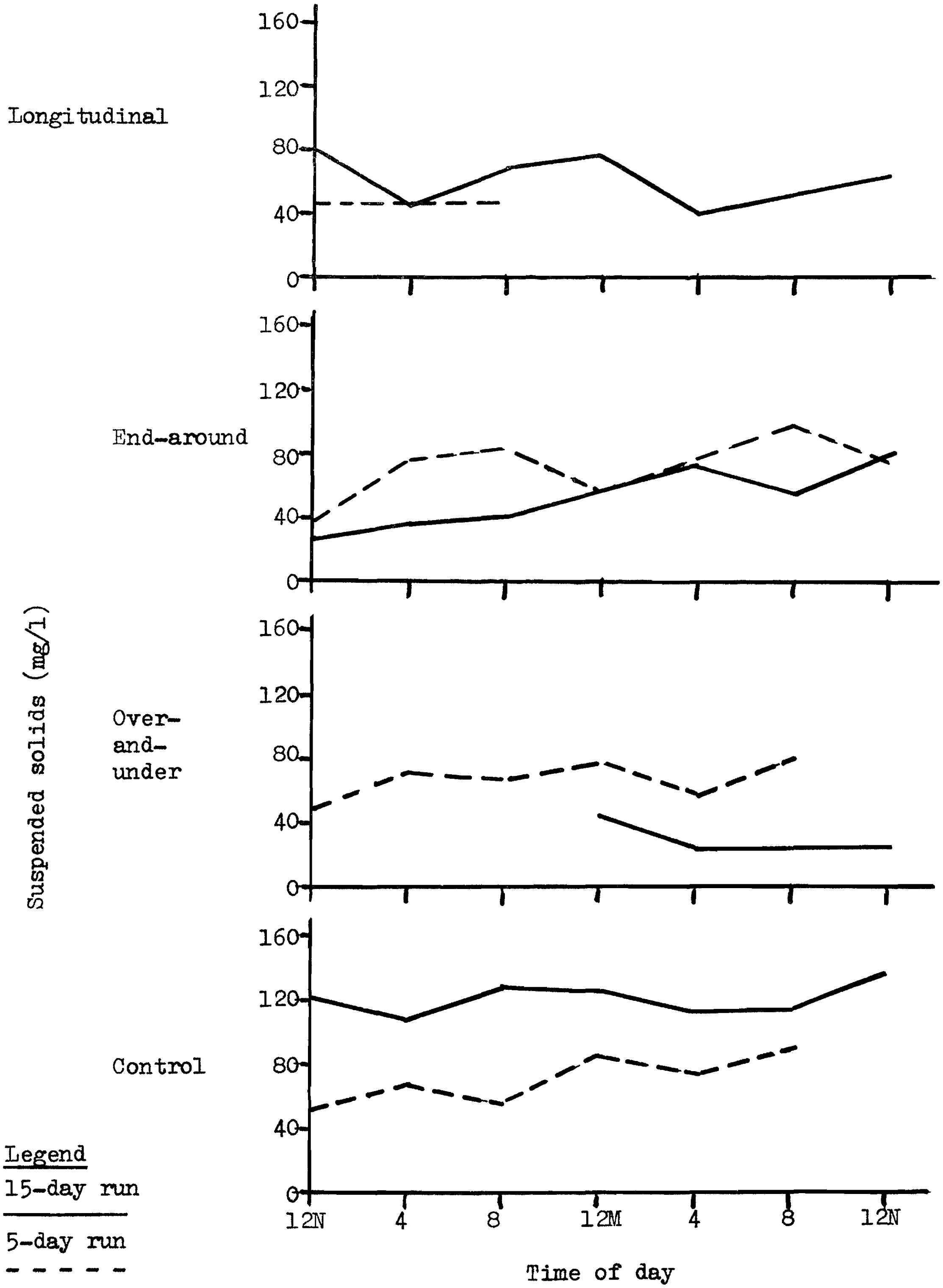


Figure 10. Diurnal variation of suspended solids concentration in the effluent of the model ponds during the 15-day and 5-day runs.

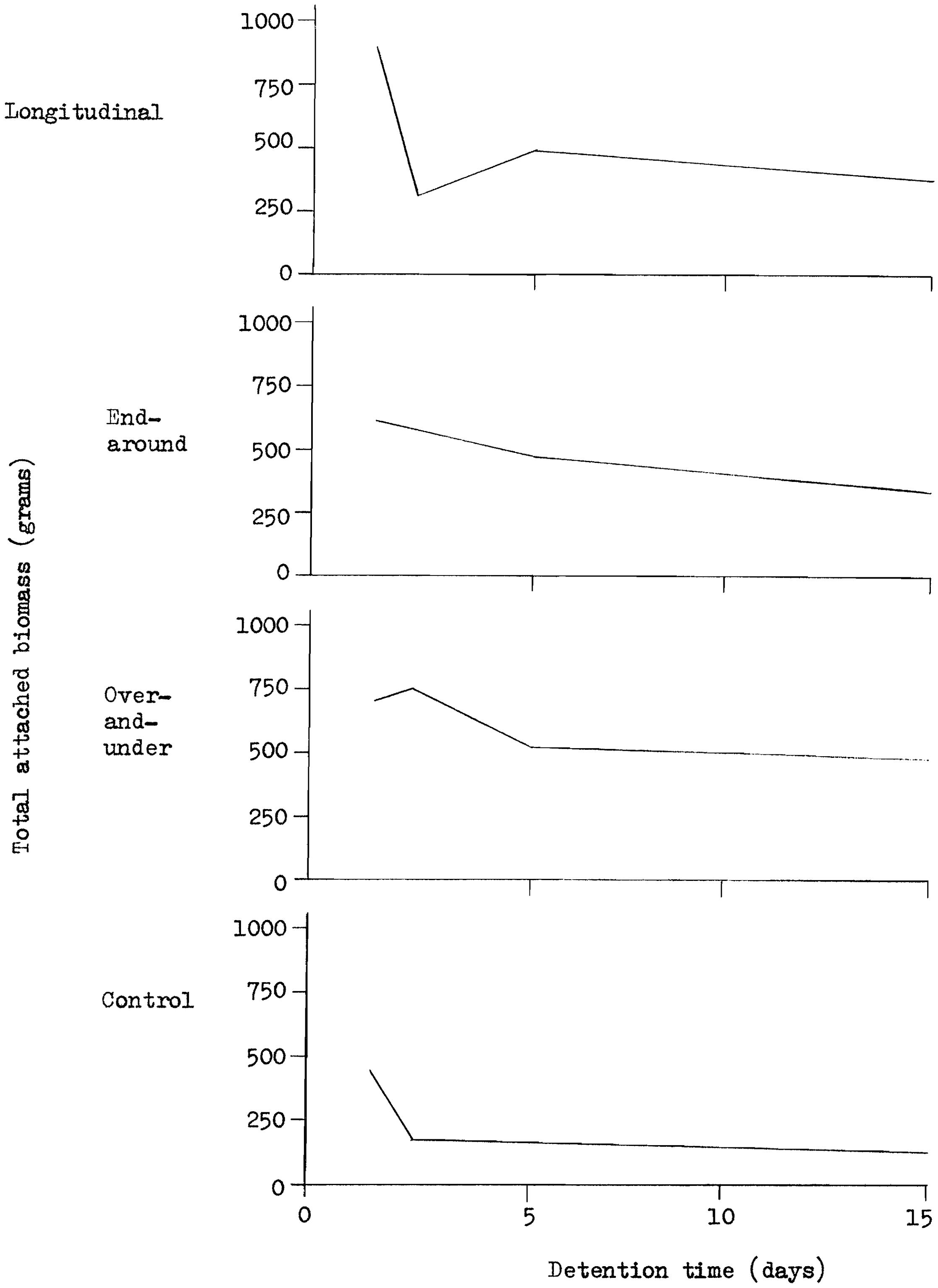


Figure 11. Total attached biomass in the model ponds at various detention times.

The model ponds were completely devoid of dissolved oxygen throughout the entire experiment. In the presence of a high organic load these algae could obtain energy from heterotrophic utilization of acetate and thus not produce oxygen.

Alkalinity, pH, and free carbon dioxide

Daily, average values for alkalinity in the ponds ranged from 214 mg/l to 257 mg/l, measured as $CaCO_3$. The average values of alkalinity during the various detention times are shown in Figure 12. Typical domestic sewage has an alkalinity of approximately 100 mg/l, measured as $CaCO_3$ (32). The high alkalinities observed during this study were caused by the local tap water which has an alkalinity of 200 mg/l, the characteristics of the synthetic waste, and biological reactions.

Diurnal fluctuations of alkalinity were monitored during the 15-day run and the 5-day run, and variations were not detectable.

Daily, average values of pH in the ponds ranged from 7.31 to 6.74. Average values of effluent pH for various detention times are shown in Figure 13. The pH was not affected by the baffles.

Diurnal fluctuations of pH were monitored during the 15-day run and the 5-day run. No significant variations were detected. The absence of a diurnal variation of pH was due to the high buffering capacity of the pond liquor.

The concentrations of free carbon dioxide in the pond effluents were measured during both the 15-day run and the 5-day run. Average, diurnal values for free carbon dioxide concentration ranged from 34 mg/l to 93 mg/l, as CO_2. The presence of free CO_2 indicates that algal photosynthesis was not the dominant mechanism of algal growth and indicated the heterotrophic nature of their growth.

Diurnal fluctuations of effluent, free carbon dioxide are shown in Figure 14. Variations occurring in the baffled ponds were somewhat erratic, possibly due to experimental error

The concentration of carbon dioxide in the control pond was relatively constant during the light cycle; however, when the lights were turned off at 8:00 p.m., an increase in the concentration of carbon dioxide was observed. This increase probably resulted from decreased photosynthetic activity of the organisms. Increased carbon dioxide concentrations, during periods of darkness, indicated that a portion of the organisms were photoassimilating organic matter (36).

Odor

During this experiment, the odors emitted from the model ponds could be detected at a distance no further than a few feet away. Other investigators (36,43) have reported that odors emitted from anaerobic ponds with similar organic loadings were highly offensive. Odors associated with the treatment of wastewater are generally caused by hydrogen sulfide and certain organic gases which are produced during the anaerobic digestion of organic matter (34).

The dark-pink coloration observed with the attached biomass in the model ponds was thought to have been purple-sulfur bacteria. *Thiorhodacae* are a purple-sulfur bacteria that can reduce hydrogen sulfide gas, in the presence of light, to elemental sulfur. *Thiorhodacae* may have been present in the attached biomass and actively reducing hydrogen sulfide gas. Because hydrogen sulfide can be reduced by photosynthetic bacteria, baffles in a pond could provide a surface which would permit large populations of these bacteria to reside in the photosynthetic zone of the pond and reduce the amount of odorous gases escaping to the atmosphere.

Effects of floating material

The model ponds used in this study were also used by Reynolds (37) in an earlier study. Reynolds installed scum baffles, upstream from the effluent weirs, to retain any floating material in the ponds. At the beginning of this study, the scum baffles were removed and any floating material that began to accumulate was removed on a daily basis. The amounts of floating materials removed are reported in Table 3.

Similar environmental conditions, synthetic substrate, hydraulic loading rates, and organic loading rates were employed in both studies. However, the performance of the ponds was dramatically affected by the accumulation of scum.

When the ponds were operated with scum baffles, large quantities of floating materials accumulated on the surfaces on the ponds. The amount of floating materials ranged from 55 grams to 154 grams per pond (37). The floating materials formed a dense layer of scum that covered most of the liquid surface. As a result of the scum layer, light penetration into the liquid and gas transfer across the liquid-air interface were restricted.

An average pH value of 7.0 was maintained while operating the ponds without scum baffles. When the ponds were operated with scum baffles, the pH value averaged about 6.0. The lower pH value was probably due to an accumulation of carbon dioxide which was trapped beneath the layer of scum.

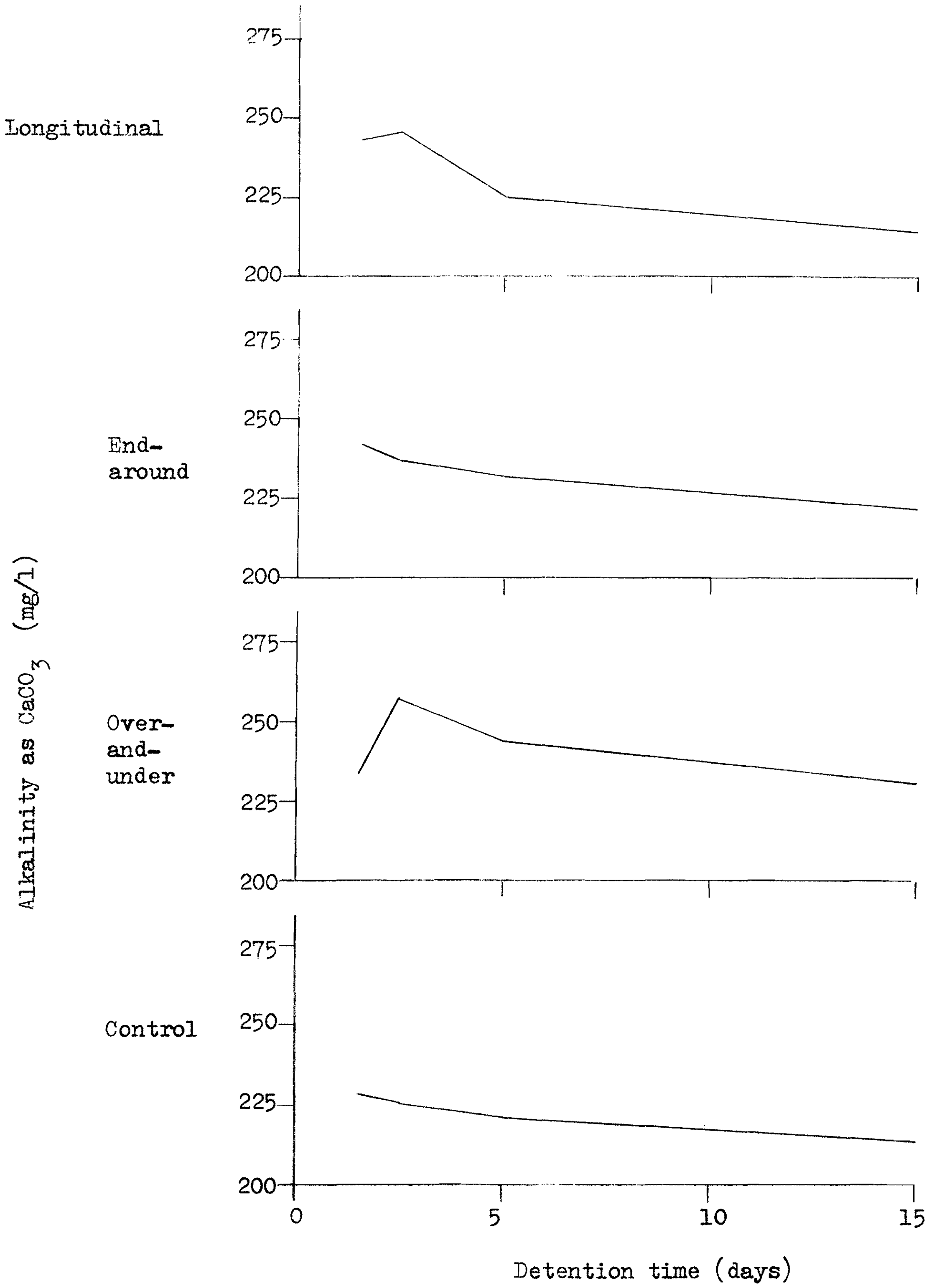


Figure 12. Alkalinity in the effluent of the model ponds for various detention times.

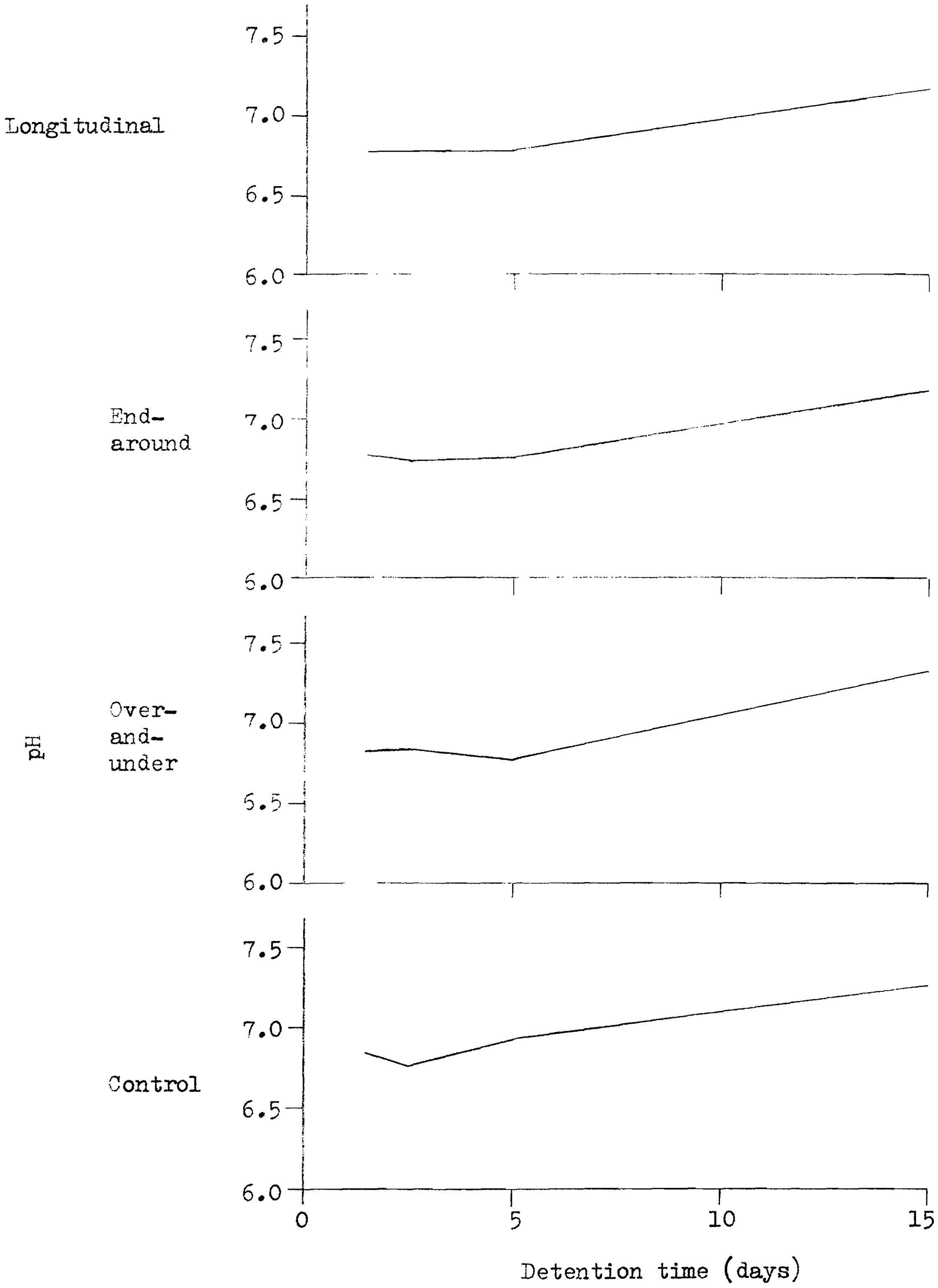


Figure 13. pH of the effluents of the model ponds for various detention times.

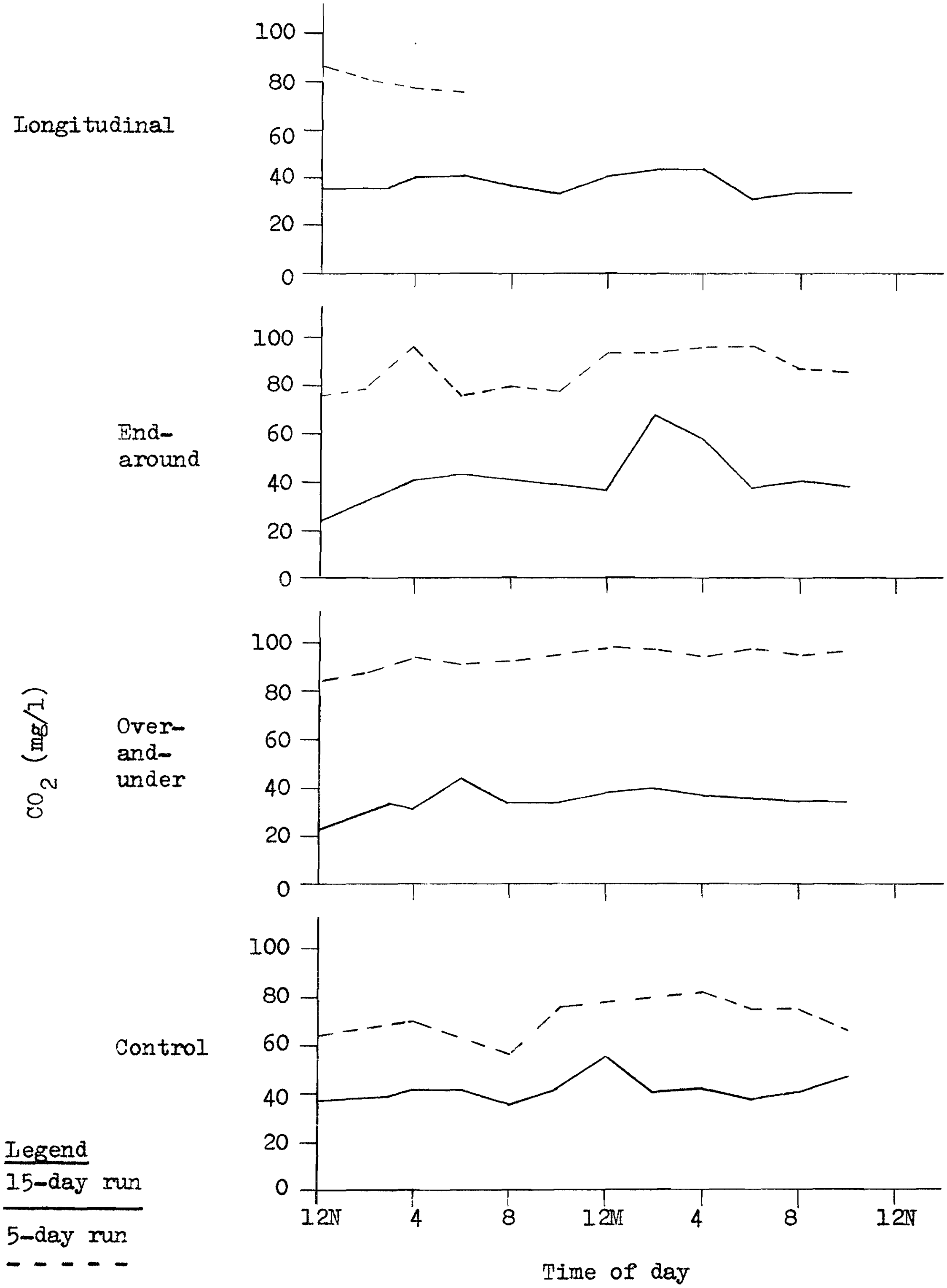


Figure 14. Diurnal variations of free carbon dioxide in the effluent of the model ponds during the 15-day and 5-day runs.

An average alkalinity of about 235 mg/l expressed as $CaCO_3$, was maintained during operation of the ponds with and without scum baffles. The alkalinity of the pond liquid resulted from the characteristics of the synthetic substrate which was similar in both cases.

Percentages of soluble, organic carbon removal for both operating conditions are shown in Figure 15 Removal of soluble, organic carbon ranged from 81 percent to 93 percent while operating the ponds without scum baffles. When the ponds were operated with scum baffles, removal of soluble, organic carbon ranged from 42 percent to 69 percent. The lower organic carbon removals probably occurred because of the exclusion of light by the scum layer

When the ponds were operated without scum baffles, the concentration of effluent suspended solids ranged from 31 mg/l to 120 mg/l. The concentration of effluent suspended solids were lower when the ponds were operated with scum baffles because the baffles restricted movement of the solids into the effluent and the dense layer of scum retarded the growth rate of suspended biomass. Figure 16 shows a comparison of effluent suspended solids for various detention times.

The mass of attached solids, during both phases of pond operation, are shown in Figure 17. When the ponds were operated without scum baffles, the mass of attached solids ranged from 155 grams to 515 grams. The mass of attached solids ranged from 33 grams to 78 grams when the ponds were operated with scum baffles. The lower mass of attached solids was probably a result of the exclusion of light indicating that photosynthesis was a more important factor in this study and that it may have been involved in the higher treatment efficiencies.

When the ponds were operated with baffles at a hydraulic detention time of 2.5 days, a serious odor problem resulted. When the ponds were operated without scum baffles under similar loading rates, there were no problems with odors. The dense layer of scum prevented odor reduction by any purple-sulfur bacteria because light penetration was restricted. Also, less removal of organic matter would have allowed partially decomposed matter to escape as gases when the ponds were operated with scum baffles.

In summary, the dense layer of scum lowered the growth rate of organisms which reduced the rate of organic carbon reduction by preventing the light from penetrating to the organisms. Odor emission from the ponds that had a layer of scum was greater than the ponds without the scum because photosynthetic activity was decreased and organic matter was not reduced as completely.

In many anaerobic ponds, a dense layer of scum is encouraged to insure anaerobic conditions, retain heat, and trap odorous gases (3,7,19). Excluding the provision for heat, the results of this comparison indicate that an anaerobic pond will perform better if no scum layer is permitted.

Hydraulic performance of the over-and-under pond

Generally, effluent suspended solids discharged from the over-and-under pond were lower than the other ponds. The over-and-under baffle configuration tended to limit the amount of effluent suspended solids by trapping the floating material and improving the sedimentation and flotation of suspended solids.

The over-and-under baffles formed physical restrictions, similar to scum baffles, which prevented much of the movement of floating material. However, this condition tended to form a layer of scum which necessitated the removal of the entrapped material to obtain satisfactory carbon removal.

Both sedimentation and flotation were probably accelerated in the over-and-under pond because the gentle up-and-down flow promoted flocculation and coagulation of the suspended solids.

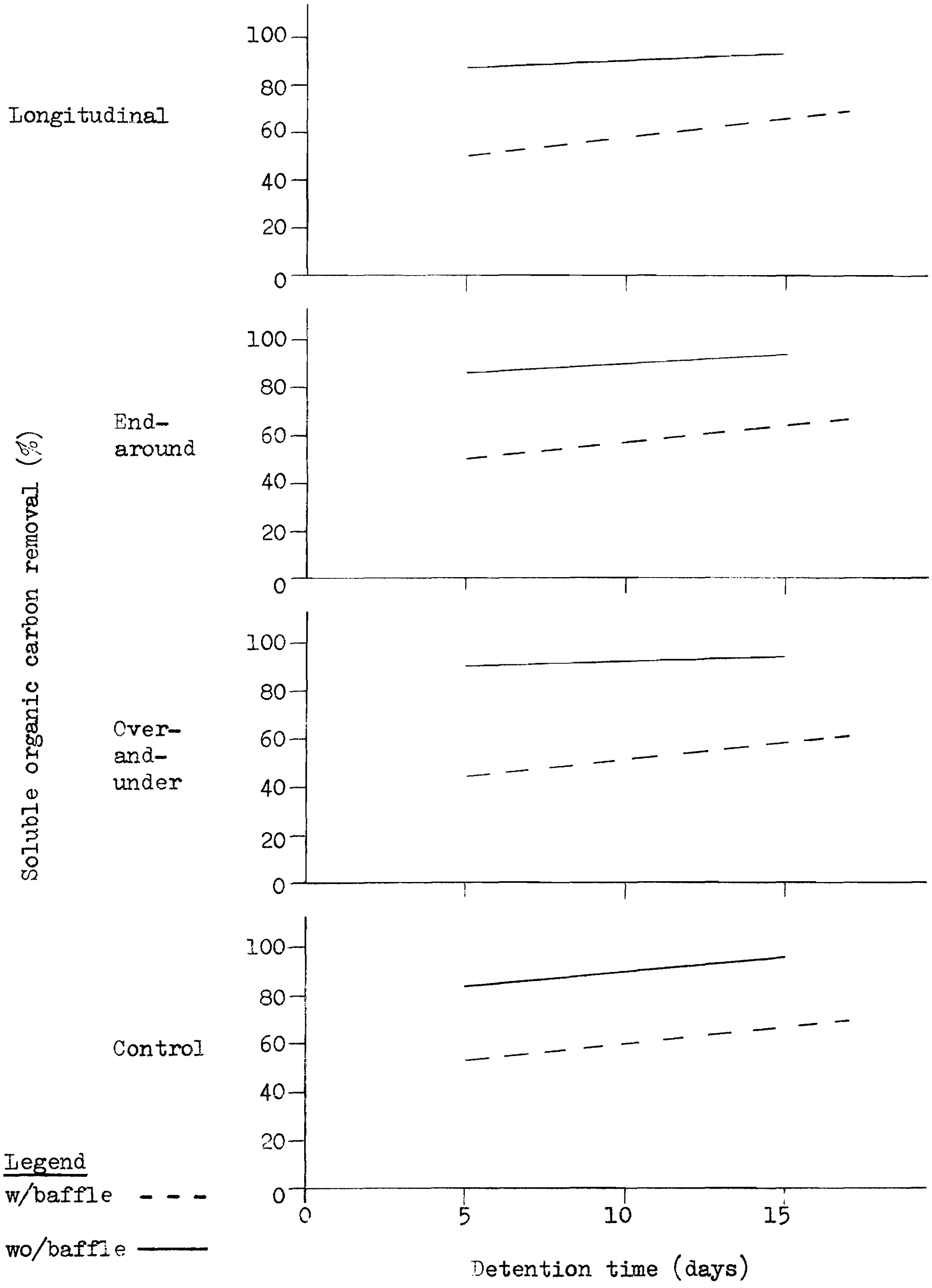


Figure 15. Effects of scum baffles on the percent of the soluble organic carbon removal for various detention times. After Reynolds (37).

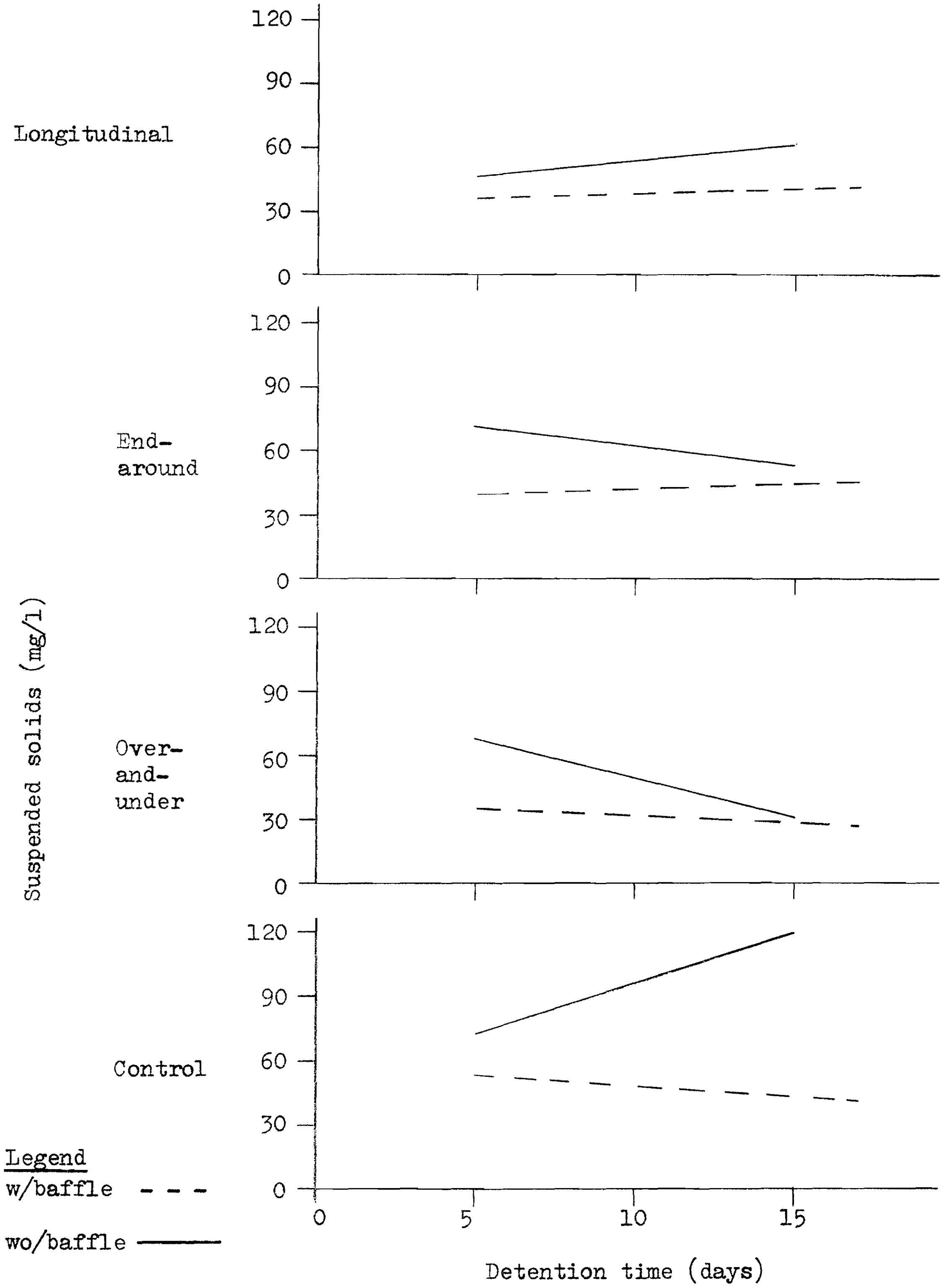


Figure 16. Effects of scum baffles on the concentration of effluent suspended solids for various detention times. After Reynolds (37).

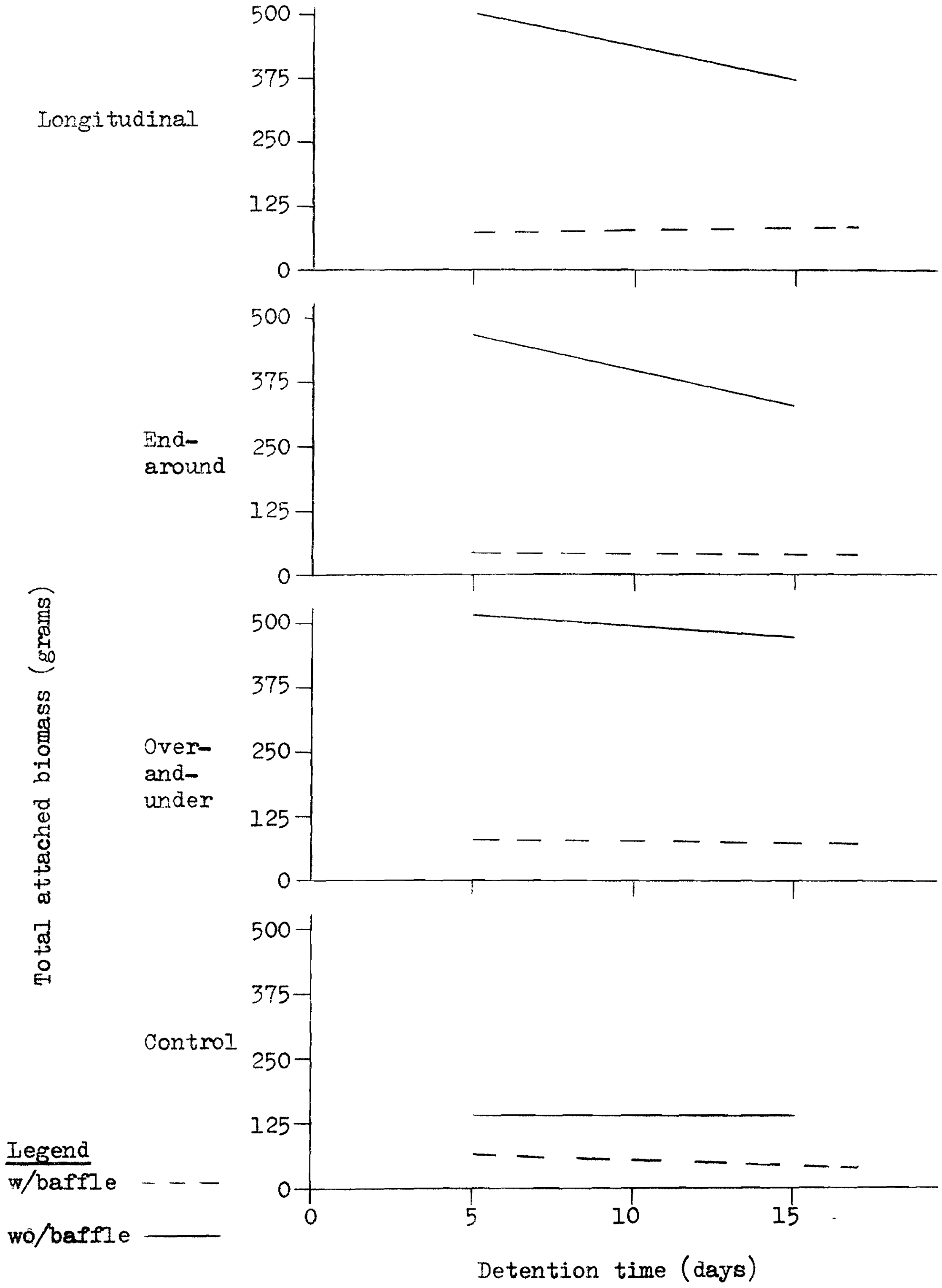


Figure 17. Effects of scum baffles on the total attached biomass for various detention times. After Reynolds (37).

THEORETICAL ANALYSIS OF RESULTS

An unbiased analysis of the operation of the individual ponds requires the use of some theoretical framework for interpreting the results. The results show that a variation in organic carbon removal due to baffling configuration occurs and this variation is a function of detention time. Thus, it appears that mixing phenomena and/or growth kinetics are involved in removal. By using specific models in interpreting the results, specific design parameters which could be applied to practical design problems can be determined and applied to the actual situations of BOD removal from municipal sewage.

Marias-Shaw model

The kinetic parameter of the Marias-Shaw mathematical model was computed using the mean steady-state values of the data obtained for influent and effluent organic carbon concentration and hydraulic detention time (Tables A-1 through A-8). The data shown in Table 6 were used in evaluating the linear form of the Marias-Shaw model developed in an earlier section of this report. The equation is:

$$\frac{S_o - S_1}{\theta} = KS_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

The biological degradation rates, K, for each of the baffled systems are represented by the slopes of the linear regression equations shown in Figure 18.

The unbaffled control model pond had a biological degradation rate of 0.815/day which was obtained from the regression equation having a correlation coefficient of 0.994.

The over-and-under baffled model pond had a biological degradation rate of 1.011/day and the correlation coefficient for the regression equation was 0.997. The slopes of the regression equations obtained from the over-and-under pond and the control pond were compared statistically and a significant difference between the two slopes existed at the 5 percent level. Therefore, a 25 percent increase in the reaction rate constant was produced by incorporating over-and-under baffles in the model pond.

Table 6. Average values of data used to evaluate the kinetic models.

Model Pond	Detention Time, θ (Days)	Influent Substrate Concentration, S (mg/l)	Effluent Substrate Concentration, S (mg/l)	Suspended Biomass, X (mg/l)	Attached Biomass, M (Grams)	Volume of Reactor, V (Gallons)
Control	15.0	199.9	19	120	111.23	200
	5.1	202.4	34	71	140.23	200
	2.4	192.3	65	57	199.16	200
	1.4	211.3	98	70	452.42	200
Over & Under	14.8	197.7	13	31	478.14	200
	4.8	191.1	18	68	516.33	200
	2.5	197.4	52	66	750.19	200
	1.5	220.6	86	66	701.52	200
Longitudinal	15.3	203.8	12	61	374.36	200
	5.0	199.9	26	47	498.09	200
	2.6	206.3	43	63	316.41	200
	1.5	219.3	68	81	881.41	200
End-around	15.0	200.2	12	53	337.89	200
	4.9	195.1	27	73	470.51	200
	2.5	201 4	39	55	572.27	200
	1.4	211.9	84	80	603.20	200

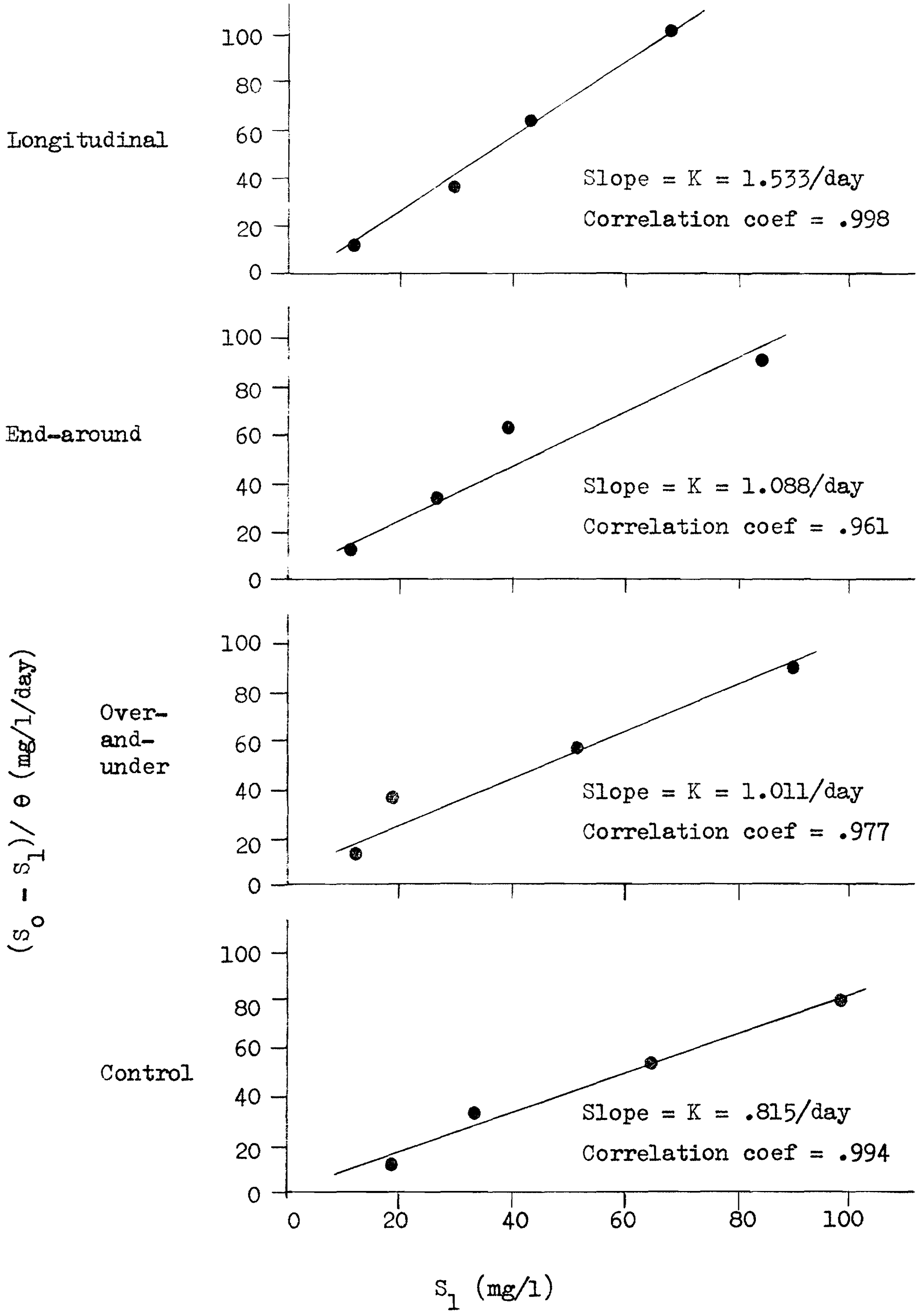


Figure 18. Determination of the biological degradation rate for the model ponds.

The end-around baffled model pond had a biological degradation rate of 1.088/day which was obtained from the regression equation having a statistical correlation coefficient of 0.961. The slope of the regression equation was compared to the control pond and a significant difference between the two slopes was found to exist at the 5 percent level. End-around baffles increased the degradation rate in the model wastewater treatment ponds by 34 percent.

The highest biological degradation rate determined with the Marias-Shaw model occurred in the longitudinal baffled model pond. A rate of 1.533/day was obtained from the regression equation which had a statistical correlation coefficient of 0.998. A statistical comparison of the performance of the longitudinal baffled system with the control pond showed the slopes of the two regression equations were significantly different at the 5 percent level. Expressed as a percentage increase, the longitudinal baffle configuration increased the biological degradation rate by as much as 88 percent.

A direct comparison between the degradation rates obtained from the various baffle configurations and the control pond is meaningful because all the baffled model ponds contained equal submerged surface areas. Thus, the materials required for construction would be approximately the same for all the baffle configurations tested in this study However, an economic comparison of the baffled systems and the control may offset the advantages produced by the increased reaction rates.

Statistically, the biological degradation rates obtained from the over-and-under pond and the end-around pond were not significantly different at the 5 percent level. However, the degradation rate obtained from the longitudinal model pond was found to be statistically different when compared to the other baffled model ponds, again at the 5 percent level of significance. Therefore, it appears that based on the Marias-Shaw model, performance in ponds is improved most by simply directing the flow so that better mixing of the influent is obtained.

The longitudinal arrangement of baffles induced the highest biological degradation rate and was therefore considered the optimum configuration for the reduction of organic carbon. However, caution should be exercised in selecting a baffle configuration solely on the basis of organic carbon removal, because other factors could affect the overall performance of the waste pond.

The degradation rate is inversely proportional to detention time, as shown by Equation 8. Therefore, increasing the degradation rate with the use of baffles decreases the land area required to degrade the same quantity of organic carbon in a larger, conventional pond. Feasibility of using baffles in wastewater treatment ponds would become a matter of engineering economy by which the costs of land and excavation are compared to the costs of installing and maintaining the baffles. A summary of the kinetic parameters and a relative comparison of the model ponds are given in Table 7.

The biological degradation rates obtained in this study were much higher than those reported in the literature. Marias (26) reported that a degradation rate of approximately 0.17/day could be anticipated for treatment of municipal sewage in a facultative pond. Eckenfelder and Ford (12) reported a degradation rate of 0.16/day for treatment of a chemical waste in a facultative model pond and 0.0216/day for anaerobic treatment of the same waste in a similar pond. The principal cause for the unusually high degradation rates obtained in this study was presumed to have been a result of the synthetic waste. The significance of the degradation characteristics of the synthetic waste was discussed in the Results and Discussion section.

Monod kinetic model

The Monod kinetic parameters were computed using the same data employed with the Marias-Shaw model (Tables A-1 through A-8) and the value for the attached and suspended biomass (Tables A-19 through A-22). These data are summarized in Table 7.

The decay rate and yield constant were determined by using Equation 24:

Table 7. Summary of the kinetic parameters determined by the Marias-Shaw model and a relative comparison of the model ponds.

Parameter	Model Pond Control	Over-and-under	End-around	Longitudinal
Degradation rate, day^{-1}	0.815	1.011	1.088	1.533
Correlation Coefficient For Regression Equation	0.994	0.977	0.961	0.998
Degradation Rate ratio	1.000	1.250	1.340	1.880
Required land area[a]	1.000	0.800	0.750	0.530

[a] Calculated as the inverse of the rate constant.

$$\frac{S_o - S_1}{X_1} = \frac{k_d}{Y}\,\theta\left[1 + \frac{\phi M}{VX_1}\right] + \frac{1}{Y} \quad \ldots\ldots(24)$$

The slope of Equation 24 is k_d/Y and the intercept is $1/Y$. Graphical solutions to determine these parameters are shown in Figure 19.

Having determined k_d, the maximum growth rate and K_s can be obtained from Equation 25.

$$\frac{\theta\left[1 + \frac{\phi M}{VX_1}\right]}{1 + \theta\left[1 + \frac{\phi M}{VX_1}\right]k_d} = \left(\frac{K_s}{\hat{\mu}}\right)\frac{1}{S_1} + \frac{1}{\hat{\mu}} \quad \ldots\,(25)$$

The slope f Equation 25 is $K_s/\hat{\mu}$, and the intercept is $1/\hat{\mu}$. Plots of the experimental values to determine the kinetic parameters are shown in Figure 20.

The control model pond had a yield constant of 0.42 and a specific organism decay rate of -0.01/day which was obtained from the regression equation having a statistical correlation coefficient of 0.510. A negative specific decay rate is not physically possible; however, the value is small enough that it can be considered zero. Assuming k_d to be zero and solving Equation 25 graphically, the data do not appear to even approximate a description of the control pond. All four detention times yield values that apparently represent only one point in the equation. Perhaps this indicates that the difference in biomass introduced by the difference in baffling surface area controls the performance of the ponds.

The over-and-under baffled model pond had a yield constant of 0.571 and a specific organism decay rate of 0.0076/day which was obtained from the regression equation having a statistical correlation coefficient of 0.997. A maximum growth rate of 0.152/day and a K_s of 143.6 mg/l were obtained from the second regression equation which had a statistical correlation coefficient of 0.888.

The end-around baffled pond had a yield constant of 0.546 and a specific organism decay rate of 0.0070/day which was obtained from the regression equation having a statistical correlation coefficient of 0.838. A maximum growth rate of 0.154/day and a K_s of 120.9 mg/l was obtained from the second regression equation which had a statistical correlation of 0.997.

The longitudinal pond had a yield constant of 0.443 and a specific organism decay rate of 0.0039/day which was obtained from the regression equation having a statistical correlation coefficient of 0.630. A maximum growth rate of 0.237/day and K_s of 253.5 mg/l was obtained from the second regression equation which had a statistical correlation coefficient of 0.958.

A statistical comparison of the slopes of both regression equations (Equation 24) for all the model ponds showed no difference at the 5 percent level of significance. Apparently the Monod model is not sensitive enough to detect differences between the baffling arrangements, or there is little difference between the biological populations in the systems. A comparison of the kinetic parameters obtained for the model ponds is shown in Table 8.

Table 8. Summary of the kinetic parameters of the model ponds obtained from the Monod model.

Model Pond	$\hat{\mu}$ day^{-1}	K_s mg/l	k_d day^{-1}	Y mg/mg	Correlation coefficient
Control	—	—	—	.418	.510
Longitudinal	.237	253.5	.0039	.443	.630
End-around	.154	120.9	.0070	.546	.838
Over-and-under	.152	143.6	.0076	.571	.997

The kinetic parameters obtained from the Monod model appeared reasonable, and perhaps higher correlation coefficients could have been obtained for all the ponds if additional hydraulic detention times and more accurate solids sampling techniques were employed.

The Monod model did not appear to provide valid kinetic parameters for the control pond. This was probably due to the low ratio of attached organisms to suspended organisms.

Although the correlation coefficients for the Marias-Shaw model were better than for the Monod model, indicating better "goodness-of-fit," the Monod model coefficients give additional information of considerable interpretive and speculative value. The decay coefficients (k_d) were typical of extended aeration plants and essentially zero. The yield coefficients (Y) indicate the approximate carbon composition of the cells (42 - 57 percent), values which are reasonable in light of typical analyses of microbial populations. Although the saturation coefficients (K_s) were quite high, they are not totally unreasonable and indicate the order of magnitude effect of organic carbon on the microbial population growth. The magnitude of K_s indicates some of the difficulty of evaluating the growth kinetics of mixed heterotrophic-photosynthetic populations and further suggest that algal communities which develop under anaerobic conditions and perform heterotrophic functions, do not utilize organic carbon substrates as efficiently as a bacteria dominated community, e.g. activated sludge communities. The rather high observed maximum specific growth rates ($\hat{\mu}$) as compared to most anaerobic ponds is probably related to the synthetic waste being more easily degraded than typical wastes. However, this observation may be related to the same phenomena discussed in reference to K_s.

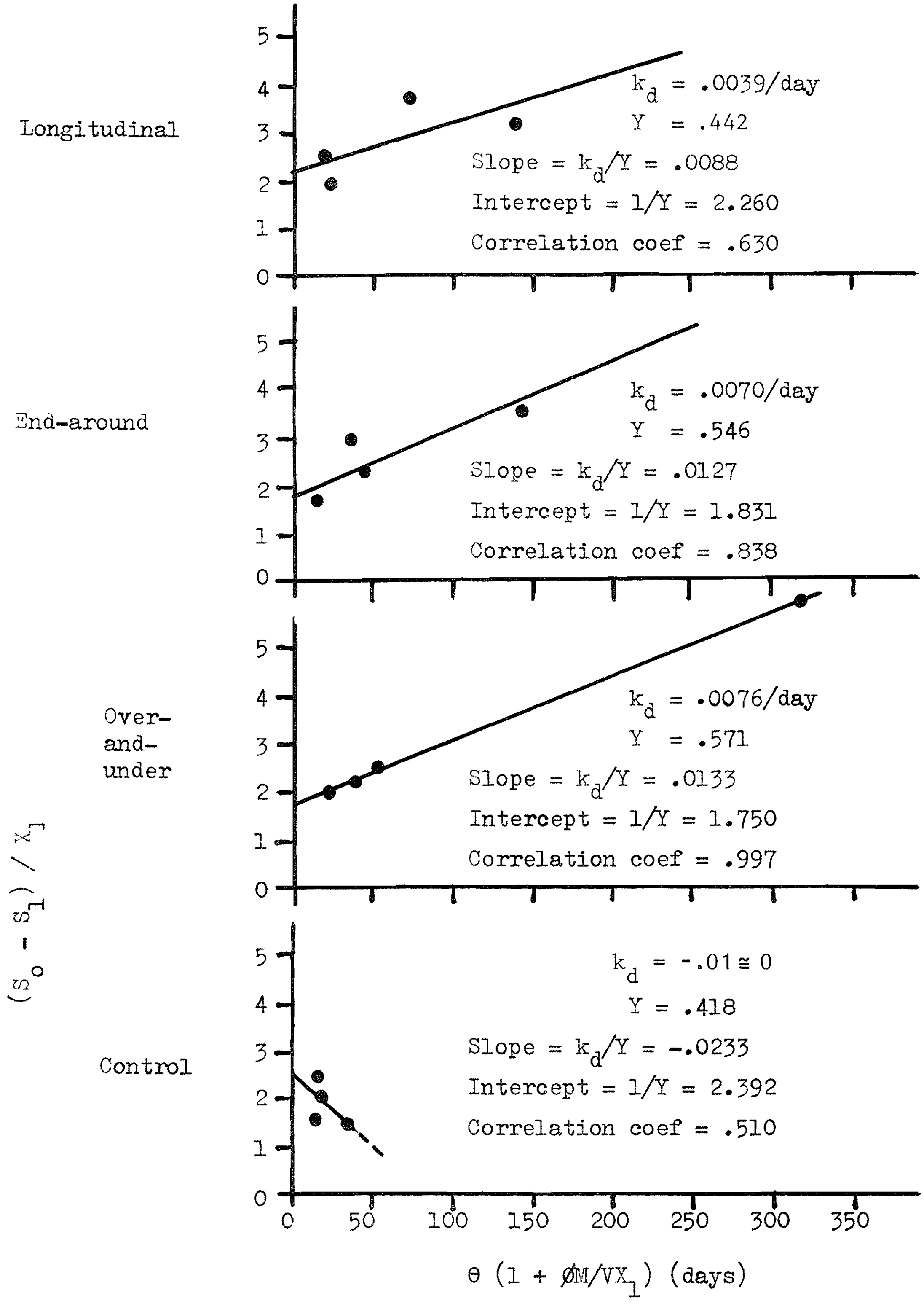


Figure 19. Determination of specific organism decay rates and yield constants for the model ponds.

Plug-flow kinetic model

Successful application of both the Marias-Shaw and the Monod kinetic models were developed assuming that the systems were completely mixed. The plug-flow kinetic model was developed to determine if the model ponds approximated plug-flow.

The kinetic parameters for the plug-flow mathematical model were computed using the data summarized in Table 7.

The plug-flow degradation rates were determined by using Equation 28.

$$\ln \frac{S_o}{S_l} = k\theta \left(X_l + \frac{\phi}{V} M\right) \quad \ldots\ldots\ldots\ldots (28)$$

The slope of Equation 28 represents the plug-flow degradation rate. Graphical solutions to determine the plug-flow degradation rates for the model ponds are shown in Figure 21.

The control model pond had a plug-flow degradation rate of 0.00023 l/mg-day obtained from the regression equation having a statistical correlation coefficient of 0.878. A value of 0.00011 l/mg-day was obtained for the over-and-under baffled model pond, and the correlation coefficient was 0.863. The end-around baffled model pond plug-flow degradation rate of 0.00015 l/mg-day was obtained from a regression equation having a statistical correlation coefficient of 0.930. A plug-flow degradation rate of 0.00012 l/mg-day was obtained for the longitudinal baffled model pond, and the corresponding correlation coefficient was 0.895. Table 9 is a summary of the statistical and kinetic parameters obtained for the model ponds using the plug-flow mathematical model.

Table 9. Summary of the kinetic parameters of the model ponds obtained from the plug-flow mathematical model.

Model Pond	k l/mg-day	Correlation coefficient
Control	.000227	.878
Over-and-under	.000109	.863
End-around	.000150	.930
Longitudinal	.000123	.895

A statistical comparison between the slopes of the regression equations obtained for the control pond and each of the baffled ponds showed that no significant difference existed between the degradation rates of any of the model ponds at the 5 percent level.

Further statistical analysis of the slopes of the regression equations showed that the slopes were not significantly different from zero at the 5 percent level. A zero slope would indicate that the plug-flow degradation rate was zero. Therefore, it appears that the performance of the model ponds is more closely approximated by a completely mixed model.

Completely mixed conditions probably resulted from the intermittent hydraulic dosing of influent to the ponds. The influent pumps were operated from 28 seconds/hour to 230 seconds/hour for the 15- and 1.5-day detention times, respectively. Visual observations indicated that this pumping schedule imported adequate energy to the pond liquid to provide substantial mixing in all of the baffle arrangements. Therefore, it was not surprising that a completely mixed model more closely described the performance kinetics. The intermittent dosing prevented the establishment of steady-state hydraulic conditions which would have tended to produce plug-flow (23,25).

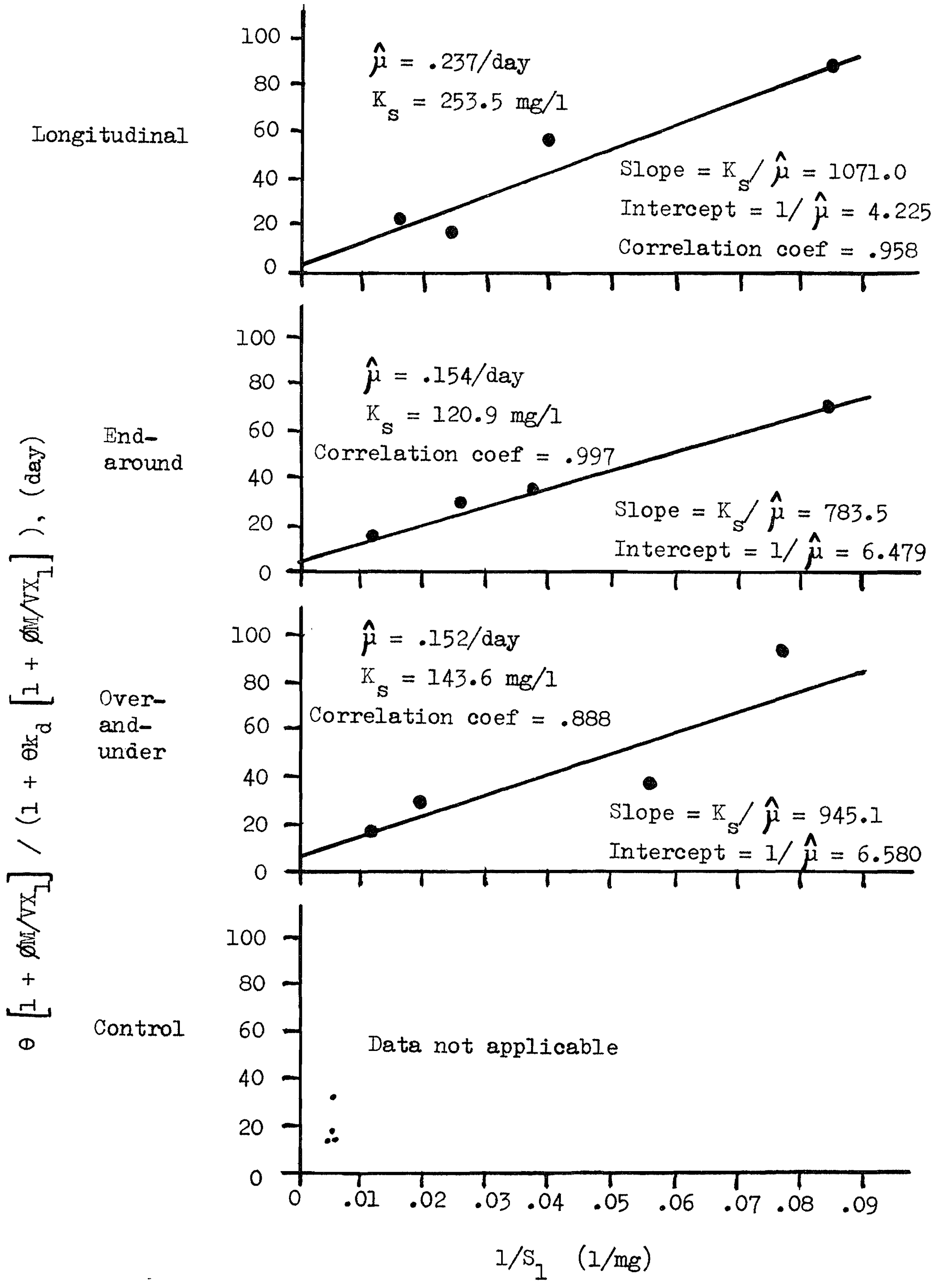


Figure 20. Determination of maximum growth rate and K_s for the model ponds.

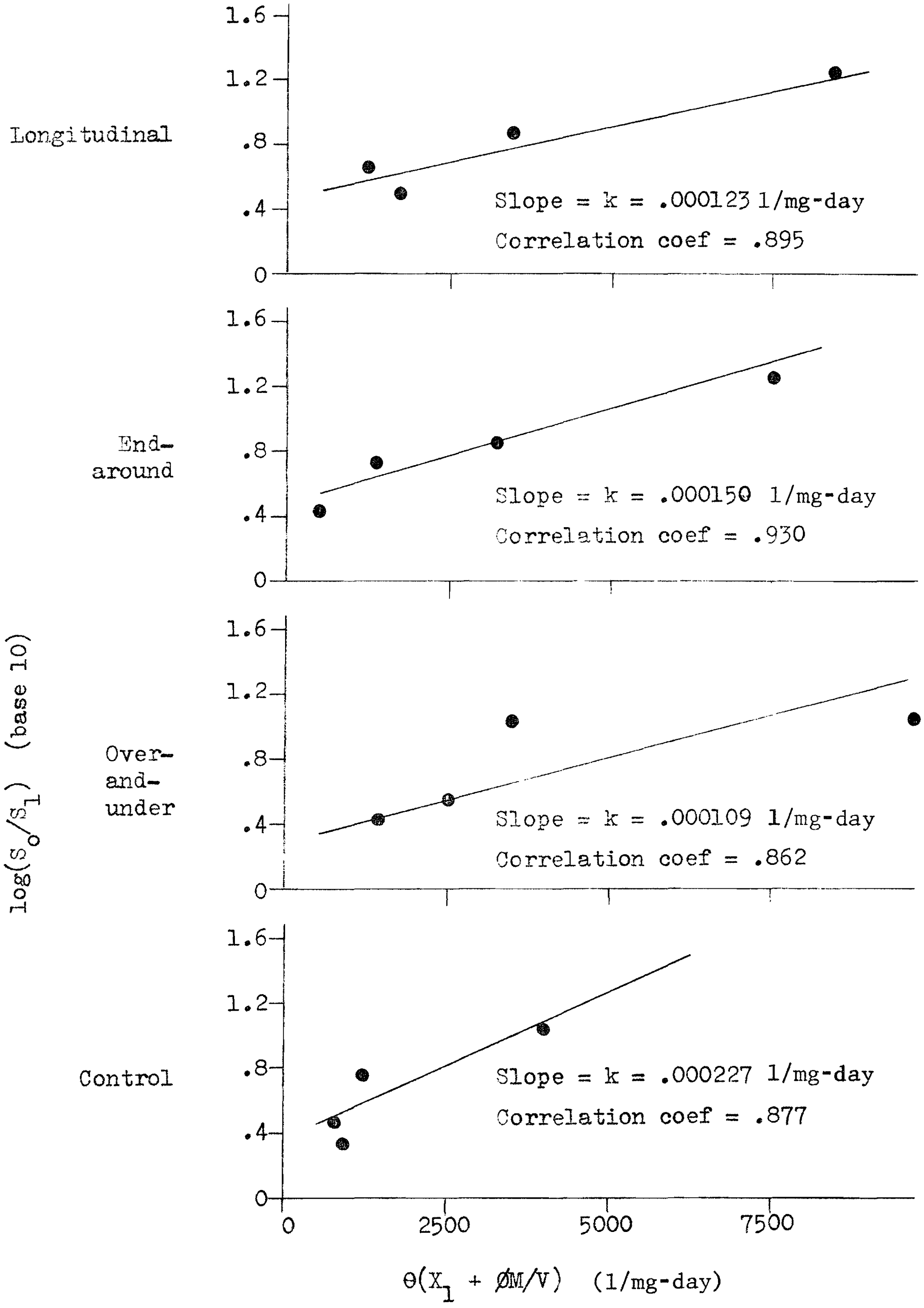


Figure 21. Determination of the plug-flow degradation rates.

CONCLUSIONS

Based on the analysis of the results of the study, the following conclusions and observations seem justified at this time:

Pond operational variables

1. All of the ponds remained completely anaerobic during the study period.
2. The synthetic waste used in this study was more biodegradable than a typical municipal sewage.
3. The growth rate of suspended biomass was apparently reduced by the effect of competitive growth of attached biomass.
4. The mass of attached biomass was a function of both baffle configuration and the submerged surface area.
5. Suspended biomass was subject to increased washout at higher hydraulic loading rates. During higher hydraulic loading rates attached solids were substantially increased.
6. Algae identified in the ponds were typical of algal genera observed in actual operating anaerobic and facultative waste stabilization ponds.
7. Organisms capable of reducing odorous gases were present on the baffle surfaces in the photosynthetic zone of the ponds.
8. A dense layer of scum on the surface of the pond liquid apparently increases the odorous gases emitted from the pond.
9. A dense layer of scum on the surface of the pond liquid decreased the kinetic rate of biodegradation, the pH of the liquid, and the amount of effluent suspended solids.
10. The hydraulic characteristics of the over-and-under pond increased the rate of sedimentation and flotation of suspended solids; however, the floating materials were trapped between the baffles and had to be removed.
11. Diurnal studies of pH, alkalinity, free carbon dioxide, and organic carbon concentrations indicated that very little diurnal variation occurred. A small amount of free carbon dioxide variation was ascribed to photosynthetic activities.
12. Although removal of organic carbon for the different pond configurations varied from about 94 - 98 percent at the longest detention time (15 days), a considerable effect of baffling was observed at the lower detention times. At 1.5 days the percent removal was 53 percent, 60 percent, 62 percent, and 70 percent for the control, end-around, over-and-under, and longitudinal, respectively. This observation is reflected in the analysis of the kinetic models (see below).

Analysis of kinetic models

1. Direct comparisons with the performance parameters of the model ponds appear valid for analysis of the three kinds of models, i.e., Marias-Shaw model, Monod model, and the plug-flow model.
2. Although both the Marias-Shaw and Monod models simulated the results quite closely, the Marias-Shaw model seemed most accurate for these experiments. However, different kinds of information are obtained from the Monod model which may be of value in interpreting the biological factors involved in pond treatment.
3. According to the Marias-Shaw model, biological degradation rates were significantly higher in the baffle ponds than in the control pond.
4. Of the different baffle configurations, the longitudinal provided the highest rate for reduction of soluble organic carbon concentrations.
5. If the kinetic constants determined for the model ponds are applicable to full-scale systems, a conventional pond without baffles would require almost twice the land area as a longitudinally baffled pond in order to produce an effluent of similar quality.
6. The analysis of the kinetic models indicated that performances of all ponds were similar to biological reactors that contained a homogeneous mixture of soluble substrate. Thus, the plug-flow model did not simulate the results very closely.
7. The performance of the ponds was described by a completely mixed model incorporating attached biomass, indicating that the assumption that growth rates of attached biomass and suspended biomass were reasonably equal was a tenable assumption; however, the performance of the control pond was not described by the completely mixed model.

RECOMMENDATIONS FOR FURTHER STUDIES

1. This study should be repeated using an actual municipal sewage as the influent substrate

2. A similitude study should be conducted to determine the scaling factors to better control the influence of hydraulic characteristics.

3. A similar study should be performed to determine the effects of baffles in facultative ponds.

LITERATURE CITED

1. Aquirre, J., and E. F. Gloyna. Waste stabilization pond performance. Technical report EHE-71-3 CRWR-77. The University of Texas. 1970. 141 p.

2. APHA. Standard methods for the examination of water and wastewater. 13th ed. American Public Health Association, Inc., New York. 1971. 874 p.

3. ASCE. Sewage treatment plant design. Manual of Engineering Practice No. 36. Fifth printing. 1972. 375 p.

4. ASCE and AWWA. Water treatment plant design. American Water Works Assoc., Inc., New York. 1969. 353 p.

5. AWWA. Water quality and treatment. McGraw-Hill Book Company. 1971. 654 p.

6 Beckman del 915 total organic carbon analyzer instructions 81706-A. Beckman Instrument Incorporated. Fullerton, California. 1968. 32 p.

7 Berend, A. Extra deep ponds. p. 450-456. *In* E. F. Gloyna and W. W. Eckenfelder (ed.). Water Resources Symposium No 1. Advances in Water Quality Improvement. 1968. 496 p.

8. Chiang, W. W. Biodegradation in waste stabilization ponds. Technical report. EHE-70-24 CRWR-74. The University of Texas. 1970. 41 p.

9. Coetzee. O. J., and N. A. Fourie. The efficiency of conventional sewage purification works, stabilization ponds respect to the survival of pathogenic bacteria and indicator organisms. Journal, Institute Sewage Purification 3:210-215. 1965.

10. Dildine, E. D., and J. R. Franzmathes. Current design criteria for oxidation ponds. p. 194-200. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

11. Dixon, W. J., and F. J. Massey. Introduction to statistical analysis. McGraw-Hill Book Company, New York. 1969. 638 p.

12. Eckenfelder, W. W., and D. L. Ford. Water pollution control. Jenkins Publishing Company, New York. 1970. 269 p.

13. Eppley, R.W., and F. M. Macaism. Rapid growth of sewage lagoon *Chlamydomonas* with acetate. Physiologia Plantarium 15(1):72-79. 1962.

14. Fair, M. G., J. C. Geyer, and D. A. Okun. Water and wastewater engineering. Vol. 2. John Wiley and Sons, Inc. 1968. 525 p.

15. Fitzgerald, G. P., and G. A. Rohlich. An evaluation of stabilization pond literature. Sewage and Industrial Wastes 30(10):1213-24. Oct. 1958.

16 Gann. J. D., R. E. Collier, and C. H. Laurence. Aerobic bacteriology of waste stabilization ponds. Journal Water Pollution Control Federation 40:185-191. 1968.

17. Gloyna, E. F. Basis for waste stabilization pond designs. p. 397-406. *In* E.F. Gloyna and W.W. Eckenfelder (ed.). Water Resources Symposium No. 1. Advances in Water Quality Improvement. 1968. 496 p.

18. Gloyna, E. F., and J. Aquirre. New experimental pond data. p. 200-210. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons, June 23-25, 1970, Kansas City, Missouri. 414 p.

19. Hammer, M. J., and C. D. Jacobson. Anaerobic lagoon treatment of packing house wastewater. p. 347-354. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

20. Hendricks, D. W., W. D. Pote, and J. G. Andrew. A thermodynamic analysis of a primary waste stabilization pond. Utah Water Research Laboratory/College of Engineering. Utah State University, Logan, Utah. 1970. 63 p.

21. Herbert, D. A theoretical analysis of continuous culture systems. p. 21-53. *In* Continuous culture of microorganisms, SCI Monograph No. 12. Society of Chemical Industry, London, England. 1961. 272 p.

22. Howe, C. O., A. P. Miller, and J. E. Etzal. Anaerobic lagooning—a new approach to treatment of industrial wastes. Engineering Bulletin of Purdue University, series 115:223-242. 1964.

23. Jensen, D. C. Baffling schemes to improve hydraulic efficiency of waste stabilization ponds. Unpublished Plan B Report. Utah State University Library, Logan, Utah. 1971. 26 p.

24. King, D. L., A. J. Tolmsoff, and M. J. Atherton. Effect of lagoon effluent on a receiving stream. p. 159-168. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

25. Mangelson, K. Hydraulics of waste stabilization ponds and its influence of treatment efficiency. Ph.D. Dissertation, Utah State University Library, Logan, Utah. 1971. 164 p.

26. Marias, G. V. R. Dynamic behavior of oxidation ponds. p. 15-46. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

27. McCarty, P. L. Anaerobic treatment of soluble wastes. p. 336-354. *In* E. F. Gloyna and W. W. Eckenfelder (ed.). Water Resources Symposium No. 1, Advances in Water Quality Improvement. 1968. 496 p.

28. McGarry, M. G., and M. B. Pescod. Stabilization pond design criteria for tropical Asia. p. 114-132. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

29. McGarry, M. G., and C. Tongkasame. Water reclamation and algae harvesting. Journal Water Pollution Control Federation 43(5):825-833. May, 1971.

30. McKinney, R. E. Microbiology for sanitary engineers. McGraw-Hill Book Company, Inc. 1962. 291 p.

31. McKinney, R. E. The role of chemically combined oxygen in biological systems. Journal Sanitary Engineer, Division ASCE, 82:944-1053. August, 1956.

32. Metcalf and Eddy, Inc. Wastewater engineering: collection, treatment, disposal. McGraw-Hill Book Company. 1972. 782 p.

33. Monod, J. The growth of bacterial cultures. Annual Review Microbiology. 3. Annual Reviews, Inc., Palo Alto, California. 1949.

34. Monod, J. The technique of continuous culture, theory and applications. Annual Institute Pasteur (France), 79, 390. 1950.

35. Nemerow, N. L. Baffled biological basins for treating poultry plant wastes. Journal Water Pollution Control Federation 41(9):1602-1612. 1969.

36. Oswald, W. J. Advances in anaerobic pond systems design. p. 409-426. *In* E. F. Gloyna and W. W. Eckenfelder (ed.). Water Resources Symposium No. 1. Advances in Water Quality Improvement. 1968. 496 p.

37. Reynolds, J. R. The effects of selected baffle configurations on the operation and performance of model waste stabilization basins. M.S. Thesis. Utah State University Library, Logan, Utah. 1971. 133 p.

38. Round, F. E. The biology of the algae. Edward Arnold Ltd., London. 1966. 242 p.

39. Rudolfs, W. Principles of sewage treatment. National Lime Association. Washington, D.C. 1955. 130 p.

40. Slanetz, L. W., Clara H. Bartley, T. G. Metcalf, and R. Newman. Survival of enteric bacteria and viruses in municipal sewage lagoons. p. 132-141. In R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

41. Smith, C. B. A decade of Ralston Purina lagoon experience. p. 93-95. *In* R. E. McKinley (ed.). Second International Symposium for Waste Treatment Lagoons. Kansas City, Missouri. 1970. 414 p.

42. Strickland, J. D. H., and T. R. Parsons. A practical handbook of seawater analysis, bulletin no. 167. Fisheries Research Board of Canada, Ottawa. 1968.

43. Svore, J. H. Waste stabilization pond practices in the United States. p. 427-434. *In* E. F. Gloyna and W. W. Eckenfelder (ed.). Water Resources Symposium No. 1, Advances in Water Quality Improvement. 1968. 496 p.

APPENDIX

Table A-1. Organic carbon concentration of pond influent (mg/l) during the hydraulic detention time of 15 days.

	Model Pond											
	Control			Over and Under			Longitudinal			End around		
Day	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC
1	16.3	224.3	213.5	14.0	194.4	185.1	15.5	214.4	204.0	15.5	214.4	204.0
2	15.8	216.6	216.5	14.5	200.5	191.2	16.3	223.0	212.6	15.0	206.9	197.3
3	14.5	200.8	193.1	15.0	207.4	199.4	15.0	207.4	199.4	15.8	217.4	209.0
4	14.0	182.9	175.7	14.5	189.2	181.8	14.3	186.1	178.8	15.0	195.7	188.0
5	14.5	193.2	178.0	15.0	199.7	184.0	15.0	199.7	184.0	15.0	199.7	184.0
6	14.5	185.3	170.8	15.0	191.6	176.5	15.8	201.0	185.2	15.0	191.6	176.5
7	15.0	194.0	184.5	15.0	194.0	184.5	15.5	200.4	190.5	15.5	200.4	190.5
8	15.3	197.9	180.4	15.0	194.8	177.5	15.5	201.1	183.3	15.5	201.1	183.3
9	15.5	205.3	191.2	15.0	198.8	185.1	15.5	205.3	191.2	16.0	211.8	197.2
10	14.0	183.5	169.2	14.5	189.9	175.1	15.0	196.2	180.1	14.3	186.7	172.2
11	14.5	193.7	180.5	15.0	200.2	186.6	14.0	187.2	174.5	14.5	193.7	180.5
12	16.0	201.1	185.2	15.0	188.7	173.8	16.5	207.3	191.0	15.3	191.8	176.7
13	16.0	210.8	194.2	15.0	197.8	182.2	15.3	201.1	185.2	16.0	210.8	194.2
14	13.5	179.3	165.3	15.0	198.8	183.2	15.3	202.0	186.2	14.0	185.8	171.2
15	16.5	237.6	216.3	14.5	208.9	190.2	15.0	216.1	196.8	14.5	208.9	190.2
16	15.0	216.1	196.8	14.5	208.9	190.2	16.0	230.4	209.8	15.0	216.1	196.8
17	14.5	193.6	187.9	15.5	206.8	200.6	15.5	206.8	200.6	14.5	193.6	187.9
18	13.8	180.9	166.5	14.8	194.0	178.6	14.8	194.0	178.6	14.5	190.7	175.5
19	15.8	202.3	196.2	15.0	192.7	186.9	15.0	192.7	186.9	14.5	186.3	180.8
$\bar{X}$ =	15.0	199.9	187.0	14.8	197.7	184.9	15.3	203.8	190.5	15.0	200.2	187.1
s =	.9	15.7	14.9	.3	6.5	7.3	.6	11.3	10.8	.6	10.7	10.8
cv=	6.0	7.9	8.0	2.5	3.3	4.0	4.0	5.6	5.7	3.9	5.3	5.8

Table A-2. Organic carbon concentration of pond influent (mg/l) during the hydraulic detention time of 5 days.

	Model Pond											
Day	Control			Over and Under			Longitudinal			End around		
	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC
1	5.0	199.9	186.7	5.5	219.4	204.8	5.0	199.9	186.7	5.0	199.9	186.7
2	5.5	225.3	212.4	4.5	185.5	175.0	5.0	205.4	193.7	5.0	205.4	193.7
3	5.5	223.0	216.4	5.0	203.0	197.0	5.0	203.0	197.0	5.0	203.0	197.0
4	5.5	219.5	210.9	5.0	199.9	192.1	5.0	199.9	192.1	5.0	199.9	192.1
5	5.0	194.9	187.2	4.7	183.4	176.2	5.0	194.9	187.2	4.0	156.5	150.4
6	4.0	162.1	149.5	4.5	181.8	167.6	5.0	201.4	185.7	5.0	201.4	185.7
7	5.0	195.7	180.9	4.5	176.5	163.2	5.0	195.7	180.9	5.3	207.1	191.5
8	5.0	198.9	183.3	4.5	179.4	165.2	5.0	198.9	183.3	4.7	187.2	172.4
$\bar{X}$ =	5.1	202.4	190.9	4.8	191.1	180.1	5.0	199.9	188.3	4.9	195.1	183.7
s =	.5	20.7	22.1	.4	14.9	15.8	.0	3.5	5.5	.4	16.7	15.4
cv =	9.8	1.0	11.6	7.7	7.8	8.8	.0	1.8	2.9	8.0	8.6	8.4

Table A-3. Organic carbon concentration of pond influent (mg/l) during the hydraulic detention time of 2.5 days.

	Model Pond											
Day	Control			Over and Under			Longitudinal			End around		
	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC
1	2.5	199.3	185.8	2.3	186.9	174.3	2.9	228.6	213.1	2.7	211.7	197.3
2	2.4	192.1	182.7	2.5	199.9	190.2	2.3	180.4	171.6	2.6	207.7	197.6
3	2.4	196.2	186.7	2.6	205.6	195.6	2.3	185.2	176.3	2.6	211.8	201.5
4	2.6	204.5	194.5	2.4	187.5	178.4	2.2	178.2	169.5	2.5	195.2	185.7
5	2.3	182.9	174.0	2.9	230.8	219.5	2.8	224.6	213.6	2.4	190.6	181.3
6	2.4	196.7	187.1	2.4	198.3	188.6	2.7	220.6	209.8	2.4	199.9	190.1
7	2.4	192.0	176.4	2.3	187.3	176.4	2.5	199.9	188.2	2.4	196.0	184.5
8	2.4	189.0	178.0	2.5	199.9	188.2	2.7	213.8	201.2	2.5	198.3	186.7
9	2.2	177.9	167.5	2.2	180.3	169.7	2.8	225.0	211.9	2.5	201.5	189.7
$\bar{X}$ =	2.4	192.3	181.4	2.5	197.4	186.8	2.6	206.3	195.0	2.5	201.4	190.5
s =	.1	8.2	8.2	.2	15.0	15.0	.3	20.6	18.7	.1	7.5	6.9
cv =	4.5	4.3	4.5	8.2	7.6	8.0	10.2	10.0	9.6	3.8	3.7	3.6

Table A-4. Organic carbon concentration of pond influent (mg/l) during the hydraulic detention time of 1.5 days.

	Model Pond											
Day	Control			Over and Under			Longitudinal			End around		
	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC	θ	TOC	SOC
1	1.5	223.3	211.8	1.7	250.7	237.8	1.6	230.5	218.6	1.6	229.0	217.2
2	1.4	207.4	196.7	1.4	213.1	202.2	1.4	211.7	200.8	1.4	213.1	202.2
3	1.4	205.9	195.3	1.5	214.6	203.5	1.5	216.0	204.9	1.4	205.9	195.3
4	1.4	210.2	199.4	1.4	201.6	191.2	1.5	223.3	211.8	1.5	214.6	203.5
5	1.5	218.9	207.7	1.5	216.0	204.9	1.6	231.9	220.0	1.4	205.9	195.3
6	1.4	207.4	196.7	1.5	221.8	210.4	1.4	201.6	191.2	1.4	213.1	202.2
7	1.4	205.9	195.3	1.5	226.1	214.5	1.5	120.4	209.0	1.4	201.6	191.2
$\bar{X}$ =	1.4	211.3	200.4	1.5	220.6	209.2	1.5	219.3	208.0	1.4	211.9	200.9
s =	.1	7.0	6.6	.1	15.3	14.6	.1	10.7	10.1	.1	9.0	8.5
cv =	3.4	3.3	3.3	7.1	7.0	7.0	5.0	4.9	4.9	4.3	4.2	4.2

Table A-5. Organic carbon concentration of pond effluent (mg/l) during the hydraulic detention time of 15 days.

			Model Pond					
	Control		Over and Under		Longitudinal		End around	
Day	TOC	SOC	TOC	SOC	TOC	SOC	TOC	SOC
2	51	18	18	10	40	12	40	12
4	73	19	21	13	36	10	37	10
6	79	12	11	11	28	6	41	10
8	76	26	21	18	34	9	41	13
10	79	25	20	14	36	18	39	19
12	70	16	13	11	24	12	34	8
14	75	19	21	13	35	15	37	11
16	75	17	21	13	36	15	31	12
$\overline{X}$	72	19	18	13	34	12	39	12
s	9	5	4	2	5	4	3	3
cv	13	24	22	19	15	32	7	28

Table A-6. Organic carbon concentration of pond effluent (mg/l) during the hydraulic detention time of 5 days.

			Model Pond					
	Control		Over and Under		Longitudinal		End around	
Day	TOC	SOC	TOC	SOC	TOC	SOC	TOC	SOC
1	64	39	32	8	64	8	64	19
2	60	46	30	22	63	34	52	32
3	50	39	25	15	72	28	56	30
4	68	36	39	26	68	25	64	29
5	64	20	50	16	70	18	56	20
6	54	38	45	25	70	46	48	31
7	52	30	28	14	40	22	40	20
8	48	30	36	22	44	30	32	18
9	52	34	26	14	48	28	39	31
10	44	28	30	17	52	24	44	44
$\overline{X}$	56	34	34	18	60	26	50	27
s	8	7	8	6	11	10	11	8
cv	14	21	24	32	18	38	22	30

Table A-7. Organic carbon concentration of pond effluent (mg/l) during the hydraulic detention time of 2.5 days.

	Model Pond							
	Control		Over and Under		Longitudinal		End around	
Day	TOC	SOC	TOC	SOC	TOC	SOC	TOC	SOC
1	94	67	71	57	75	48	76	43
2	99	65	81	49	72	37	59	30
3	92	61	64	36	60	40	64	40
4	104	62	88	66	72	40	62	41
5	97	68	85	60	76	42	70	38
6	100	63	75	56	68	42	64	42
7	94	62	72	46	68	42	52	31
8	94	69	74	58	74	52	64	42
9	102	72	60	38	60	40	58	42
10	84	58						
$\bar{X}$	96	65	74	52	69	43	63	39
s	6	4	9	10	6	5	7	5
cv	6	7	12	20	9	11	11	13

Table A-8. Organic carbon concentration of pond effluent (mg/l) during the hydraulic detention time of 1.5 days.

	Model Pond							
	Control		Over and Under		Longitudinal		End around	
Day	TOC	SOC	TOC	SOC	TOC	SOC	TOC	SOC
1	125	107	145	63	135	53	149	71
2	-	97	149	93	140	76	133	85
3	133	120	127	100	127	73	125	84
4	141	97	129	94	125	77	132	88
5	-	90	127	84	107	73	141	97
6	121	78	111	84	97	58	127	81
$\bar{X}$	130	98	131	86	122	68	135	84
s	9	14	14	13	17	10	9	9
cv	7	15	11	15	14	15	7	10

Table A-9. Total attached biomass for the hydraulic detention time of 15 days.

		Model Pond					
Control		Over & Under		Longitudinal		End around	
Site	grams	Site	grams	Site	grams	Site	grams
1	16.58	1	19.80	1	56.37	1	24.20
2	1.79	2	143.94	2	13.96	2	132.25
3	81.58	3	131.02	3	60.53	3	83.64
4	11.28	4	44.22	4	13.67	4	76.51
		5	56.79	5	72.80	5	21.29
		6	19.61	6	157.03		
		7	11.41				
		8	28.59				
		9	6.48				
		10	5.23				
		11	1.39				
		12	8.74				
		13	.92				
Total	111.23		478.14		374.36		337.89

Table A-10. Total attached biomass for the hydraulic detention time of 5 days.

		Model Pond					
Control		Over & Under		Longitudinal		End around	
Site	grams	Site	grams	Site	grams	Site	grams
1	4.76	1	19.90	1	35.76	1	58.64
2	22.21	2	129.23	2	5.28	2	181.74
3	86.54	3	96.07	3	81.45	3	68.46
4	26.72	4	73.04	4	21.85	4	69.46
		5	57.82	5	102.79	5	92.21
		6	53.02	6	250.96		
		7	24.45				
		8	14.99				
		9	12.36				
		10	.91				
		11	19.45				
		12	3.27				
		13	11.82				
Total	140.23		516.33		498.09		470.51

Table A-11. Total attached biomass for the hydraulic detention time of 2.5 days.

		Model Pond					
Control		Over & Under		Longitudinal		End around	
Site	grams	Site	grams	Site	grams	Site	grams
1	19.31	1	61.33	1	37.76	1	91.00
2	35.92	2	190.13	2	18.89	2	227.51
3	32.67	3	89.93	3	77.89	3	153.46
4	111.26	4	64.93	4	29.67	4	53.08
		5	57.08	5	38.28	5	47.22
		6	106.36	6	113.92		
		7	46.68				
		8	22.65				
		9	38.98				
		10	18.21				
		11	13.73				
		12	14.78				
		13	25.40				
Total	199.16		750.19		316.41		572.27

Table A-12. Total attached biomass for the hydraulic detention time of 1.5 days.

		Model Pond					
Control		Over & Under		Longitudinal		End around	
Site	grams	Site	grams	Site	grams	Site	grams
1	22.00	1	71.86	1	50.26	1	70.94
2	73.83	2	110.75	2	31.06	2	108.38
3	137.72	3	100.52	3	96.08	3	240.01
4	218.87	4	89.72	4	52.21	4	99.34
		5	65.12	5	157.18	5	84.53
		6	68.23	6	254.62		
		7	45.10	7	240.00		
		8	34.23				
		9	31.56				
		10	25.28				
		11	12.02				
		12	13.70				
		13	33.48				
Total	452.42		701.57		881.41		603.20

Table A-13. Diurnal variation of pH and alkalinity (as mg/l $CaCO_3$) during the hydraulic detention time of 15 days.

			Model Pond					
	Control		Over and Under		Longitudinal		End around	
Time	pH	Alk	pH	Alk	pH	Alk	pH	Alk
12N	7.55	220	7.82	236	7.46	224	7.64	218
1	7.33	212	7.52	232	7.24	216	7.28	216
2	7.32	210	7.32	232	7.16	210	7.31	218
3	7.31	206	7.32	230	7.20	216	7.27	220
4	7.31	210	7.34	230	7.16	212	7.28	222
5	7.24	208	7.29	226	7.23	212	7.27	216
6	7.29	208	7.28	230	7.25	212	7.28	226
7	7.30	212	7.34	230	7.31	210	7.28	220
8	7.55	218	7.42	234	7.24	212	7.31	218
9	7.23	218	7.28	230	7.22	210	7.11	220
10	7.18	210	7.32	224	7.35	214	7.07	220
11	7.24	220	7.49	230	7.34	242	7.28	242
12M	7.20	216	7.40	232	7.30	214	7.15	224
1	7.04	218	7.21	234	7.05	214	7.00	220
2	7.30	218	7.21	230	7.00	214	6.97	226
3	7.20	220	7.19	232	7.02	212	6.96	216
4	7.15	214	7.27	240	7.15	212	7.00	226
5	7.20	210	7.15	228	7.02	212	7.00	220
6	7.20	218	7.15	228	7.04	214	7.00	224
7	7.26	216	7.18	230	7.12	214	7.05	224
8	7.27	214	7.18	230	7.06	206	7.05	218
9	7.31	214	7.26	230	7.20	214	7.22	222
10	7.12	214	7.33	232	7.15	214	7.23	220
11	7.28	210	7.20	232	7.16	212	7.22	222
$\overline{X}$	7.27	214	7.31	231	7.18	214	7.18	222
s	.11	4	.15	3	.12	7	.16	5
cv	1.55	2	2.01	1	1.65	3	2.23	2

Table A-14. Diurnal variation of pH and alkalinity (as mg/l $CaCO_3$) during the hydraulic detention time of 5 days.

	Model Pond							
	Control		Over and Under		Longitudinal		End around	
Time	pH	Alk	pH	Alk	pH	Alk	pH	Alk
12N	6.70	222	6.75	243	6.80	234	6.70	246
1	6.70	219	6.75	251	6.70	225	6.70	227
2	6.91	216	6.80	254	6.80	223	6.80	235
3	6.98	220	6.82	240	6.80	221	6.83	226
4	6.86	221	6.80	245	6.82	225	6.79	230
5	6.92	219	6.82	247	6.83	225	6.80	233
6	6.90	218	6.75	243	6.80	224	6.75	228
7	6.95	219	6.80	236			6.83	228
8	6.95	228	6.80	249			6.83	233
9	6.82	216	6.80	248			6.75	233
10	6.85	216	6.80	246			6.80	233
11	6.82	222	6.75	234	No data available past 7 p.m. due to breakdown.		6.80	247
12M	6.85	225	6.80	248			6.75	232
1	6.85	225	6.78	248			6.76	232
2	6.84	222	6.77	242			6.72	228
3	6.78	219	6.78	243			6.75	231
4	6.82	220	6.81	244			6.72	229
5	6.78	218	6.79	245			6.75	230
6	6.85	221	6.79	243			6.72	230
7	6.82	220	6.78	243			6.78	230
8	6.80	221	6.77	242			6.73	229
9	6.79	222	6.78	245			6.78	230
10	6.83	231	6.80	244			6.75	231
11	6.83	223	6.81	242			6.75	235
$\bar{X}$	6.84	221	6.79	244	6.79	225	6.76	232
s	.07	4	.02	4	.04	4	.04	5
cv	1.02	2	.32	2	.63	2	.58	2

Table A-15. Variation of pH and alkalinity (as mg/l $CaCO_3$) during the hydraulic detention time of 2.5 days.

	Model Pond							
	Control		Over and Under		Longitudinal		End around	
Day	pH	Alk	pH	Alk	pH	Alk	pH	Alk
1	6.80	-	6.90	-	6.88	-	6.90	-
2	6.80	-	6.70	-	6.70	-	6.70	-
3	6.70	-	6.70	-	6.68	-	6.65	-
4	6.70	225	6.80	256	6.70	246	6.65	237
5	6.83	225	6.81	258	6.87	243	-	237
6	6.90	225	7.08	258	6.90	245	6.80	238
$\overline{X}$	6.79	225	6.83	257	6.79	245	6.74	237
s	.08	0	.14	1	.10	2	.11	1
cv	1.14	0	2.10	0	1.54	1	1.61	0

Table A-16. Variation of pH and alkalinity (as mg/l $CaCO_3$) during the hydraulic detention time of 1.5 days.

	Model Pond							
	Control		Over and Under		Longitudinal		End around	
Day	pH	Alk	pH	Alk	pH	Alk	pH	Alk
1	6.76	-	6.63	-	6.60	-	6.98	-
2	6.76	-	6.68	-	6.70	-	6.68	-
3	7.17	-	6.95	-	7.00	-	6.95	-
4	6.89	-	6.73	-	6.75	-	6.75	-
5	6.83	-	6.89	-	6.78	-	6.73	-
6	6.73	228	6.93	234	6.85	224	6.73	246
7	6.73	239	6.93	234	6.85	242	6.73	243
$\overline{X}$	6.84	229	6.82	234	6.79	243	6.79	244
s	.16	-	.14	-	.13	-	.12	-
cv	2.30	-	1.98	-	1.87	-	1.76	-

Table A-17. Diurnal variation of free carbon dioxide (mg/l) during the hydraulic detention time of 15 days.

		Model Pond					
Control		Over and Under		Longitudinal		End around	
Time	CO_2	Time	CO_2	Time	CO_2	Time	CO_2
12N	38	12N	22	12N	36	12N	23
3	39	3	32	3	36	3	38
4	41	4	30	4	40	4	40
6	42	6	43	6	41	6	42
8	36	8	32	8	36	8	40
10	43	10	32	10	32	10	38
12M	54	12M	38	12M	40	12M	36
2	40	2	40	2	43	2	68
4	44	4	37	4	44	4	59
6	38	6	34	6	30	6	38
8	40	8	32	8	32	8	40
10	46	10	32	10	32	10	38
$\bar{X}$	42		34		37		42
s	5		5		5		11
cv	11		16		13		27

Table A-18. Diurnal variation of free carbon dioxide (mg/l) during the hydraulic detention time of 5 days.

		Model Pond					
Control		Over and Under		Longitudinal		End around	
Time	CO_2	Time	CO_2	Time	CO_2	Time	CO_2
12N	64	12N	85	12N	86	12N	77
2	67	2	87	2	81	2	79
4	70	4	93	4	76	4	95
6	64	6	90	6	74	6	76
8	55	8	91	8	-	8	80
10	73	10	93	10	-	10	79
12M	75	12M	97	12M	-	12M	94
2	80	2	96	2	-	2	94
4	81	4	93	4	-	4	96
6	74	6	97	6	-	6	95
8	73	8	94	8	-	8	88
10	67	10	96	10	-	10	85
$\bar{X}$	70		93		79		87
s	7		4		5		8
cv	10		4		7		9

Table A-19. **Diurnal variation of effluent suspended solids (mg/l) during the hydraulic detention time of 15 days.**

Time	Control	Model Pond Over and Under	Longitudinal	End around
12N	120	-	80	28
4	108	-	44	36
8	128	-	68	40
12M	124	44	76	56
4	112	-	40	72
8	112	24	52	56
12N	136	24	64	80
$\bar{X}$	120	31	61	53
s	10	12	16	19
cv	8	38	26	36

Table A-20. **Diurnal variation of effluent suspended solids (mg/l) during the hydraulic detention time of 5 days.**

Time	Control	Model Pond Over and Under	Longitudinal	End around
12N	51	50	46	40
4	69	72	47	78
8	56	68	47	82
12M	85	78	-	54
4	74	58	-	76
8	88	80	-	98
12N	-	-	-	76
$\bar{X}$	71	68	47	73
s	15	12	1	18
cv	21	46	1	24

Table A-21. Daily variation of effluent suspended solids (mg/l) during the hydraulic detention time of 2.5 days.

		Model Pond		
Day	Control	Over and Under	Longitudinal	End around
1	42	64	52	66
2	58	60	74	54
3	56	-	56	54
4	56	64	64	42
5	54	60	58	52
6	76	74	68	56
7	60	72	70	62
$\overline{X}$	57	66	63	55
s	10	6	8	8
cv	17	9	1	14

Table A-22. Daily variation of effluent suspended solids (mg/l) during the hydraulic detention time of 1.5 days.

		Model Pond		
Day	Control	Over and Under	Longitudinal	End around
1	68	62	86	84
2	86	78	102	80
3	70	52	68	82
4	78	84	70	64
5	62	60	-	88
6	58	62	68	84
$\overline{X}$	70	66	81	80
s	10	12	14	8
cv	15	18	18	10