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Robert P. Huguenard
University of Central Florida

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COST EFFECTIVE DESIGN OF THE ACTIVATED SLUDGE WASTEWATER TREATMENT SYSTEM

BY

ROBERT PAUL HUGUENARD
B.S., Florida State University, 1982

THESIS

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ABSTRACT

In current design practice the components of the complete mix activated sludge system are designed as individual units with little or no appreciation for the process interactions which occur between system components. To achieve acceptable process efficiency and to realize cost effectiveness a unified design approach is necessary. This research effort was initiated to define the characteristics of the economic optimum complete mix activated sludge configuration while considering system interactions.

A computer program was developed for the completion of the process design and the economic analysis of the aeration basins, the settling basins, and the return sludge pumping facilities for the complete mix activated sludge system. The process design was formulated subject to constraints on the following:

1. effluent suspended solids
2. effluent substrate concentration
3. underflow solids concentration
4. maximum and minimum mixed liquor suspended solids concentration
5. maximum and minimum values for settling basin depth

Recognizing the importance of the final settling basin to the overall economics and performance of the activated

sludge process emphasis was placed on settling basin design. Settling basin surface area requirements for thickening were identified using the settling flux approach. To ensure comparison of systems capable of producing equivalent effluent qualities settling basin performance was evaluated using a model reported in the literature. The model selected shows sensitivity to settling basin detention time, overflow rate and mixed liquor suspended solids concentration.

Using the optimization routine, simulations were performed to identify the optimum system configuration as defined by this model. The optimum system aeration basin hydraulic detention times were found to be higher than those typically used, while the optimum system mixed liquor suspended solids concentrations were found to be lower than those typically used. Optimum system settling basin hydraulic detention times and depths were found to exceed conventional detention times and depths in current usage. Although the optimization routine developed in this research may not have wide spread applicability, the results are felt to be significant in identifying optimum system trends.

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CHAPTER I

INTRODUCTION

The activated sludge wastewater treatment system is used extensively for the treatment of municipal and industrial wastewaters. The complete mix activated sludge system is frequently used because of its ability to withstand shock loading. This system is presented schematically in Figure 1 and consists of: (1) aeration basins where wastewater is contacted with suspended biological solids, (2) settling basins where biological solids are settled and a clarified effluent is produced, and (3) a pumping system which returns solids to the aeration basins.

In current practice, the aeration basins and settling basins are designed as individual units with little or no appreciation for the process interactions which occur between system components. To achieve acceptable process efficiency and realize cost effectiveness a unified design approach similar to that proposed by Keinath et al. (1977) must be used. Economic tradeoffs between treatment system components, produced by system interactions, must be analyzed to identify a least cost system which meets desired treatment goals.

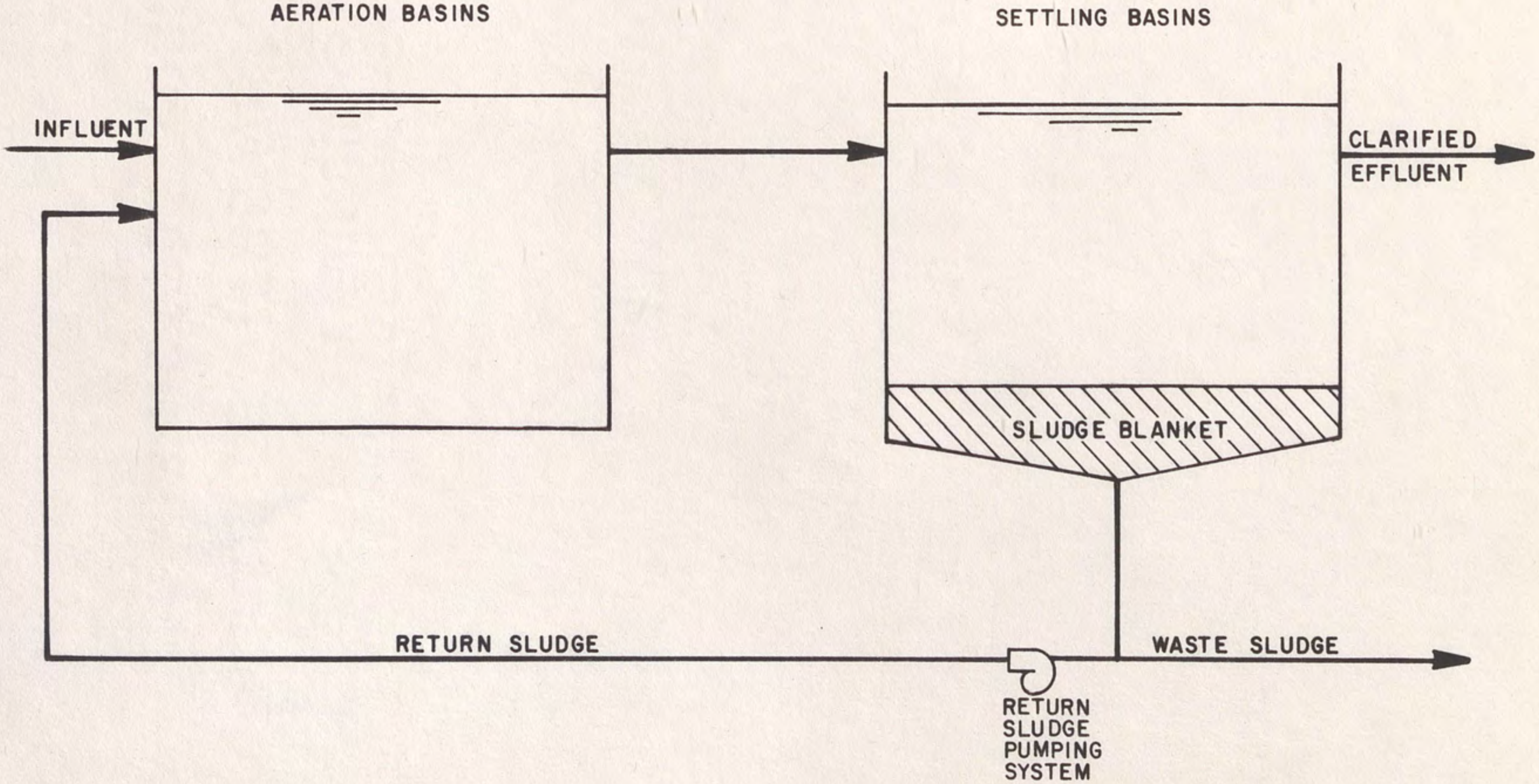

Figure 1: The Complete Mix Activated Sludge System

Chapman (1983) reported that overall economics and efficiency of the activated sludge process are profoundly influenced by the performance of the final settler. Unfortunately, contemporary settling basin design practices most often used do not lend themselves to cost and performance optimization of the activated sludge system. Utilization of the settling flux approach to settling basin design coupled with a settling basin performance model, would allow evaluation of economic tradeoffs between system components while maintaining process performance standards. The settling flux approach to design is used in current design practice, however, applications are usually limited to industrial wastewater treatment system design.

The objective of this research was to develop a routine for the economic optimization of the complete mix activated sludge system for a typical municipal wastewater application. The optimization routine provided process design and economic evaluation (both capital costs and operation and maintenance costs) for the following treatment plant components:

1. Aeration basin structure
2. Aeration equipment
3. Settling basin structure
4. Clarifier mechanism
5. Return sludge pumping facilities

The optimization routine utilizes the settling flux design approach coupled with a settling basin performance model developed by Tuntoolavest et al. (1980). The settling basin performance model is sensitive to settling basin overflow rate, settling basin detention time and mixed liquor suspended solids concentration.

Using the optimization routine, a FORTRAN computer program was written to allow rapid identification of optimum activated sludge system designs. Optimum system designs are selected from the set of treatment system configurations capable of producing a desired effluent suspended solids concentration and a desired effluent soluble substrate concentration. The optimum system is selected based on economics. Settling data from two municipal wastewater treatment facilities were used to generate optimum designs to determine the effects of several process design variables on the optimum system design. Variables evaluated included desired effluent suspended solids concentration, minimum underflow concentration, maximum cell yield, raw wastewater flow rate, influent substrate concentration, and sludge age. In addition, results of simulations were analyzed to identify the characteristics of an optimum complete mix activated sludge system as defined by this model. Emphasis was placed on optimum system settling basin geometry, especially optimum depth.

CHAPTER II

LITERATURE REVIEW

The overall economics and performance of the activated sludge process are profoundly influenced by the final settling basin. Because of their biological nature, particulates which are not removed by gravitational sedimentation often make up the majority of the oxygen demanding materials discharged from a typical activated sludge facility. Recognizing the overwhelming importance of the settling basin to the activated sludge process, this literature review will focus on the final settling basins. Factors influencing activated sludge final settling basins will be discussed, followed by a review of current settling basin design practices. In addition, settling flux theory and settling basin performance models will be reviewed.

Factors Influencing Settling Basin Performance

Many factors affect the performance of an activated sludge final settling basin; the most important factors are noted in Table 1. The factors are classified as biological process factors and factors associated with settling basin characteristics. Biological process factors affect the characteristics of the mixed liquor, hence affecting the settling characteristics of the solids. Settling basin

TABLE 1

FACTORS AFFECTING ACTIVATED SLUDGE FINAL SETTLING BASIN PERFORMANCE

Biological Process

- Biological characteristics of the mixed liquor
- MLSS concentration
- Rate of aeration
- Recycle ratio

Settling Basin Characteristics

- Surface area (i.e. - overflow rate)
- Clear zone detention time
- Depth
- Inlet characteristics
- Weir placement

characteristics are the physical characteristics of the settling basin determined during design.

The biological characteristics are important in determining the settleability of a sludge. Biological characteristics of a sludge are determined by wastewater characteristics (BOD5, nutrient and trace element concentrations, dissolved oxygen content, process loading, etc.).

Several researchers have concluded that effluent suspended solids concentration increases as the mixed liquor suspended solids concentration increases (Chapman 1983, Tuntoolavest et al. 1980, and Pflanz 1969). Chapman (1983) reports an increase in effluent suspended solids level of 4 mg/l for each 1000 mg/l increase in mixed liquor suspended solids concentration.

The aeration rate may effect the sludge settleability if aeration rates are so high that shear forces break the floc particles apart. On the other hand, if aeration rates are too low, insufficient oxygen levels may result. Higher effluent suspended solids concentrations may result in either case.

Chapman (1983) reports that an increased feed flow resulting from an increased recycle rate results in deterioration of effluent quality. Chapman (1983) goes on to state that the net effect of increasing the flow rate into the settling basin by increasing recycle rate, is to increase momentum and therefore increase velocity of the circular flow pattern in the tank. An increase in the recycle rate also results in an increase in solids loading to the settling basins. The quantity of small particles entering the settling basin increases in proportion to the increase in solids loading. The escalation in the quantity of small particles may result in an increase in the effluent suspended solids concentration.

The settling basin surface area determines the overflow rate and the area for thickening. Considerable performance data has been reported which indicates a significant dependence of settling basin efficiency on overflow rate (Chapman 1983, Tuntoolavest et al. 1980, Heinke et al. 1977, and Agnew 1972). These investigations represent laboratory and plant-scale studies all verifying that suspended solids removal efficiency increases in response to a reduction in overflow rate.

The activated sludge process produces a flocculent slurry. The flocculation process has been characterized by the dimensionless product of the velocity gradient, floc concentration, and time (Ives 1968). Particle settling velocities normally increase with an increase in the floc diameter, resulting in an increase in removal efficiency. In theory, a longer detention time would allow more particle collisions and would therefore influence removal efficiency for flocculent materials. Indeed, experimental evidence verifies an improvement in removal efficiency with an increase in detention period for flocculent slurries (Dietz and Keinath 1984, Parker 1983, Dietz 1982, Tuntoolavest et al. 1980, and Heinke et al. 1977).

An increase in settling basin detention period can be accomplished by increasing the surface area or by increasing the depth. Research by Dietz and Keinath (1984) suggest that an increase in depth is the most economical method of providing additional detention time. Chapman (1983) reports that greater settling basin depths help provide a consistent effluent when a high peak flow to average flow ratio exists, and provide storage for sludge displaced from the aeration basin during periods of peak hydraulic flow.

Inlet characteristics and weir placement are other factors which may affect settling basin efficiency (Stuckenberg et al. 1981). Inlet location (center feed versus peripheral feed), feed well diameter, and feed well submergence each affect the hydraulics of the settling basin. Small feed well diameters or excess submergence of the feed well may cause scour of the sludge blanket and resuspension of settled solids resulting in excess solids loss. Other inlet conditions may also cause non-ideal hydraulic conditions. Settling basin hydraulics must be considered for weir placement as well. Poor placement of weirs may result in short circuiting resulting in excess solids loss.

Review of Current Design Practice

Standards published by the Great Lakes - Upper Mississippi River board of State Sanitary Engineers (Ten State Standards) and the Water Pollution Control Federation (Manual of Practice No. 8) are widely used for the design of activated sludge final settling basins. The following review will focus on these design standards.

Guidelines for the activated sludge final settling basin design proposed in the Ten State Standards (1978) include consideration of overflow rate, weir loading, and side water depth. Design criteria are summarized in Table 2. Settling basin surface area is determined by the more stringent of two loading constraints, hydraulic loading or solids loading. Overflow rate is determined by the settling basin surface area. Although a minimum depth was specified (12 feet), criteria for a minimum detention period were not indicated.

Design guidelines are treated in more detail in the Water Pollution Control Federation Manual of Practice Number 8 (1977). Suggested guidelines are summarized in tables 3-a, 3-b, and 3-c. Once again, settling basin surface area is determined by the more stringent of two loading constraints, hydraulic loading or solids loading.

Hydraulic loading guidelines are summarized in Table 3-a. Surface areas are calculated for each of the three flow conditions, the largest area is the surface area

TABLE 2

SUMMARY OF ACTIVATED SLUDGE FINAL SETTLING BASIN DESIGN GUIDELINE TEN STATE STANDARDS - 1978 EDITION

Parameter	Recommended Values
Overflow rate (peak hourly flow)	< 1200 gal./day-ft^2
Solids Loading (peak rates)	50 lb./day-ft^2
Side Water Depth	≥ 12 feet
Weir Loadings	
ADF* ≤ 1 MGD	$< 10{,}000$ gal./day-ft.
ADF > 1 MGD	$< 15{,}000$ gal./day-ft.

*ADF - Average daily flow rate in millions of gallons per day (MGD)

TABLE 3-a

OVERFLOW RATE GUIDELINES FOR ACTIVATED SLUDGE FINAL SETTLING BASINS, WPCF MANUAL OF PRACTICE NUMBER 8-1977

Flow Condition	Maximum Overflow Rate ($gal/day-ft^2$)
24 hour average flow rate	800
3 hour sustained peak flow rate	1400
2 hour sustained peak flow rate	1600

TABLE 3-b

SOLIDS LOADING GUIDELINES FOR ACTIVATED SLUDGE FINAL SETTLING BASINS, WPCF MANUAL OF PRACTICE NUMBER 8-1977

Sludge Volume Index* (mg/l)	Maximum Solids Loading ($lb/day-ft^2$) Single Point Drawoff	Multi Point Drawoff
250	17	25
200	27	36
150	40	51

* These are representative points selected from settling volume index versus solids loading curves presented in WPCF Manual of Practice Number 8 (1977).

TABLE 3-c

SIDE WATER DEPTH GUIDELINES FOR ACTIVATED SLUDGE CIRCULAR FINAL SETTLING BASINS, WPCF MANUAL OF PRACTICE NUMBER 8-1977

Tank Diameter (feet)	Side Water Depth (feet)	
	Minimum	Suggested
<40	10	11
40-70	11	12
70-100	12	13
100-140	13	14
>140	14	15

required to meet hydraulic loading constraints. The settling basin surface area required to meet solids loading constraints is also calculated. Solids loading guidelines are summarized in
Table 3-b. If the surface area required to meet solids loading guidelines is larger than that required to meet hydraulic loading guidelines, the solids loading surface area is used for design.

Minimum depths and the recommended depths for activated sludge final settling basins are summarized in Table 3-c. The need for larger depths with increased settling basin surface area is recognized, however no provision is made for independent specification of hydraulic detention time. Detention time is essentially determined by default upon selection of surface area and depth. Settling basin detention times resulting from depths and maximum overflow rates recommended in the Water Pollution Control Federation Manual of Practice Number 8 (1977) are presented in Table 4.

Although experimental evidence and sound theoretical justification exists to specify detention period as an independent design criteria, current design practice is dominated by the consideration of overflow rate. Minimum settling basin depths are generally recognized, however the effect of increased settling basin depth (detention time) on system performance is not evident from the referenced guidelines. Manual of practice FD-8 (1985), a recent

TABLE 4

SETTLING BASIN DETENTION TIMES RESULTING FROM RECOMMENDED DESIGN CONSTRAINTS, WPCF MANUAL OF PRACTICE NUMBER 8 - 1977

Tank Diameter (Feet)	Detention Time* (Hours)
< 40	2.5
40 - 70	2.7
70 - 100	2.9
100 - 140	3.1
> 140	3.4

* Calculated for an overflow rate of 800 gpd/ft^2 and depths recommended in Table 3-C. For an overflow rate of 600 gpd/ft^2 these detention times would be multiplied by four-thirds.

publication of the Water Pollution Control Federation, recognizes settling basin side water depth as a variable in settling basin efficiency. Research by Parker (1983) is cited in justifying larger settling basin depths, however no association between increased depth and increased detention time is made.

Review of Settling Flux Theory

Another approach to the design of final settling basins for the activated sludge process is based on the settling flux concept (Dick 1970). Use of this method requires actual settling data (i.e., settling velocity versus suspended solids concentration) for the wastewater to be treated. The settling flux approach to design is based on thickening constraints. However, settling basin designs would also be checked for consistency with clarification constraints as previously discussed.

Solids Flux Concept

Solids flux is the downward movement of solids in the settling basin (i.e., mass movement across a plane with an area equal to the settling basin surface area). The settling flux approach to design involves determining the total solids flux that can be applied to a settling basin. The total flux is the sum of two components, the settling flux and the bulk flux. The settling flux is the product of the settling velocity and the suspended solids concentration as noted on the following page:

GS = CONC (SV)

where,

GS = Settling flux (mg-m/l-hour)

CONC = Suspended solids concentration (mg/l)

SV = Settling velocity (m/hour)

The bulk flux is the product of the bulk underflow withdrawal velocity and the suspended solids concentration as noted below:

GB = CONC (QR) / AREA

where,

GB = Bulk flux (mg-m/l-hour)

QR = Recycle pumping rate (m^3/hour)

AREA = Settling basin surface area (m^2)

The two flux components and the total flux can be represented graphically as shown in Figure 2. The limiting flux (GL), (i.e., the flux corresponding to the minimum in the total flux curve), is the maximum solids flux that can be transmitted to the bottom of the settling basin for a particular recycle rate (QR). The underflow concentration (CU) and the limiting flux vary with changes in the recycle rate. An escalation in the recycle rate increases the slope of the bulk flux line which results in a larger limiting flux and a smaller underflow concentration. Each time the slope of the bulk flux line changes the total flux curve must be recalculated.

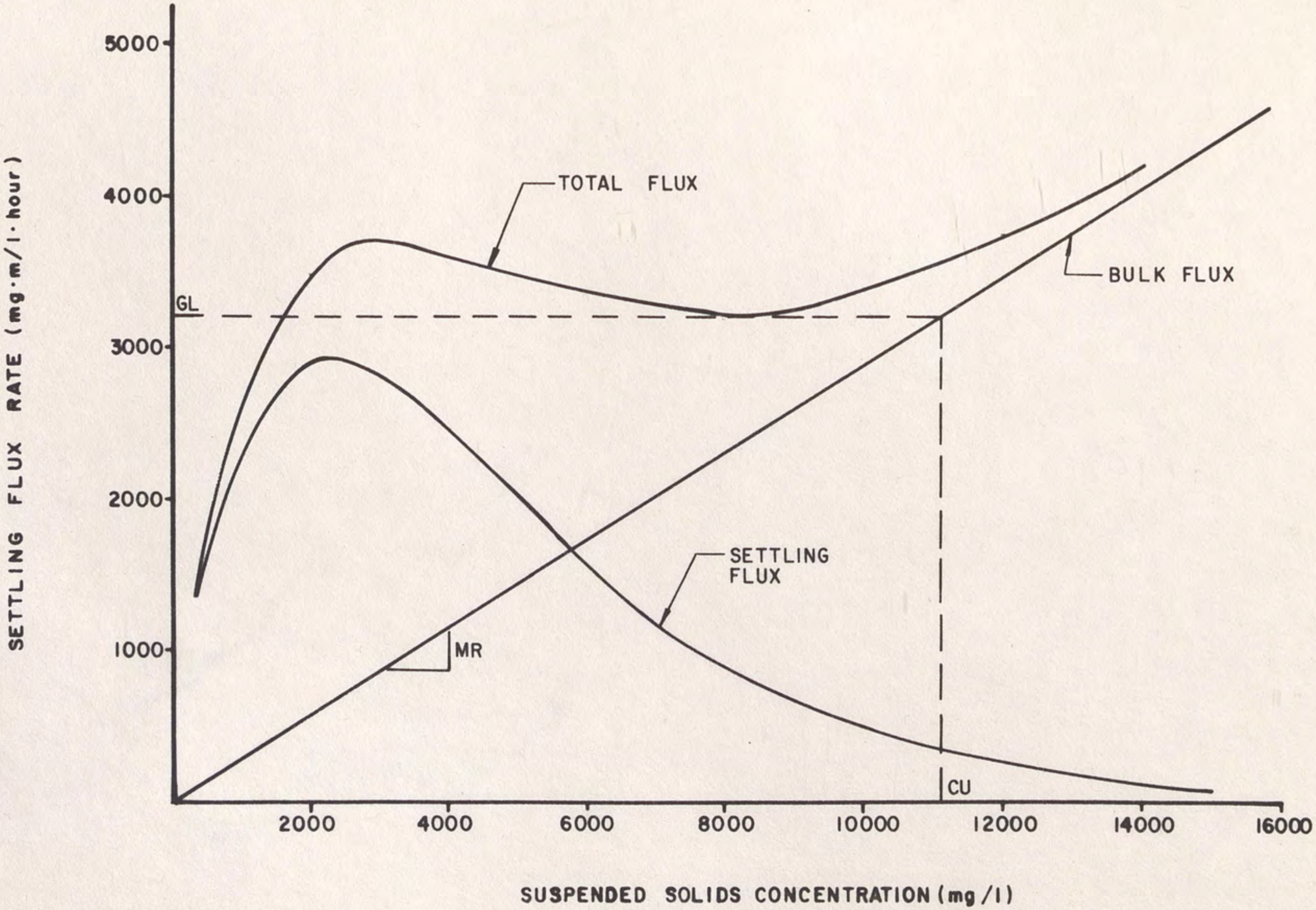

Figure 2: Total Flux Method

Yoshioka Technique

Yoshioka et al. (1957) developed a graphical technique which allows determination of the limiting flux by drawing a line tangent to the settling flux curve and intersecting the concentration axis at the desired underflow concentration (see Figure 3). This line is the thickening constraint line and has a slope equal to the negative of the slope of the bulk flux line (-MR) for the same recycle rate. This method produces the same results as the total flux method, but is a simpler and more practical application of settling flux theory.

State Point Concept

Two operating lines can be defined on the settling flux plot, the overflow rate operating line and the recycle rate operating line (see Figure 4). The overflow rate operating line intersects the origin and has a slope equal to the overflow rate (ORA) as noted below:

ORA = MO

where,

ORA = Overflow rate (m/hour)
MO = Slope of the overflow rate operating line (m/hour)

The intersection of the overflow rate operating line and the recycle rate operating line is defined as the operating point or the state point (Keinath et al. 1977). The recycle rate operating line is the thickening constraint

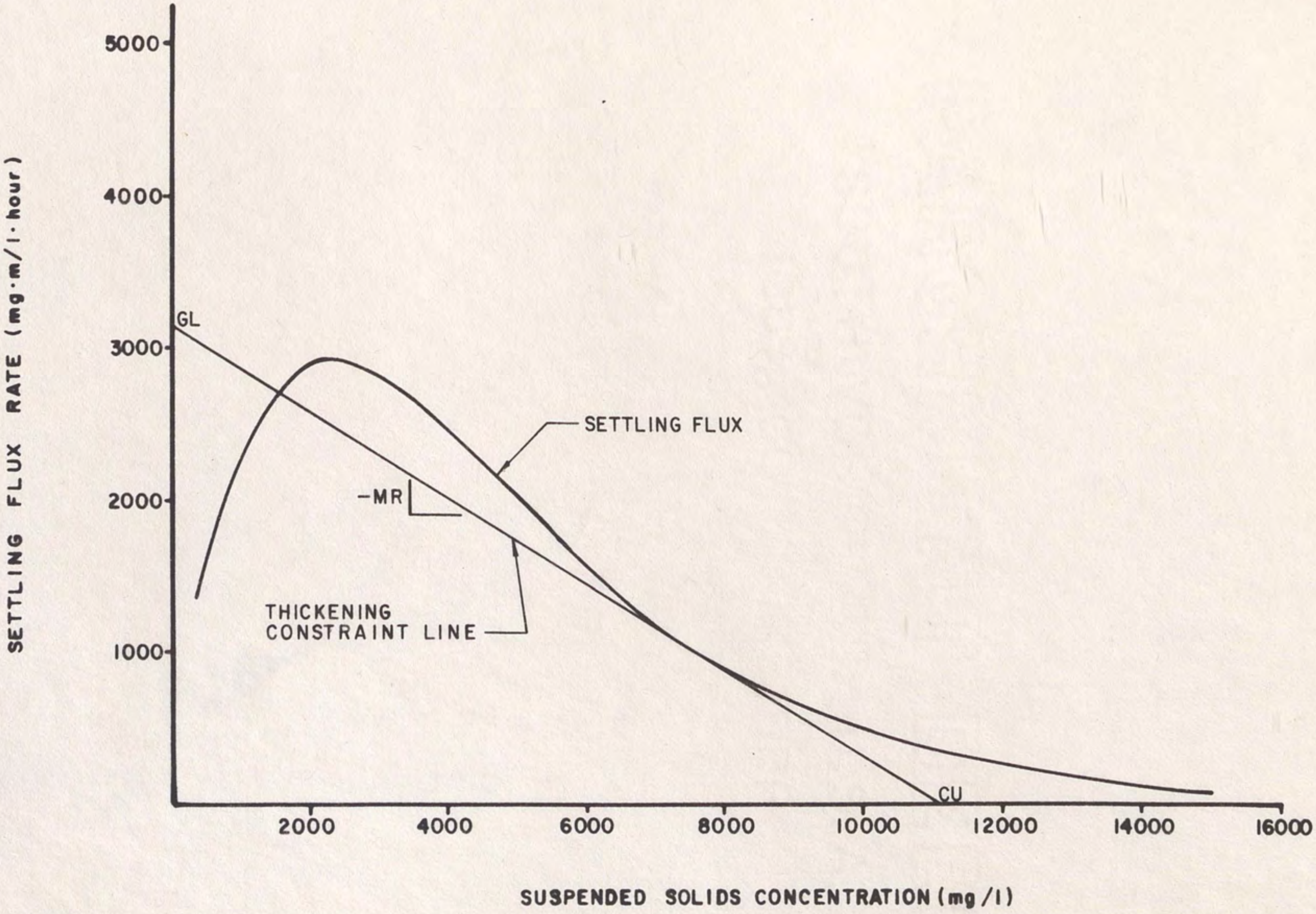

Figure 3: Settling Flux Method - Yoshioka, et. al.

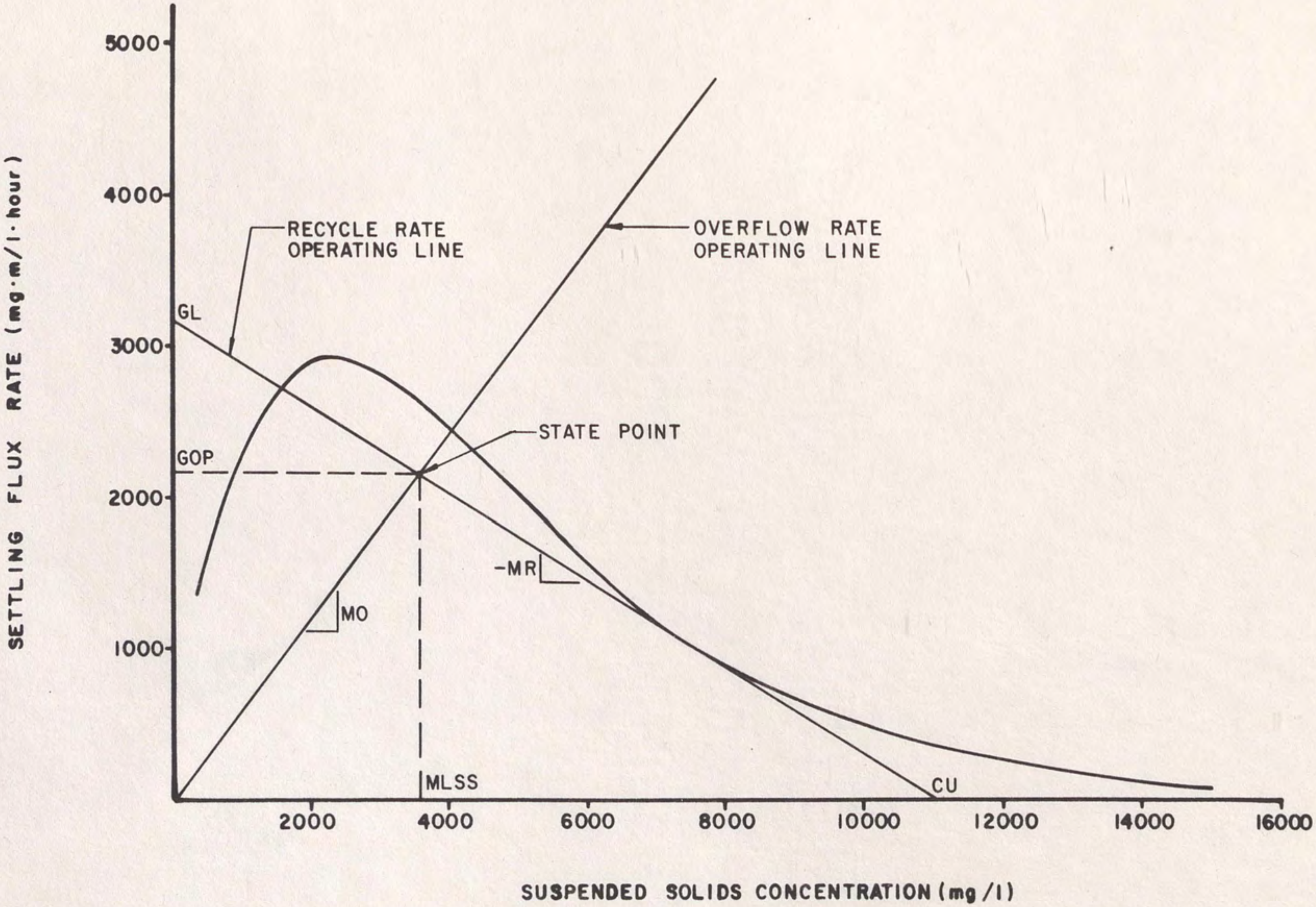

Figure 4: State Point Concept

line which passes through the state point. The concentration coordinate of the state point is the mixed liquor suspended solids concentration (MLSS) for the aeration basin. The flux coordinate of the state point is the operating settling flux rate (GOP) for the settling basin.

Design Using The Settling Flux Method

When the settling flux method is used, workable designs result when the state point lies under the settling flux plot. An infinite number of possible workable designs results. However, economic considerations eliminate many of the possible workable designs. A description of the components of the settling flux approach to design is included in this section.

The overflow rate operating line has a slope MO as depicted in Figure 5. As the slope MO increases the settling basin overflow rate increases. In terms of settling basin design, a smaller settling basin surface area is required for a larger overflow rate. Inspection of the following equation for settling basin surface area verifies this relation:

$$AREA = Q / MO = Q/ORA$$

where:

Q = Average daily flow rate (m^3/hour)

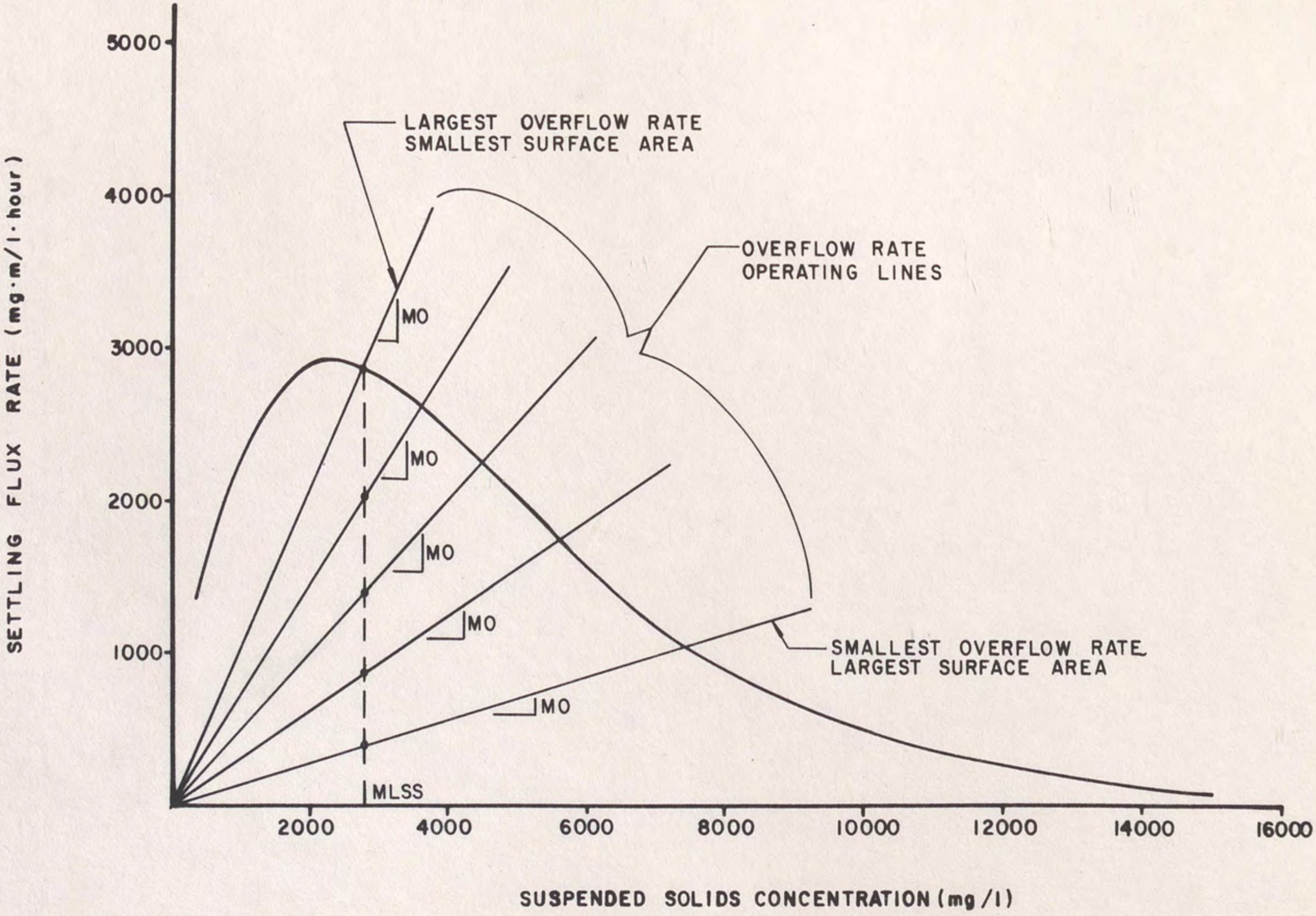

Figure 5: Overflow Rafe Operating Lines

At very small overflow rates the settling basin design becomes impractical due to extremely high settling basin costs. The overflow rate is restricted from becoming extremely large by the settling flux curve (i.e., the state point can not lie above the settling flux curve).

The recycle rate operating line has a slope -MR as depicted in Figure 6. As the slope -MR increases (becomes a larger negative number), the recycle pumping rate increases. This relationship is shown in the equation noted below:

$$QR = (MR)(AREA)$$

where:

MR = Negative of the slope of the recycle rate operating line (m/hour)

On the other hand, as the recycle rate increases, the underflow concentration decreases as illustrated on Figure 6.

Interactions between the overflow rate, underflow concentration and the recycle rate can be explained in terms of the state point concept. For a particular design MLSS concentration, as the state point moves directly upward on the settling flux plot the design is impacted in three ways: 1) the settling basin surface area decreases resulting in an increase in overflow rate; 2) the recycle pumping rate increases; and, 3) the underflow suspended solids concentration decreases. This situation is depicted graphically on Figure 7.

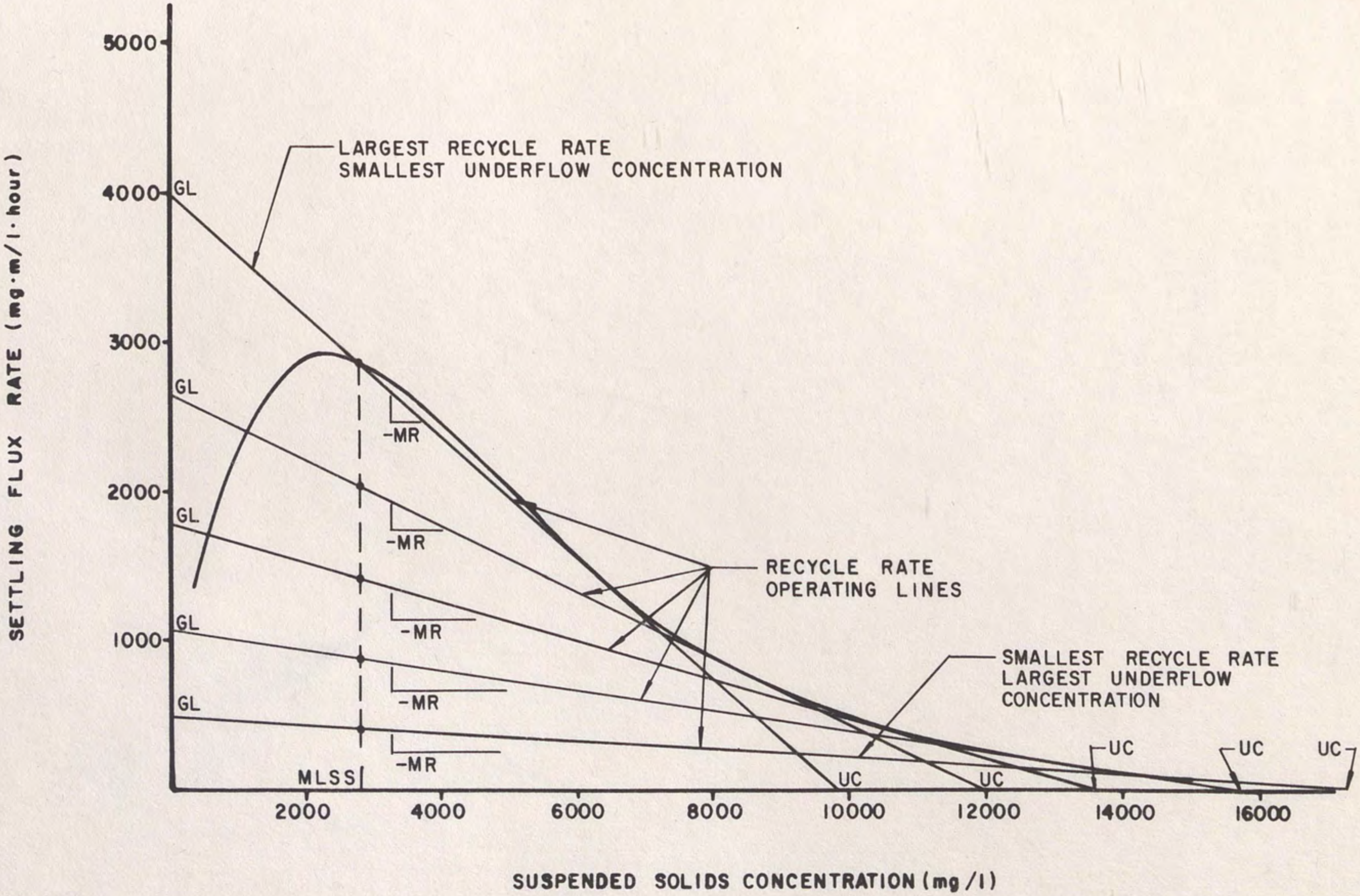

Figure 6: Recycle Rate Operating Lines

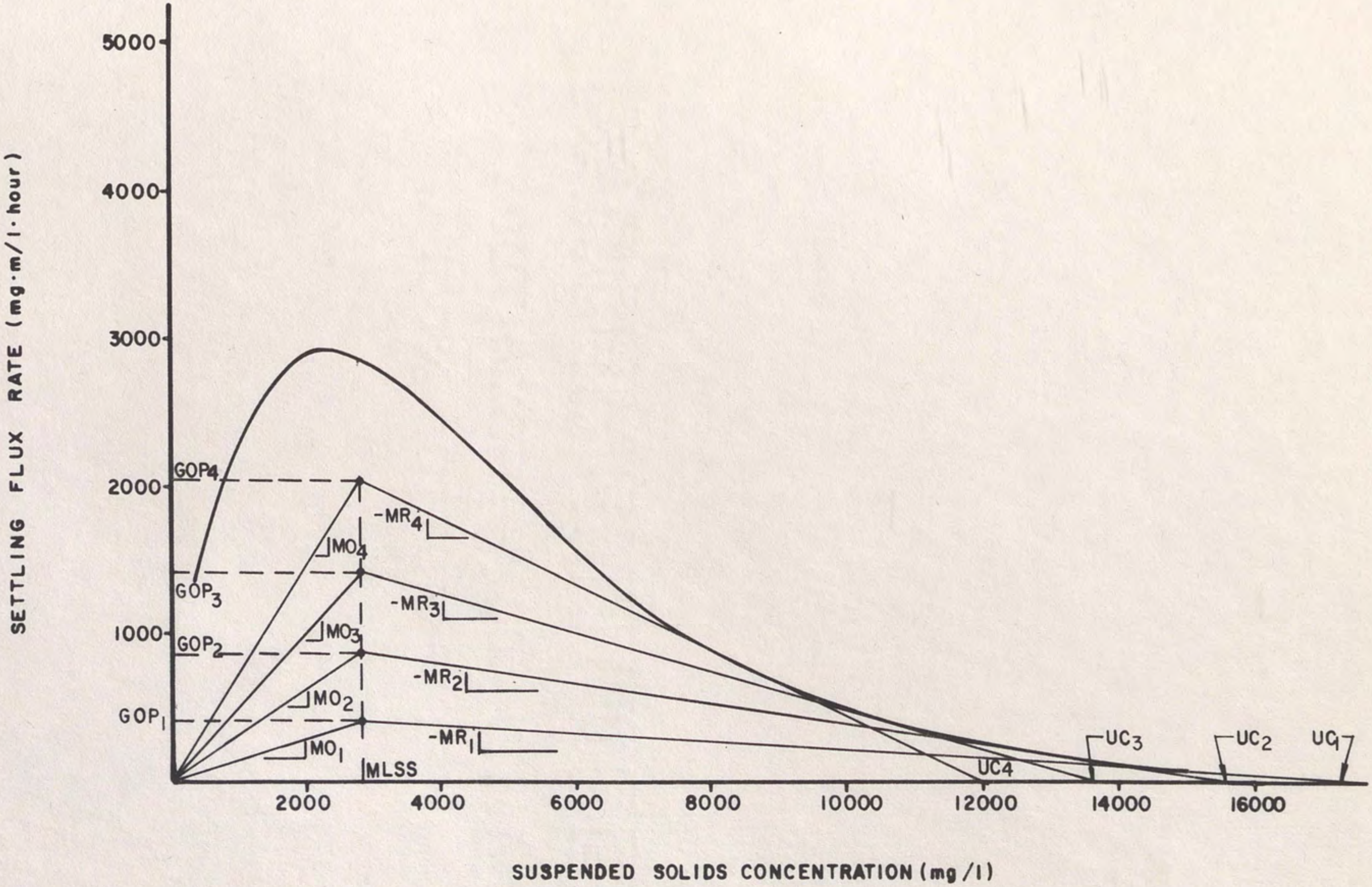

Figure 7: System Interactions with a Constant MLSS Concentration

When the state point is allowed to move from lower to higher MLSS concentrations on the settling flux plot, the system design is impacted in four ways: 1) aeration basin detention time decreases resulting in a decrease in aeration basin volume; 2) settling basin surface area increases resulting in a decrease in overflow rate; 3) the recycle pumping rate increases; and, 4) the underflow concentration decreases. This situation is depicted in Figure 8.

Review of Settling Basin Performance Models

A meaningful comparison of activated sludge system configurations requires a method to ensure that systems being compared produce equivalent effluent quality. A settling basin performance model would allow such a comparison. In addition, a settling basin performance model would allow design for clarification as well as thickening constraints.

A review of the literature reveals several performance models which predict effluent suspended solids concentration as a function of settling basin overflow rate, settling basin detention time, and mixed liquor suspended solids concentration. Among the models reported are the following:

1) Agnew (1972)

$$XE = 34(ORA)^{0.12}(PLI)^{0.27}(MLSS)^{-0.35}(DTIME)^{-1.03}$$

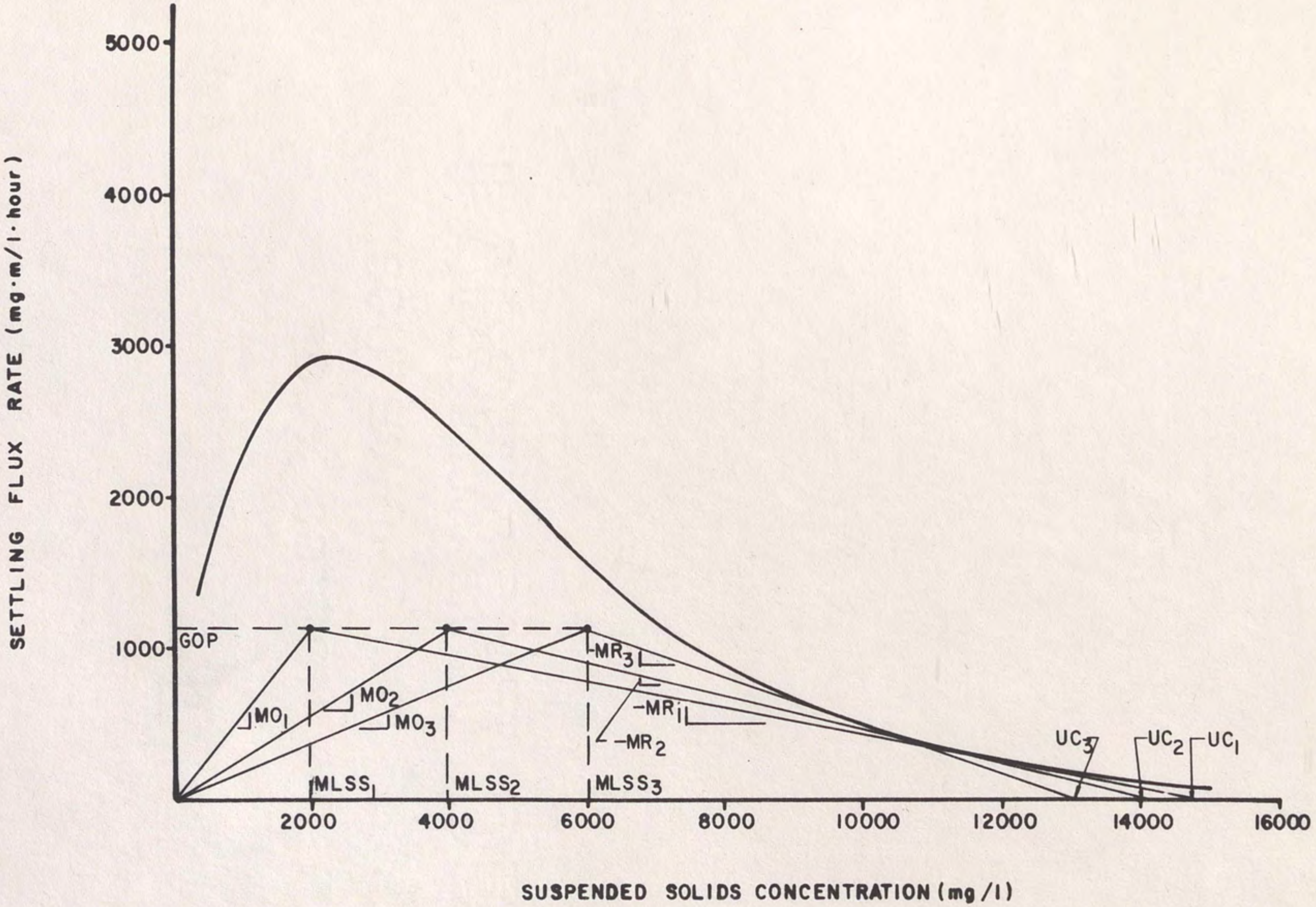

Figure 8: System Interaction with a Variable MLSS Concentration

2) Chapman (1983)

$$XE = -180.6 + 0.004(MLSS) + 0.23\ Q_A/A + SWD\ (27.49 - 0.0323\ Q_A/A)$$

3) Smith (1969)

$$XE = 1.928\ (ORA)^{0.494}\ (MLSS)^{-0.82}(DTIME)^{0.439}$$

4) Tuntoolavest et al. (1980)

$$XE = 0.01345(MLSS) - 0.00248(MLSS)(DTIME) + 0.0000066(MLSS)(ORA) - 6.51$$

where,

XE = Effluent suspended solids concentration (mg/l)

MLSS = Mixed liquor suspended solids concentration (mg/l)

ORA = Overflow rate (gpd/ft^2)

PLI = Process loading intensity (kg BOD/day - kg MLSS)

DTIME = Settling basin detention time (hours)

SWD = Side water depth (ft.)

QA/A = (Q + QR)/AREA = feed flow rate to the settling basin per unit surface area (gpd/ft^2).

Agnew (1972) developed his model based on results of a testing program that was carried out on final settling basins at three treatment facilities. Chapman (1983) developed a performance model using testing program results from a pilot scale settling basin which received its feed flow from a modified activated sludge treatment plant. Smith (1969) and Tuntoolavest et al. (1980) each developed models based on the results of testing programs on pilot scale treatment plants. Tuntoolavest's facility maintained the best control of the biological characteristics of the mixed liquor. Consequently, the Tuntoolavest model will be utilized for this study.

Tuntoolavest's study was carried out at the Purdue University Activated Sludge Pilot Plant. The plant was operated at 0.5 gpm and a constant solids retention time of 10 days. The treatment plant utilized a synthetic wastewater which contained dry-moist dog food as the organic fraction. The performance model reflects the importance of MLSS concentration, settling basin hydraulic detention time and overflow rate on effluent suspended solids concentration. The usefulness of this model for actual design of activated sludge secondary settling basins is limited to the specific wastewater for which it was developed. However, in this research, the model is used to help identify optimum system trends rather than for the design of specific systems.

Summary

The design process for the complete mix activated sludge system is complicated by interactions between the aeration basin and the settling basin. Consequently, the procedure for cost optimization of the complete mix activated sludge system is complex. The final settling basins play a major role in system interactions and in the system performance, therefore system design centers around the settling basin design.

The geometry of a circular settling basin is determined by the overflow rate and detention time. The overflow rate can be selected based on thickening constraints. The detention time could then be calculated based on clarification constraints. Several settling basin performance models for predicting effluent suspended solids concentration have been developed. A model with sensitivity to overflow rate, detention time and MLSS concentration was selected due to theoretical and experimental evidence supporting the importance of these variables to settling basin performance. The importance of biological characteristics of the mixed liquor on settling basin performance is significant but is very difficult to quantify. Other factors with less significant impacts (e.g., rate of aeration and recycle ratio) have not been well addressed at this time.

Although experimental and theoretical justifications exist for specification of settling basin detention time as an independent design criteria, current design practice is dominated by the consideration of overflow rate. If the settling basin surface area is selected using thickening constraints, the required detention time is met by selecting the settling basin depth. Several settling basin configurations (a surface area and a depth) could provide the desired effluent suspended solids concentration. Of these configurations, one represents the least cost configuration.

CHAPTER III

OPTIMIZATION PROCEDURE

An optimization routine was developed to perform a process design and to identify the most cost effective complete mix activated sludge treatment facility for a given wastewater and effluent quality constraints. The optimization routine considers the following treatment system components:

1. Aeration basin structure
2. Aeration equipment
3. Settling basin structure
4. Clarifier mechanism
5. Return sludge pumping facilities

The process design was formulated subject to constraints on effluent suspended solids, underflow solids concentration, maximum and minimum values for mixed liquor suspended solids concentration, and maximum and minimum values for settling basin depth. The process design was also constrained by the availability of specific equipment (i.e., standard size clarifier mechanisms, pumps, mechanical aerators, and pipes).

The specific objectives of the research program mandated careful attention to cost factors associated with settling basin geometry. Particular attention was therefore given to cost items which are sensitive to settling basin depth and diameter. The general procedure involved determination of unit quantities of concrete, earthwork, etc. associated with construction of a structure of specified dimensions. Structural requirements were considered in the process design, such that deeper basins were allowed a greater slab and wall thickness. Equipment vendors were contacted to obtain cost estimates for clarifier mechanisms, mechanical aerators, and pumps. In this manner sensitivity of the cost estimates to important design variables was assured.

In order to simplify the optimization procedure, consideration was limited to circular settling basins, rectangular aeration basins, mechanical surface aeration systems, and centrifugal sludge return pumps. This limitation is not believed to compromise the general applicability of the study results.

Methodology

The optimization methodology was developed around the settling basin design, utilizing the settling flux design approach. Design constraints were imposed to define the limits of practical system designs. The area bounded by the defined limits will be referred to as the feasible design space. An incremental search was used to locate the optimum design within the feasible design space. A more detailed discussion of the basis of the optimization methodology will be presented in this section.

Upon establishing a settling flux curve, the state point concept (Keinath et al. 1977) was utilized for settling basin design. In theory, any point under the settling flux curve is a feasible state point (see Figure 9). In reality, the feasible design space can be narrowed down considerably. Considering economics, a reasonable range of MLSS concentrations can be selected. Figure 10 depicts the boundaries imposed by a lower and an upper MLSS concentration constraint. In addition, a minimum settling basin underflow concentration constraint is imposed during design, thus limiting the feasible design space further (see Figure 11).

System Interactions

Physical and cost relationships for the activated sludge system were investigated to develop a reasonable search technique for location of an optimum system design. Interactions can be defined with respect to the location of the state point on the settling flux curve. Physical interactions and resulting cost relationships for a constant MLSS concentration with a variable operating flux rate and conversely for a variable MLSS concentration are discussed in the following paragraphs.

For a particular MLSS concentration, as the operating settling flux rate increases, the following system changes occur:

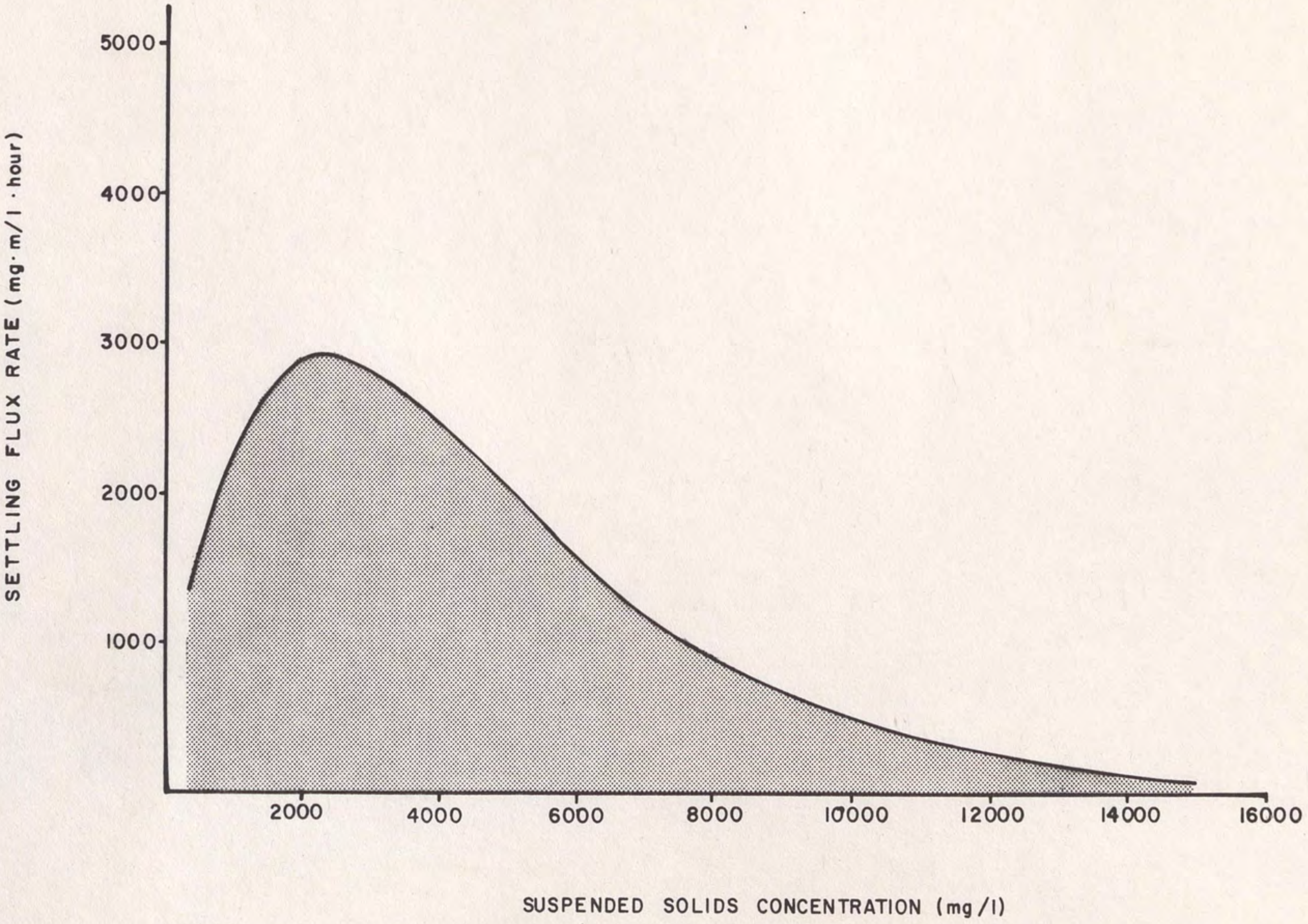

Figure 9: Theoretical Feasible Design Space

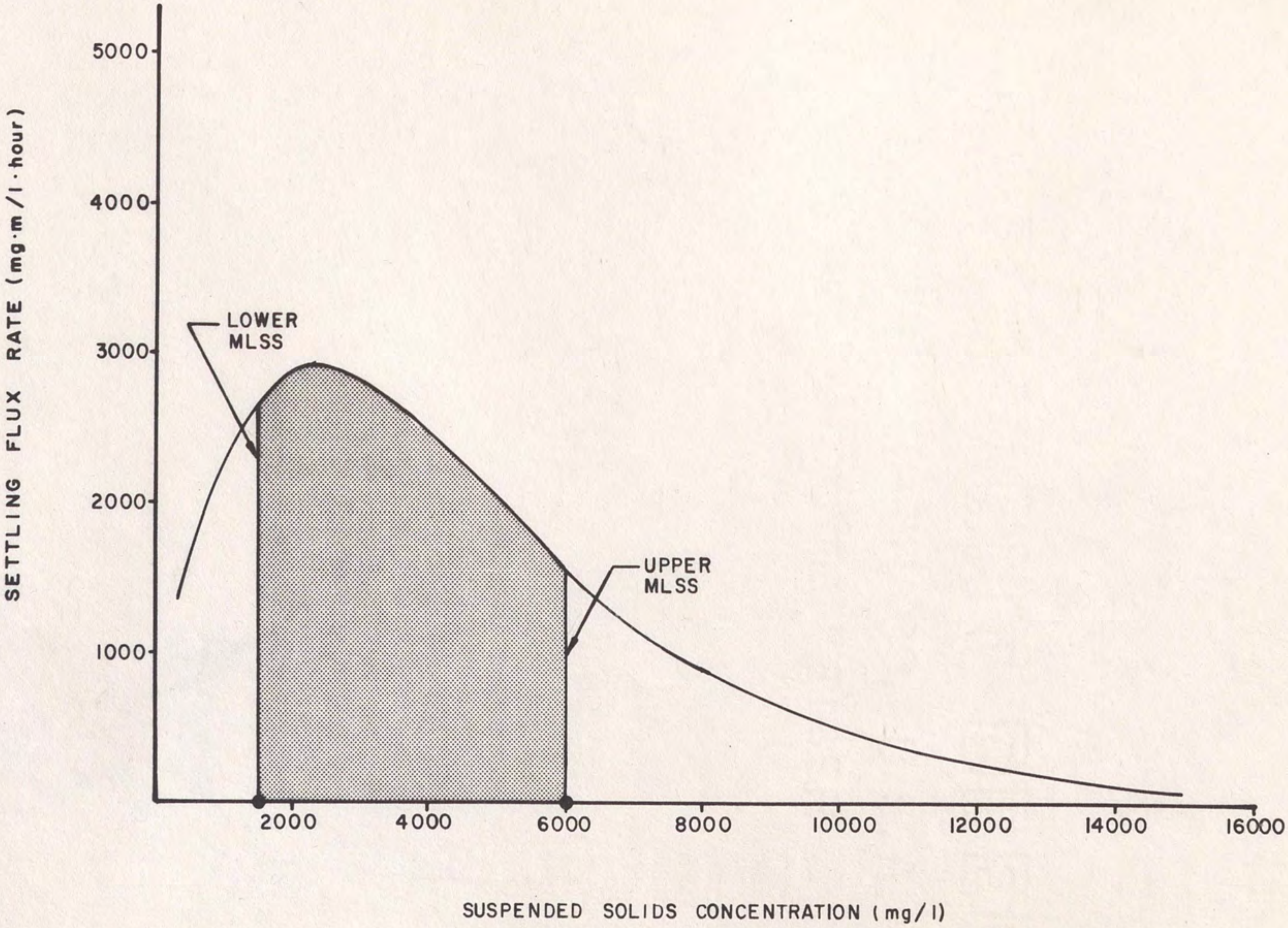

Figure 10 : MLSS Constraints

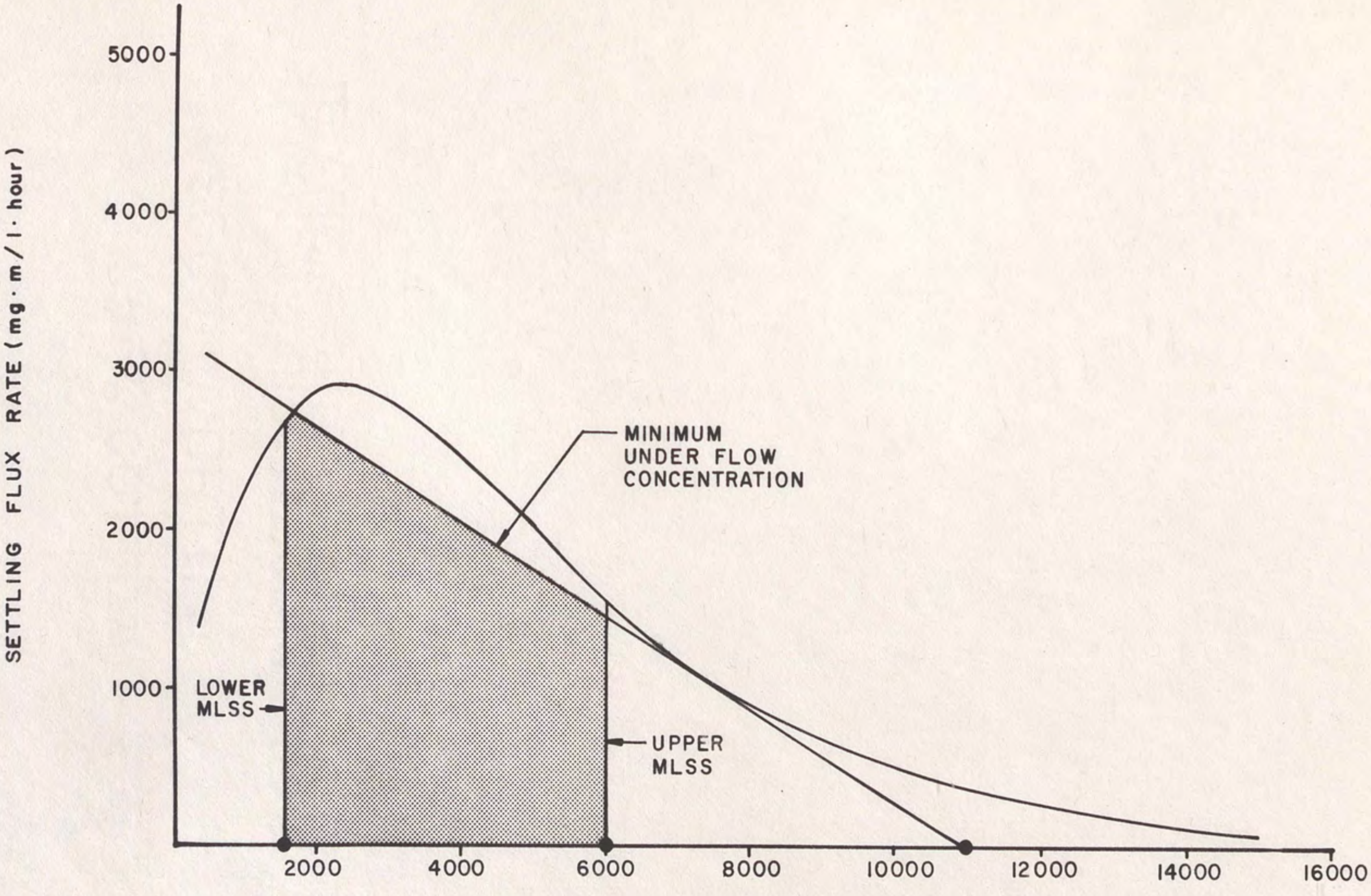

Figure 11: MLSS and Minimum Under Flow Constraints

1) The settling basin surface area required decreases resulting in an increase in the overflow rate.
2) Due to an increase in the overflow rate, the hydraulic detention time increases as specified by the settling basin performance model (Tuntoolavest et al. 1980). The settling basin depth increases to provide a larger detention time.
3) The return sludge pumping rate increases.
4) The underflow concentration decreases.

The economic implications of these changes are as follows:

1) An economic trade-off exists between settling basin surface area and depth. A decrease in surface area represents a cost savings, while an increase in depth represents an increase in cost. The resulting cost function for settling basins is presented in Figures 12 and 13.
2) An increase in the return sludge pumping rate results in an increase in pumping facilities cost.

Total system costs and component costs were calculated for the state points presented in Figure 12. The resulting cost functions are presented graphically in Figure 13. Costs are presented as the total annual equivalent costs (i.e., operation and maintenance costs plus the annual equivalent cost of the capital cost).

A second set of relationships are seen when the MLSS concentration is allowed to vary. The following system changes occur with an increase in MLSS concentration:

1) The settling basin surface area required increases resulting in a decrease in the overflow rate.
2) Due to a decrease in the overflow rate, the hydraulic detention time decreases as specified by the settling basin performance model (Tuntoolavest et al. 1980). The settling basin depth decreases to provide a smaller detention time.

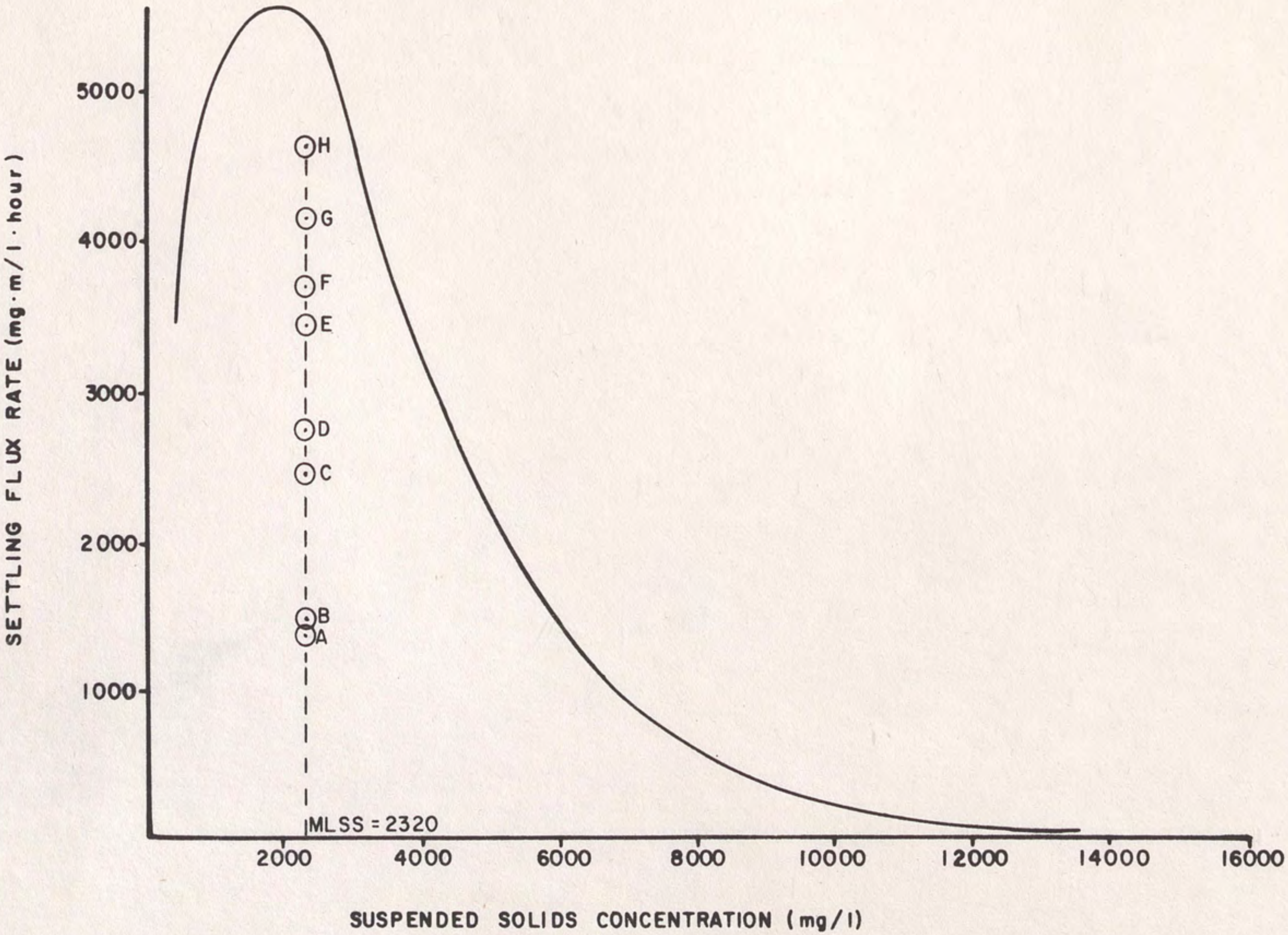

Figure 12: State Points Associated with the Cost Function for a Constant MLSS Concentration

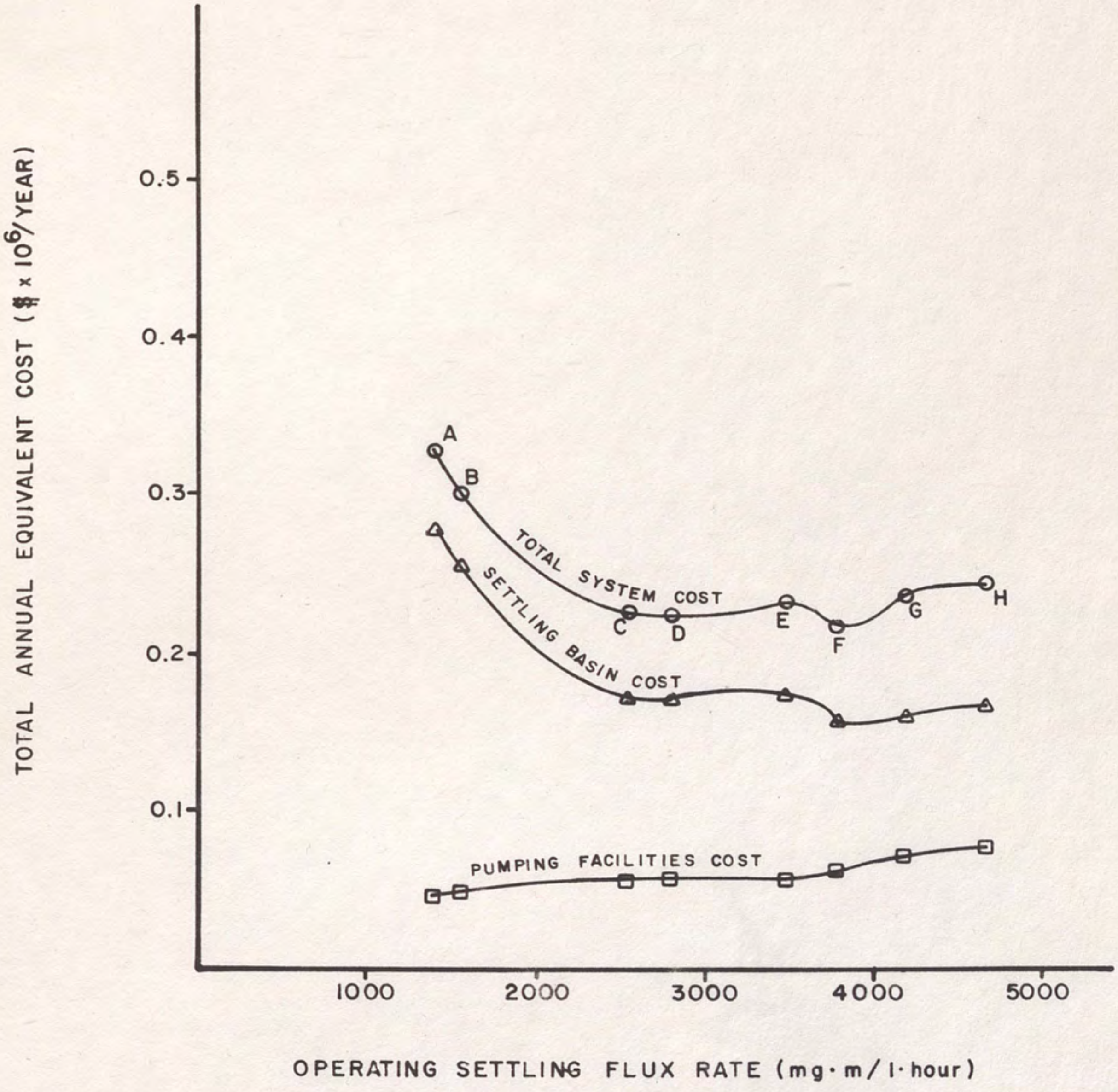

Figure 13: Cost Function for a Constant MLSS Concentration

3) The aeration basin hydraulic detention time decreases resulting in a decrease in aeration basin volume. Aeration energy requirements usually do not change since substrate removal is constant and oxygen requirements are usually the limiting factor when mechanical aerators are used.

4) The return pumping rate increases.

5) The underflow concentration decreases.

The economic implications of these changes are as follows:

1) The increased cost due to larger settling basin surface areas is the predominant cost factor, resulting in an increase in settling basin costs with an increase in MLSS concentration.

2) Aeration basin costs (annualized cost) decrease with a decrease in aeration basin volume.

3) An increase in the return sludge pumping rate results in an increase in pumping facilities cost.

Total system costs and component costs were calculated for the state points presented in Figure 14. The resulting cost functions are presented graphically in Figure 15. Costs are presented as the total annual equivalent cost (i.e., operation and maintenance cost plus the annual equivalent cost of the capital cost).

Search Technique

The search technique formulated involves evaluating costs at incremental MLSS concentrations. The least cost option for each MLSS concentration would be determined followed by a comparison of the least cost options to find an optimum design. In the interest of minimizing calculations, a large increment would be used to locate a

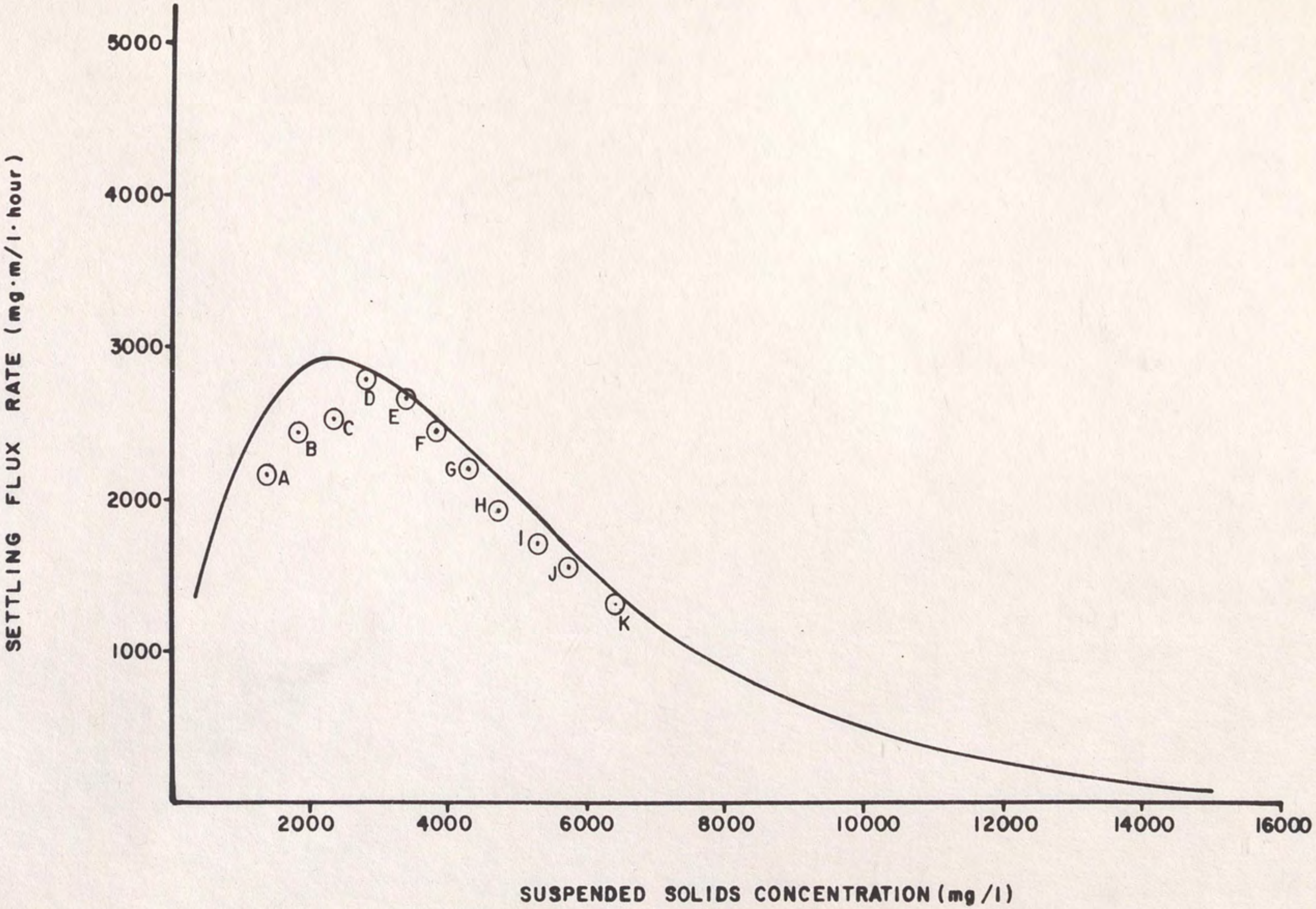

Figure 14: State Points Associated with the Cost Function for a Variable MLSS Concentration

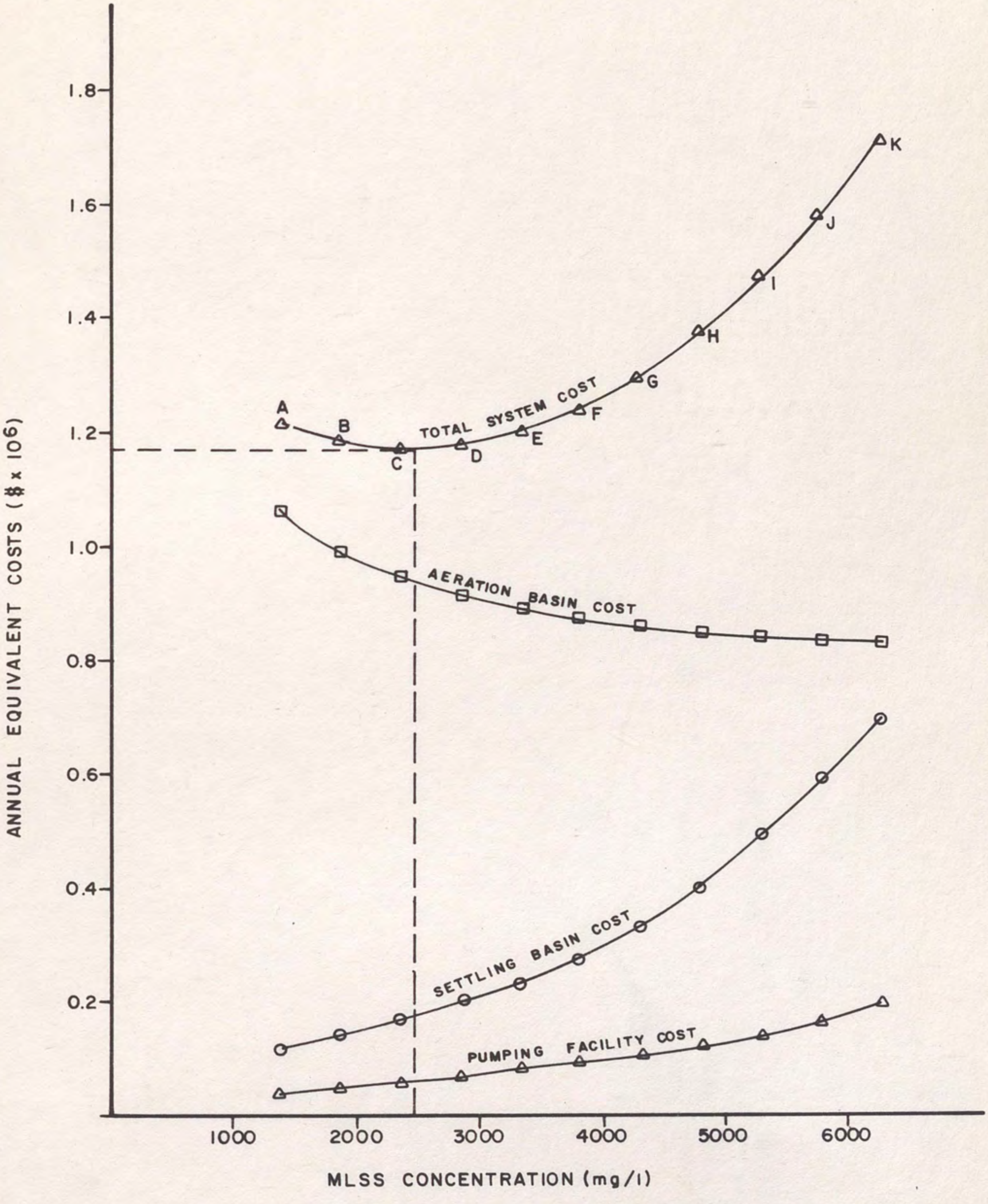

Figure 15: Variation of Component Cost and Total System Cost with MLSS Concentration

rough optimum design, then a smaller increment would be used to search in the general area of the rough optimum design to establish the optimum design. Increments of 500 mg/l and 100 mg/l respectively were used for this research.

Evaluations at individual MLSS concentrations were incremented with respect to overflow rate. Considering settling basin diameter constraints imposed by available clarifier mechanism sizes, attainable overflow rates were utilized as evaluation increments. The initial evaluation for each individual MLSS concentration occurs at the first attainable overflow rate less than or equal to the maximum overflow rate established by thickening and minimum underflow concentration constraints (i.e., state point H on Figure 12). After the overflow rate is determined, the location of the state point is established, then settling basin and pumping facilities costs are determined. Each additional evaluation occurs at the next highest attainable overflow rate (i.e., state point G on Figure 12). Calculations are terminated when evaluation N+1 results in a higher total cost than that for evaluation N. Evaluation N would be the least cost option for that particular MLSS concentration.

Summary of the Optimization Methodology

An outline of the optimization methodology follows:

I. Establish a settling flux curve

II. Establish constraints

  A. Lower and upper MLSS limitations

  B. Minimum underflow concentration

  C. Maximum effluent suspended solids concentration

III. Increment MLSS concentration (large increment)

IV. Locate least cost design for each MLSS
  A. Aeration basin process design and costs

  B. Increment overflow rate

    1. Evaluation N

      a. Establish overflow rate

      b. Locate state point

      c. Determine recycle rate and underflow concentration

      d. Settling basin process design and costs

      e. Return sludge pumping process design and costs

    2. Repeat 1 until N+1 cost is larger than N cost. Select evaluation N as least cost option.

V. Compare least cost designs to determine the rough optimum design.

VI. Increment MLSS concentration for search near rough optimum design (small increment)

VII. Repeat IV.

VIII. Compare least cost designs to determine the optimum design.

CHAPTER IV

COMPUTER PROGRAM

If calculated by hand, one iteration through the optimization methodology proposed in Chapter III would be quite time consuming. Completion of an entire optimization problem would be very burdensome. To allow practical application of this procedure, a FORTRAN computer program using the optimization methodology was developed. This chapter discusses the applications for the program and provides a detailed description of the program.

Applications

The computer program was written to aid in identifying the characteristics of an optimum complete mix activated sludge system and as a tool for evaluation of the sensitivity of process design to several process variables. The value of this program as a direct design tool depends on advancements in the area of settling basin performance modeling. The current technology for predicting the effluent suspended solids concentration from an activated sludge final settling basin is limited. Use of this program as a design tool is also hindered due to the requirement for specific data for the intended application.

Program Description

The optimization program consists of a main program and nine subroutines. The main program reads data, prints results and generally directs the flow of information. The nine subroutines provide process design and cost estimation for the activated sludge system components. The program is described in portions. The main program is described first since it is the backbone of the program. Subroutine descriptions follow in the order of normal program execution. A listing of subroutines and a brief description of their functions is presented in Table 5.

Main Program

The main program (1) reads data, (2) directs the flow of information and performs limited process design calculations, and (3) prints results. The main program is described in three sections corresponding to the functions described above.

Input

Most data required to complete the optimum design of a complete mix activated sludge system is read into the computer by the main program. Data which is most likely to remain constant from one run to the next is built into the program (i.e., the value of each of these variables is defined by assignment statements at the beginning of the program). Data which is subject to change from one run to the next is read in before each run.

TABLE 5

SUBROUTINES AND THEIR FUNCTIONS

Subroutine	Function
LLSQ	Fits curve to settling data using a linear regression technique.
AERATE	Provides process design and cost calculations for the aeration basin system.
LFLUX	Determines the operating flux and the limiting flux for a given underflow concentration.
SIZE	Determines the settling basin diameter.
RECYCL	Determines the return pumping rate and the underflow concentration for an established state point.
DPTH	Determines the settling basin depth.
PUMP	Provides process design and cost calculations for the return sludge pumping facilities.
CLARI	Provides material quantity estimation and cost calculations for the settling basin system.
INDCO	Determines indirect capital costs and calculates the annual equivalent cost of the total capital costs.

Variables defined by assignment statements can be redefined by the user by entering the program and changing the desired values. Variables defined by assignment statements in the main program include unit prices, interest rate and evaluation period for economic analysis, the Marshall and Swift Equipment Cost Index, and the percent volatile solids for the mixed liquor suspended solids. Unit price data built into the main program is identified in Table 6. Assignment statements are also used to identify constants and cost information in the subroutines.

The remaining data is input by the designer; required user input variables are identified in Table 7. Optional user input variables are also identified in Table 7. Instead of using the settling basin performance model (Tuntoolavest et al. 1980) to determine settling basin detention time, the designer may designate a constant detention time. The lower and upper limits for aeration basin hydraulic detention time have been pre-set, however, the designer may override the pre-set values and select different limits. Data input by the designer is echo printed to the output file.

Process Design Direction

Settling data provided by the designer is statistically evaluated and the settling flux curve is established using subroutine LFLUX. The boundaries for the optimum system

TABLE 6

UNIT PRICE DATA BUILT INTO THE MAIN PROGRAM

Item	Variable Designation	Unit Price	Units
Reinforced Concrete Wall in Place	UPICW	$280.00	yd^3
Reinforced Concrete Slab in Place	UPICS	$200.00	yd^3
Excavation	UPIEX	$ 2.50	yd^3
Crane Rental	UPICR	$ 50.00	hour
Building Cost	UPIBC	$ 30.00	ft^2
Salary - Labor	LABRI	$ 14.00	hour
Salary - Maintenance	SALM	$ 12.00	hour
Salary - Plant Operator	SALOP	$ 18.00	hour
Power Cost	UPIPC	$ 0.08	KWH

Note: Unit price costs are 1985 costs

TABLE 7

USER INPUT VARIABLES

Item	Designation	Units
Required Data		
Effluent Suspended Solids Concentration	XE	mg/l
Minimum Underflow Concentration	MUC	% solids
Settling Data Pairs	SV(I) CONC(I)	m/hours or ft/day mg/l or lb/c.f.
Maximum Possible Cell Yield	YMAX	mg VSS/mg BOD5
Endogenous Decay Coeff.	KD	day^{-1}
Half Velocity Constant	KS	mg BOD5/l
Maximum Rate of Substrate Utilization per Unit Mass of Microorganisms	KMAX	day^{-1}
Average Daily Flow Rate	Q	GPD
Influent Substrate Concentration	S	mg BOD5/l
Mean Solids Residence Time	SRT	Days
Optional Data		
Settling Basin Detention Time	OPTDT	Hours
Lower Limiting Aeration Basin Detention Time	LOWDET	Hours
Upper Limiting Aeration Basin Detention Time	HIDET	Hours

search, the lower and upper MLSS values are then calculated as follows:

LOMLSS = 24 YMAX (S - SE)SRT / [PVS (1 + KD SRT) HIDET]

HIMLSS = 24 YMAX (S - SE)SRT / [PVS (1 + KD SRT) LOWDET]

where,

LOMLSS = Lower limiting MLSS concentration (mg/l)

HIMLSS = Upper limiting MLSS concentration (mg/l)

YMAX = Maximum possible cell yield (mg VSS/mg BOD5)

S = Influent substrate concentration (mg/l)

SE = Effluent substrate concentration (mg/l)

SRT = Sludge age (days)

PVS = Percent volatile solids (%/100)

KD = Endogeneous decay coefficient (day^{-1})

HIDET = Upper limiting aeration basin detention time (hours)

LOWDET = Lower limiting aeration basin detention time (hours)

24 = Conversion factor from days to hours

A search increment (INCRMT) of approximately 500 mg/l is established, with a minimum of eight increments over the range of LOMLSS to HIMLSS.

An iterative loop is established to provide process design and economic evaluations for successive MLSS concentrations from LOMLSS to HIMLSS at an increment equal to INCRMT. For a particular MLSS concentration the aeration basin design remains constant regardless of the recycle sludge pumping rate, however, several settling basin configurations (surface area versus depth) of equal efficiency may exist. The least cost configuration (settling basin plus pumping) is determined for each MLSS concentration. These are compared to determine a rough optimum option. Details of the least cost design evaluation are described in the following paragraphs.

Subroutine AERATE provides process design and economic analysis for the aeration basin system. The limiting settling flux is then determined by subroutine LFLUX for each given MLSS concentration and the minimum underflow concentration. Using the limiting settling flux provided by subroutine LFLUX, subroutine SIZE determines the diameter (DIA) and number (NBASIN) of equal-sized settling basins with a total area greater than or equal to that area required to produce the overflow rate associated with the limiting settling flux.

A second iterative loop is established inside of the first loop to evaluate alternative settling basin and return sludge pumping configurations in order to select a least cost configuration for each MLSS concentration. The total settling basin surface area is established using the following equations:

$$\text{AREA} = 3.1416\ \text{NBASIN}\ (\text{DIA}^2)\ /\ 4.0$$

where,

AREA = Total settling basin area (ft^2)

NBASIN = Total number of settling basins

DIA = Settling basin diameter (feet)

The overflow rate is then established as noted:

ORA = Q / AREA

where,

ORA = Settling basin overflow rate (gpd/ft^2)

Q = Average daily flow rate (gpd)

The operating settling flux rate (GOP) is then easily established:

GOP = ORA (MLSS / 589.08)

where,

GOP = Settling flux rate (mg-m/l-hour)

589.08 = Conversion factor

The state point (MLSS, GOP) is now established for this alternative. Subrouting RECYCL uses the state point to construct a recycle operating line and in doing so establishes the minimum return sludge pumping rate and the maximum underflow solids concentration. The settling basin depth is established by subroutine DPTH using the settling basin performance model (Tuntoolavest et al. 1980).

Subroutine PUMP selects return sludge pumping equipment and provides a cost for the return sludge pumping facilities. Subroutine CLARI provides a cost for the settling basin system. The total cost (aeration basin cost + settling basin cost + pumping facilities cost) is calculated and stored.

The settling basin size is increased to the next commercially available surface area by increasing the settling basin diameters by one increment. If the initialsettling basin diameter is 100 feet, the number of units is increased by one and the diameter is selected to produce a total area greater than or equal to the initial total area. In this way, the state point is moved downward on the settling flux plot while remaining at the same MLSS concentration. The overflow and recycle pumping rates both decrease.

The process design and cost analysis for the settling basin system and the recycle sludge pumping facilities is executed for this alternative by returning to the beginning of the second iterative loop. The resulting total cost (aeration basin cost + settling basin cost + pumping facility cost) is calculated and compared to the previous total cost. The iterative procedure is repeated until cost N+1 is greater than cost N. Alternative N is identified as the least cost alternative for the specific MLSS concentration.

Upon determining a rough optimum MLSS concentration, a fine search using a small MLSS increment is initiated in the area of the rough optimum design. The new search range is equal to INCRMT (previous increment). The new increment is approximately 100 mg/l, however, a minimum of five increments are used. The total cost for options with MLSS concentrations one increment less than and one increment greater than the rough optimum are calculated. The two costs are compared to determine the direction of decreasing costs. If costs are decreasing for lower MLSS concentrations, the new lower and upper MLSS concentrations (boundaries) are found as follows:

LOMLSS = OPMLSS - (NUMBER - 1) INCRMT

HIMLSS = OPMLSS - INCRMT

where,

OPMLSS = Rough optimum MLSS concentration (mg/l)

NUMBER = Number of increments

INCRMT = Search increment

If, on the other hand, cost are decreasing for higher MLSS concentrations, the new lower and upper MLSS concentrations (boundaries) are found as follows:

LOMLSS = OPMLSS + INCRMT

HIMLSS = OPMLSS + (NUMBER - 1) INCRMT

Using the new LOMLSS, HIMLSS and INCRMT the main iterative loop is re-initialized. The identical procedure is followed; least cost configurations are found at each MLSS concentration and then compared to determine an optimum cost option. The results from this iteration produces the final optimum complete mix activated sludge system.

Results

Design information, capital costs, annual operation and maintenance costs, and total annual equivalent costs for the settling basin system, the aeration basin system, and the sludge pumping facilities are printed to an output file. Results are printed after each iteration through the second iterative loop and at the end of the program to identify the optimum complete mix activated sludge system.

Subroutine LLSQ

Subroutine LLSQ algebraically defines the settling flux plot by fitting a curve to the settling data provided by the designer. Two curve fitting parameters, VO and K, are calculated for later use in the program.

Vesilind (1968) found that a transform of the settling data (the plot of the natural logarithm of the settling velocity versus suspended solids concentration) results in a linear function. Therefore a linear least squares technique can be used to fit a line to the plot of the natural logarithm of the settling velocity versus suspended solids concentration. The fitted line has the equation:

$$\mathrm{LN(SV)} = \mathrm{M(CONC)} + b$$

$$\text{or} \quad \mathrm{SV} = e^{\mathrm{M(CONC)}}\, e^{b}$$

where,

SV = settling velocity (m/hour)

CONC = suspended solids concentration (mg/l)

M = slope of the LN(SV) vs. CONC line (l/mg)

b = settling velocity intercept of the LN(SV) vs. CONC line

The settling flux rate is the product of the suspended solids concentration and the settling velocity at that concentration. The equation of the settling flux plot can therefore be defined as:

$$\mathrm{FLUX} = \mathrm{CONC(VO)}\ e^{-C/K}$$

where,

$\mathrm{VO} = e^{b}$

$\mathrm{K} = -1/\mathrm{M}$ (mg/l)

FLUX = settling flux rate (mg-m/l-hour)

VO and K are curve fitting parameter while FLUX and CONC are variables.

Subroutine AERATE

Subroutine AERATE provides process design for the aeration basin system for a given flow rate, wastewater characteristics, kinetic constants, and treatment standards. In addition, an annual equivalent cost is developed for the aeration basin system. The cost analysis considers both capital and operation and maintenance costs.

Process Design

Algebraic manipulation of the Lawrence and McCarty (1970) bioxidation model for complete mix activated sludge systems allows determination of the hydraulic detention time for a given MLSS concentration:

$$\mathrm{HDT} = \mathrm{YMAX(S-SE)(SRT)(24)/[PVS\ (1.0 + KD\ SRT)\ MLSS]}$$

where,

HDT = aeration basin hydraulic detention time (hours)

YMAX = maximum yield (mg VSS/mg BOD5)

S = influent substrate concentration (mg/l)

SE = effluent substrate concentration (mg/l)

SRT = sludge age (days)

PVS = fraction volatile solids

KD = endogeneous decay coefficient (day^{-1})

MLSS = mixed liquor suspended solids concentration (mg/l)

A preliminary aeration basin volume is calculated using the following equation:

$$VAT = Q(HDT)/179.52$$

where,

VAT = aeration basin volume (ft^3)

Q = average daily flow rate (gpd)

179.52 = conversion factor

To allow for peak demands and emergencies the preliminary aeration basin volume is multiplied by an excess capacity factor. Bernard and Eckenfelder (1971) recommend the following:

$$ECFT = 1.3 - (.002(Q)/1000000)$$

where,

ECFT = aeration basin excess capacity factor

An ECFT of 1.3 was incorporated into this design procedure. The hydraulic detention time is recalculated to incorporate the excess capacity:

$$HDT = [179.52(VAT)/Q]ECFT$$

Mechanical aerators are sized considering both oxygen requirements and mixing requirements. Oxygen requirements are calculated using biological kinetics as follows:

$$OXREQ = [Q(S-SE)/2{,}876{,}132][1.42 - (1.42\ YMAX/(1.0 + KD\ SRT))]$$

where,

OXREQ = oxygen required (lb/hour)

1.42 = conversion factor from BOD5 to ultimate BOD

2,876,132 = conversion factor

The oxygen rating of the low speed mechanical aerators was assumed to be 3.4 lb O_2/hp-hour for standard test conditions (Reynolds 1982). The actual rate of oxygen mass transfer at field condition is calculated using the equation noted below (Reynolds 1982):

$$AOR = SOR(ALPHA)(CW-CL)(1.024^{T-20})/9.17$$

where,

AOR = rate of oxygen transfer at operating conditions (lb/hp-hour)

SOR = oxygen rating of the aerator under standard test conditions (lb/hp-hour)

ALPHA = relative rate of oxygen transfer as compared to tap water (K_La wastewater/K_La water)

CW = saturation dissolved oxygen concentration at operating conditions (mg/l)

CL = dissolved oxygen concentration in the MLSS (mg/l)

T = operating temperature of the wastewater (degrees centigrade)

The horsepower required to meet the oxygen demand is equal to:

HPOX = OXREQ/AOR

where,

HPOX = total horsepower needed to meet oxygen demand (hp)

To allow for peaks in mass loading and flow rate, an excess capacity factor used in sizing mechanical aerators to meet oxygen demand is recommended by Bernard and Eckenfelder (1971) as noted below:

ECFA = 1.8 - (0.004(Q)/1000000)

where,

ECFA = mechanical aerator excess capacity factor

An ECFA of 1.8 was used in this model. The horsepower required to meet oxygen demand is recalculated as noted below:

HPOX = HPOX(ECFA)

Reynolds (1982) recommends 0.5 to 1.0 horsepower per 1000 cubic feet of aeration basin volume to meet mixing requirements. A rate of 0.75 horsepower per 1000 cubic feet is used for this design. Aerators are sized based on the larger of the horsepower requirements that are necessary to meet oxygen demand or mixing needs. The oxygen demand horsepower requirements are normally larger for mechanical aerators.

Selection of the number of aeration tanks and the number of aerators per tank is made based on the average daily flow rate (Q). If Q exceeds 100 million gallons per day (mgd) the aeration basin system is designed using multiple batteries of tanks. Flow is split evenly between batteries, never to exceed 100 mgd to a battery (CAPDET 1982). Selection of the number of tanks (NT) and the number of aerators per tank (NAPT) is made based on the selection process presented in Table 8.

The horsepower required for each individual mechanical aerator (HPN) is calculated using the following equation:

$$HPN = HP/[NAPT(NT)(NB)]$$

where,

HPN = horsepower required for each individual aerator (hp)

HP = total horsepower requirements (hp)

NB = number of batteries of tanks

The smallest available aerator with horsepower (HPSN) larger than or equal to HPN is selected. Mechanical aerators are available in 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 100, 125, and 150 horsepower sizes. If HPN is larger than 150 horsepower and NT is smaller than 4, NT is increased by one. If HPN is larger than 150 horsepower and NT is larger than or equal to 4, NT is increased by two. HPN should then be recalculated and the available aerator size selected.

TABLE 8

SELECTION OF THE NUMBER OF AERATION BASINS AND THE NUMBER OF AERATORS PER BASIN

Q (MGD)	Number of Aeration Tanks - NT	Number of Aerators Per Tank - NAPT
0 - 2	2	1
2 - 4	3	1
4 - 10	4	1
10 - 20	6	2
20 - 30	8	2
30 - 40	10	3
40 - 50	12	3
50 - 70	14	3
70 - 100	16	4

Source: CAPDET 1982

The volume of each individual aeration tank (VATN) is equal to:

$VATN = VAT/[NT(NB)]$

where,

VATN = individual aeration basin volume (ft^3)

The depth of the aeration basins is controlled by the size of the mechanical aerators. The depth must be great enough to prevent interference with the mixing current and oxygen transfer. The following equations express the relationship between the recommended basin depth and aerator capacity (CAPDET 1982):

when $HPSN \leq 100$ HP $\quad DW = 4.816(HPSN^{0.2467})$

when $HPSN > 100$ HP $\quad DW = 15$

where,

DW = aeration basin depth (feet)

HPSN = The horsepower of the smallest available aerator with horsepower larger than or equal to HPN.

Since rectangular aeration basins are used, the ratio of the width to the length of an aeration basin is equal to the number of aerators per tank. Therefore, an aeration basin with one aerator will be square while an aeration basin with N aerator will have the length equal to N times the width. Length and width are found as noted below:

$W = [VATN/DW(NAPT)]^{0.5}$

$L = W(NAPT)$

where,

W = individual aeration basin width (feet)

L = individual aeration basin length (feet)

When the number of aeration tanks is greater than or equal to four, a piping gallery will be used to house the various piping systems and control equipment. The width of the pipe gallery is calculated based on an experience curve and shown below (CAPDET 1982):

$$PGW = 20 + [0.3(Q)/1000000(NB)]$$

where,

PGW = pipe gallery width (feet)

Economic Analysis

Capital cost items considered include aeration equipment, excavation, concrete slabs and walls, equipment installation costs and miscellaneous costs associated with the installation of equipment. Selection of the number and size of aerators was discussed previously. The amount of excavation was calculated using guidelines presented in "CAPDET" (1982). The thickness and quantity of concrete walls and slabs were also estimated using "CAPDET" (1982) guidelines. Equipment installation costs include labor and crane hours required to complete installation of the mechanical aerators. Labor and crane hours for installation of each aerator are based on aerator horsepower (CAPDET 1982). Miscellaneous equipment installation costs include electrical wiring, setting, painting, inspection, etc. These costs are calculated as a percentage of the purchased equipment cost (CAPDET 1982).

Unit costs for mechanical aerators ranging in size from 5 to 150 horsepower were obtained from a vendor. Other unit costs used in evaluating capital costs for the aeration basin system are presented in the description of the main program.

The total bare construction cost is calculated and is then adjusted to include indirect costs. Subroutine INDCO calculates indirect costs (engineering fees, contingencies, etc.) as a percentage of the total bare construction cost and then sums the two to produce the total capital cost. Subroutine INDCO then converts the total capital cost to an annual equivalent cost.

Annual operation and maintenance cost items considered include operation man hour requirements, maintenance man hour requirements, energy consumption, and operation and maintenance material supply cost. Operation and maintenance man hour requirements are calculated as a function of the total horsepower of the aeration equipment (CAPDET 1982). Energy requirements are estimated assuming that all aerators will be operated 90 percent of the time for each year (CAPDET 1982). Operation and maintenance material supply costs are calculated as a percentage of the installed cost for aerators as outlined in "CAPDET" (1982).

The total annual operation and maintenance costs are calculated using the unit costs presented in the description of the main program. The total annual equivalent cost for the aeration basin system is determined by summing the annual equivalent cost (of the total capital cost) and the annual operation and maintenance cost.

Subroutine LFLUX

Subroutine LFLUX identifies the operating settling flux (GOP) for a given underflow suspended solids concentration (CU) and mixed liquor suspended solids concentration (MLSS). In addition, subroutine LFLUX identifies the maximum operating settling flux rate (GMAX) for a particular MLSS concentration with respect to the minimum underflow concentration (MUC) and thickening constraints. Identification of each of these points is illustrated in Figure 16 and described in the following paragraphs.

For a given CU and MLSS concentration the operating settling flux is found by defining a recycle operating line through the CU and tangent to the settling flux curve. Two tangent lines can be defined for each CU (see Figure 17). The tangent line which intersects the settling flux curve between the origin and the point of tangency is the recycle rate operating line (line A). The operating settling flux rate (GOP) is the settling flux corresponding to the state point, which is the point of intersection of the recycle operating line and the desired MLSS concentration.

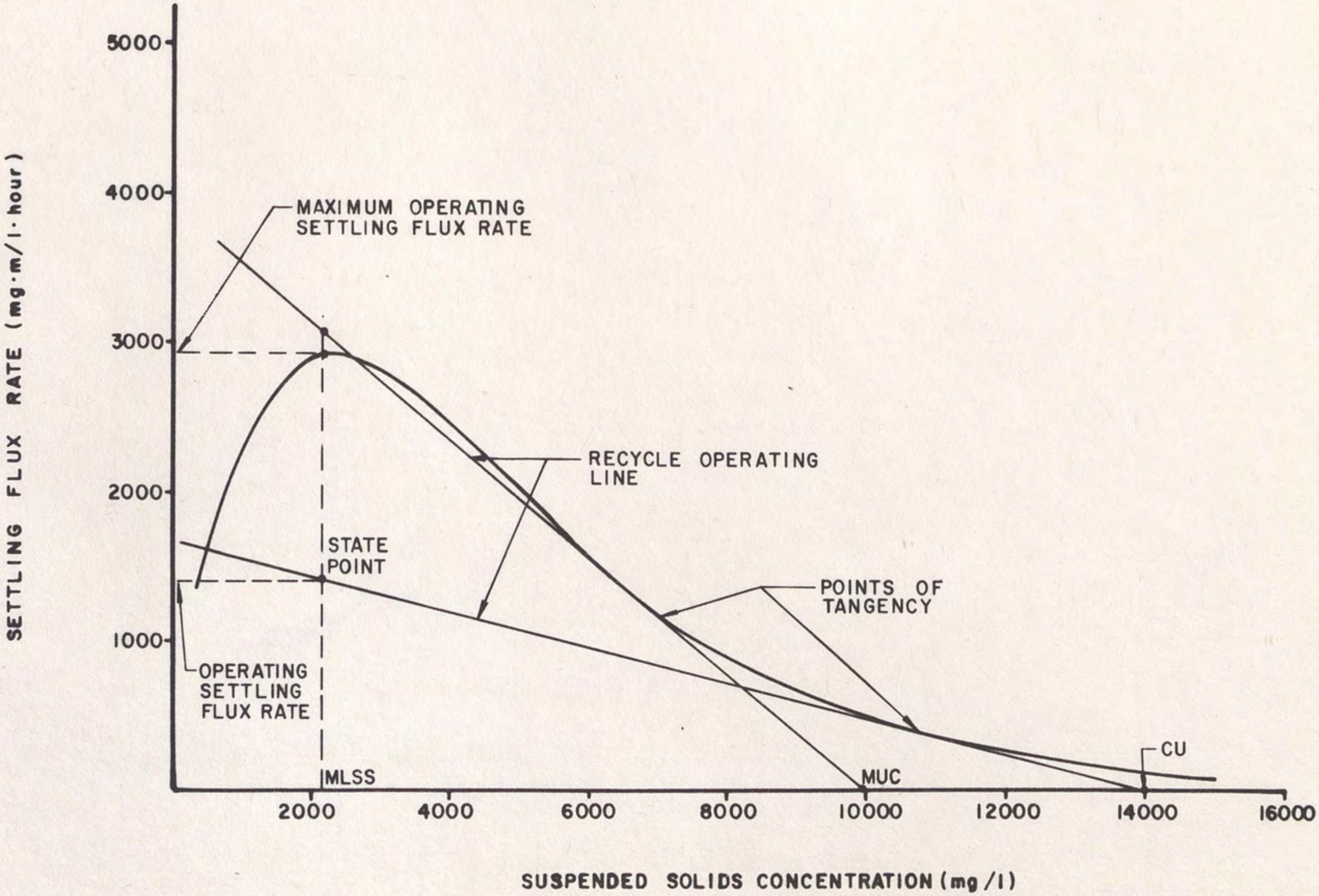

Figure 16: Identification of the Operating Settling Flux and Maximum Operating Settling Flux Rates.

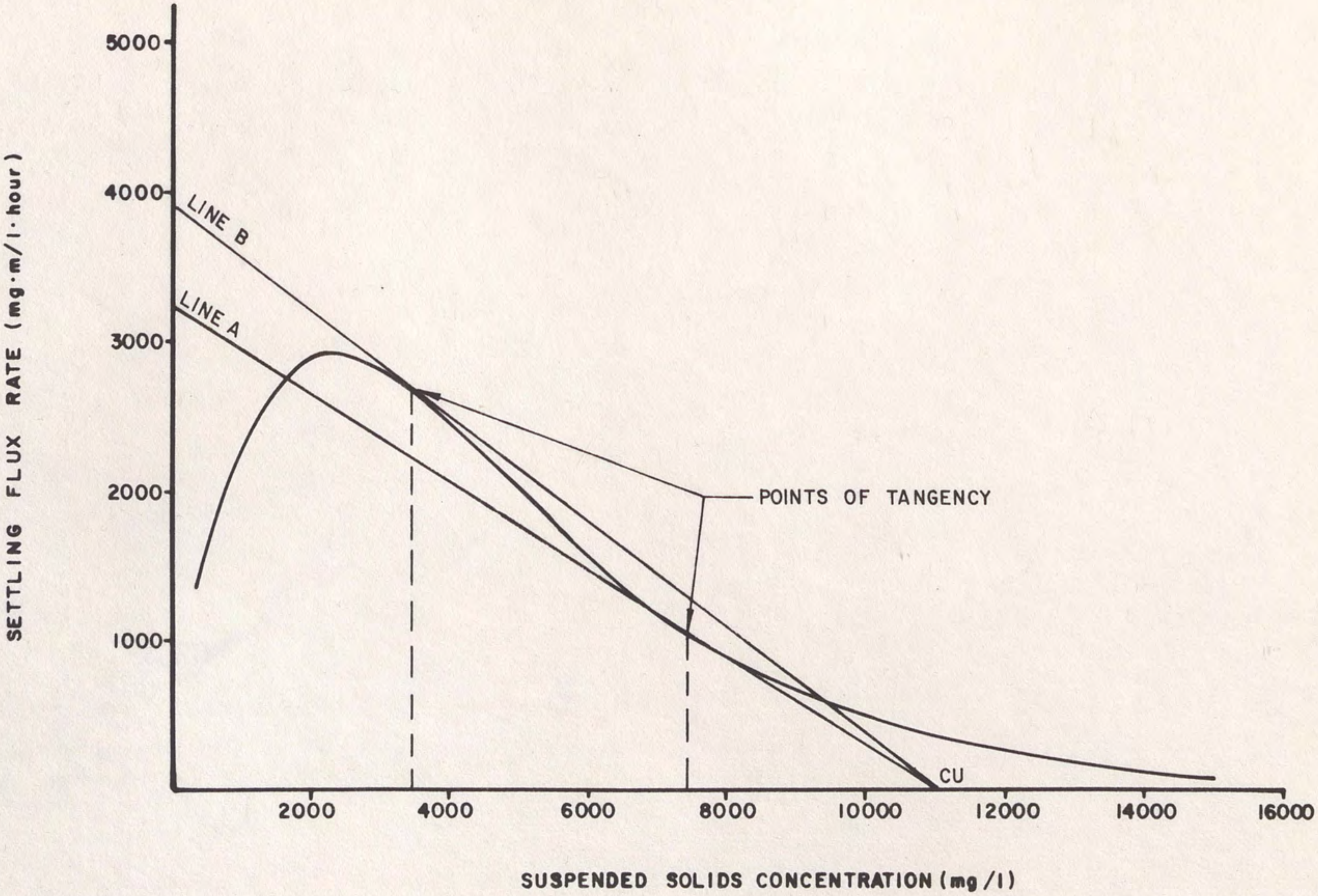

Figure 17: Identification of the Recycle Rate Operating Line

The maximum operating settling flux rate for a particular MLSS concentration is the operating settling flux rate found when the CU is equal to the MUC. However, when the state point defined in this manner is above the settling flux curve, the limiting settling flux rate is equal to the settling flux rate defined by the settling flux curve at the desired MLSS concentration. If the designer chooses a MUC which is too low, a tangent cannot be defined to the settling flux curve. In this case, the MUC is redefined by default as the minimum underflow concentration physically allowed using the settling flux data. This point is defined as the underflow concentration resulting when a recycle operating line is drawn tangent to the settling flux curve at the inflection point.

Subroutine SIZE

Subroutine SIZE determines the number of settling basins and the diameter for a given MLSS concentration and maximum operating flux rate. The number of units and diameter are determined for the first state point for each MLSS concentration (e.g., Figure 12, state point H). Subsequent settling basin quantity and diameter selections are made in the main program.

Settling basin diameters are limited to those conforming to available circular clarifier mechanism sizes. Diameters in five foot increments ranging from 20 feet to 100 feet are considered in diameter selection.

Clarifier mechanisms of larger diameter are available, however, larger settling basinswere avoided due to their susceptibility to operating problems caused by wind effects on the surface of the tank. The effects of wind are surface mixing and mixing well below the surface which may cause increased solids loss resulting in dramatic decreases in settling basin efficiency (WPCF 1977).

The maximum allowable overflow rate, at the desired MLSS concentration, is calculated using the maximum operating settling flux rate determined by subroutine LFLUX. The area required to achieve the maximum allowable overflow rate is found by dividing the average daily flow rate by the maximum allowable overflow rate. The minimum number of equal-sized basins (from 20 to 100 feet in diameter) is identified to provide a total area equal to or greater than the area required to achieve the maximum overflow rate.

Subroutine RECYCL

Subroutine RECYCL determines the underflow concentration (CU) and the sludge recycle flow rate (QR) for a given state point with coordinates (MLSS, GOP). CU is the underflow suspended solids concentration associated with the tangent line (recycle rate operating line) passing through the state point. The product of the slope of the recycle operating line times the total settling basin surface area is equal to QR.

The recycle operating line is established using a simple search technique. In the search technique CU is varied until the recycle operating line intersects the desired MLSS concentration at an operating settling flux equal to GOP. The operation flux at each CU is determined using subroutine LFLUX.

Subroutine DPTH

Subroutine DPTH determines the settling basin clear zone detention time based on a settling basin performance model sensitive to MLSS concentration, overflow rate, and detention time. Alternatively, the designer can specify a specific clear zone detention time. The clear zone detention time is then used to calculate the settling basin clear zone depth.

The settling basin performance model used was developed by Tuntoolavest et al. (1980) as noted below:

$$XE = 0.01345(MLSS) - 0.00248(MLSS)(DTIME) + 0.0000066(MLSS)(ORA) - 6.51$$

where,

XE = effluent suspended solids concentration (mg/l)

MLSS = mixed liquor suspended solids concentration (mg/l)

DTIME = settling basin clear zone detention time (hours)

ORA = overflow rate (gpd/ft^2)

The authors investigated systems with overflow rates which ranged from 400 to 1200 gpd/ft^2, but reported that the response was not sensitive to overflow rates at the lower end of this range. It was also reported that performancewas very sensitive to changes in detention period for systems with low overflow rates (i.e., 400 gpd/ft^2). For this study the cited performance model was modified to remove sensitivity of settling basin performance to overflow rate for overflow rates less than 600 gpd/ft^2. The following equation was employed for overflow rates of 600 gpd/ft^2 and less:

$$XE = 0.01345(MLSS) - 0.00248(MLSS)(DTIME) + 0.00396(MLSS) - 6.51$$

Settling basin depths are established using detention times and overflow rates. For practicality, depths were constrained to values between 8 and 30 feet. Detention times were recalculated based on the actual depth specified considering these constraints.

Subroutine PUMP

Subroutine PUMP provides process design for the return sludge pumping facilities for a given average return pumping rate. In addition, an annual equivalent cost is developed for the return sludge pumping facilities. The cost calculations consider both capital and operation and maintenance costs.

Process Design

The design flow rate (RETFLO) for return sludge pumps is 1.5 times the average daily influent flow rate (Q). Selectionof the pump horsepower, pump size (in inches), return sludge pipe diameter and the number of pumps is based on the design flow rate. If the design flow exceeds 6440 gallons per minute, the system is designed using multiple batteries of pumps. The design flow is split evenly between batteries with a maximum flow of 6440 gallons per minute per battery.

System curves were developed for pipes from 4 inches to 14 inches in diameter. System curves were then plotted on pump curves for centrifugal sludge pumps ranging in size from 4 inches to 8 inches. The "best" pump sizes and horsepowers were selected for 31 design flow increments from 280 to 6440 gallons per minute. For a given design flow subroutine PUMP selects the number of pumps per battery, pump horsepower, pump size, return sludge pipe size, pump efficiency, a Darcy-Weisbach friction factor, and a unit cost for one pump. One spare pump is added for each battery of pumps.

Economic Analysis

Capital cost items considered include pumps, variable speed motors, pump building, excavation, equipment installation costs, and other minor construction costs. Unit costs for pumps were obtained from a vendor. Motor costs were assumed to be approximately equal to the pump cost. The pump building area was calculated based on the design return sludge pumping rate using guidelines presented in "CAPDET" (1982). The volume of earthwork is based on pump building area. Pump installation costs were estimated to be 200 percent of the installed equipment cost. Other minor cost(piping, overhead crane, etc.) are calculated as a percentage of the construction cost (CAPDET 1982).

The total bare construction cost is calculated and is then adjusted to include indirect costs. Subroutine INDCO calculates indirect costs (Engineering fees, contingencies, etc.) as a percentage of the total bare construction costs and then sums the two to produce the total capital cost. Subroutine INDCO then converts the total capital cost to an annual equivalent cost.

Annual operation and maintenance cost items considered include operation man hour requirements, maintenance man hour requirements, energy consumption, and operation and maintenance material supply cost. Operation and maintenance man hour requirements are based on the design return flow rate (RETFLO) as presented in "CAPDET" (1982). Energy requirements are estimated using pump efficiency, head loss, and average daily flow rate, assuming continuous service. Operation and maintenance material supply cost are calculated as a percentage of the installed cost for pumps (CAPDET 1982).

The total annual operation and maintenance costs are calculated using the unit costs presented in the description of the main program. The total annual equivalent cost for the return sludge pumping facilities is determined by summing the annual equivalent cost (of the total capital cost) and the annual operation and maintenance cost.

Subroutine CLARI

Subroutine CLARI provides material quantity estimations and economic analysis for the settling basin system given the number of basins and basin geometry. An annual equivalent cost is developed considering both capital and operations and maintenance costs.

Economic Analysis

Capital cost items considered include clarifier mechanisms, excavation, concrete slabs and walls, equipment installation costs and other miscellaneous costs. The number of settling basins and their geometries were previously established, so the number and size of clarifier mechanisms is known. The quantity of excavation was calculated using guidelines presented in "CAPDET" (1982). Thickness of walls and slabs were calculated with respect to settling basin depth. Material quantity calculations were based on these thicknesses (CAPDET 1982). Equipment installation costs include labor and crane hours required to install clarifier mechanisms. Labor and crane hours required to install each clarifier mechanism were based on settling basin diameter (CAPDET 1982). Miscellaneous costs for equipment installation and other construction are calculated as percentages of the equipment purchase cost and the total construction cost, respectively. Miscellaneous costs include electrical controls, influent pipe, effluent weir, scum baffles, painting, etc.

Unit costs for clarifier mechanism ranging in size from 20 to 100 feet in diameter were obtained from a vendor. Costs were obtained for both suction and scraper type mechanisms.

The total bare construction cost is calculated and is then adjusted to include indirect costs. Subroutine INDCO calculates indirect costs (engineering fees, contingencies, etc.) as a percentage of the total bare construction cost and then sums the two to produce the total capital cost. Subroutine INDCO then converts the total capital cost to an annual equivalent cost.

Annual operation and maintenance cost items considered include: operation man hour requirements, maintenance man hour requirements, energy consumption, and operation and maintenance material supply cost. Operation and maintenance man hour requirements are calculated as a function of the total settling basin area. Energy requirements are also based on the total settling basin area. Operation and maintenance material supply cost is calculated as a percentage of the settling basin total bare cost (CAPDET 1982).

The total annual operations and maintenance costs are calculated using the unit costs presented in the description of the main program. The total annual equivalent cost for the settling basin system is determined by summing the annual equivalent cost (of the total capital cost) and the annual operation and maintenance cost.

Subroutine INDCO

Subroutine INDCO determines the indirect capital costs given a total bare construction cost. Indirect costs are listed in Table 9 along with their values (expressed as a percentage of the total bare construction cost). The total capital cost is calculated as noted below:

$$CAPCO = TBCC(1+IC)$$

where,

CAPCO = Total capital cost ($)

TBCC = Total bare construction cost ($)

IC = Sum of indirect cost percentages divided by 100

TABLE 9

INDIRECT COSTS

Item	% of Total Bare Construction Cost
Technical Services (excluding engineering fee)	3.0
Engineering Fee	7.0
Legal and Administrative Fee	3.0
Contingencies	9.0
Contractor's Profit and Overhead	23.0

Source: CAPDET 1982

The annual equivalent cost is calculated using the following equation:

$$AECCAP = \frac{CAPCO(IR/100)(1 + IR/100)^{EP}}{(1 + IR/100)^{EP} - 1}$$

where,

AECCAP = Annual equivalent cost of the total capital cost (\$/year)

IR = Interest rate (%)

EP = Evaluation period (years)

CHAPTER V

SENSITIVITY ANALYSIS

A sensitivity analysis was performed to identify those variables to which the optimum complete mix activated sludge system cost and configuration are particularly sensitive. Simulations for the analyses were performed using the computer optimization routine. Initially, simulations were executed using a base set of data to establish a control optimum solution for comparison to other simulation results. Parameters in the base data set were then varied singularly while holding the remaining parameters equal to their base values. Identification of the base data and parameter variations selected for the sensitivity analyses will be addressed in this section.

Base Data

Two sensitivity analyses were performed, one using settling data from the Clemson, South Carolina, Municipal Wastewater Treatment Plant and the other using settling data from the Gaffney, South Carolina, Wastewater Treatment Plant (Keinath et al. 1976). In this way a comparison of the effects of settling characteristics on the optimum system configuration may also be made. Base data for the optimum system sensitivity analyses are presented in tables 10, 11, and 12.

Typical values for kinetic coefficients for the activated sludge process as presented by Metcalf and Eddy (1979) were used for the base values for kinetic parameters. Values selected for influent substrate concentration, mean solids residence time and effluent suspended solids concentration are typical values for municipal activated sludge plants (Metcalf and Eddy 1979). The average daily flow rate selected was a median value of the range of flow rates investigated. A base minimum underflow concentration of 0.5 percent solids was selected for the simulations using Clemson Municipal Treatment Plant data while a base minimum underflow concentration of 0.9 percent was selected for the simulations using Gaffney Municipal Treatment Plant data.

Settling flux plots developed by fitting curves to the Clemson and Gaffney Municipal Treatment Plant settling data are presented in figures 18 and 19 respectively. Settling characteristics for the two wastewaters are clearly different. The Gaffney mixed liquor exhibits good settling characteristics at low MLSS concentrations (0 to 5000 mg/l) but relatively poor characteristics at higher MLSS values. The Clemson mixed liquor exhibits poor settling characteristics at low MLSS concentrations (0 to 5000 mg/l) but better characteristics at higher MLSS concentrations.

TABLE 10

BASE DATA FOR OPTIMUM SYSTEM SENSITIVITY ANALYSIS

Parameter	Value
1) Kinetic Parameters	
a) Maximum cell yield (YMAX)	0.6 mg VSS/mg BOD5
b) Endogenous decay coefficient (KD)	0.06 day^{-1}
c) Half velocity constant (KS)	60 mg BOD5/l
d) Maximum rate of substrate utilization per unit mass of microorganisms (KMAX)	5.0 day^{-1}
2) Wastewater Characteristics	
a) Average daily flow rate (Q)	15 MGD
b) Influent substrate concentration (S)	200 mg BOD5/l
c) Settling velocity versus suspended solids concentration data	See tables 11 & 12
3) Process Characteristics	
a) Mean solids residence time (SRT)	5.0 days
b) Minimum underflow concentration (MUC)	See tables 11 & 12
4) Effluent Quality	
a) Effluent suspended solids concentration (XE)	15 mg/l

TABLE 11

BASE SETTLING DATA FOR THE SENSITIVITY ANALYSES USING THE CLEMSON MUNICIPAL TREATMENT PLANT DATA

Suspended Solids Concentration (mg/l)	Settling Velocity (m/hour)
2173	1.58
3008	0.96
3875	0.61
5310	0.31
6875	0.16
8170	0.10
10,635	0.04

NOTE: The base minimum underflow concentration for the sensitivity analysis using the Clemson municipal treatment plant settling data is 0.5 percent solids (5000 mg/l).

TABLE 12

BASE SETTLING FOR THE SENSITIVITY ANALYSIS USING THE GAFFNEY MUNICIPAL TREATMENT PLANT DATA

Suspended Solids Concentration (mg/l)	Settling Velocity (m/hour)
641	7.36
1378	4.34
3685	0.84
4486	0.65
4646	0.51
5159	0.33
6889	0.13
7129	0.13
7402	0.10
7658	0.10
7722	0.10

NOTE: The base minimum underflow concentration for the sensitivity analysis using the Gaffney municipal treatment plant settling data is 0.9 percent solids (9000 mg/l).

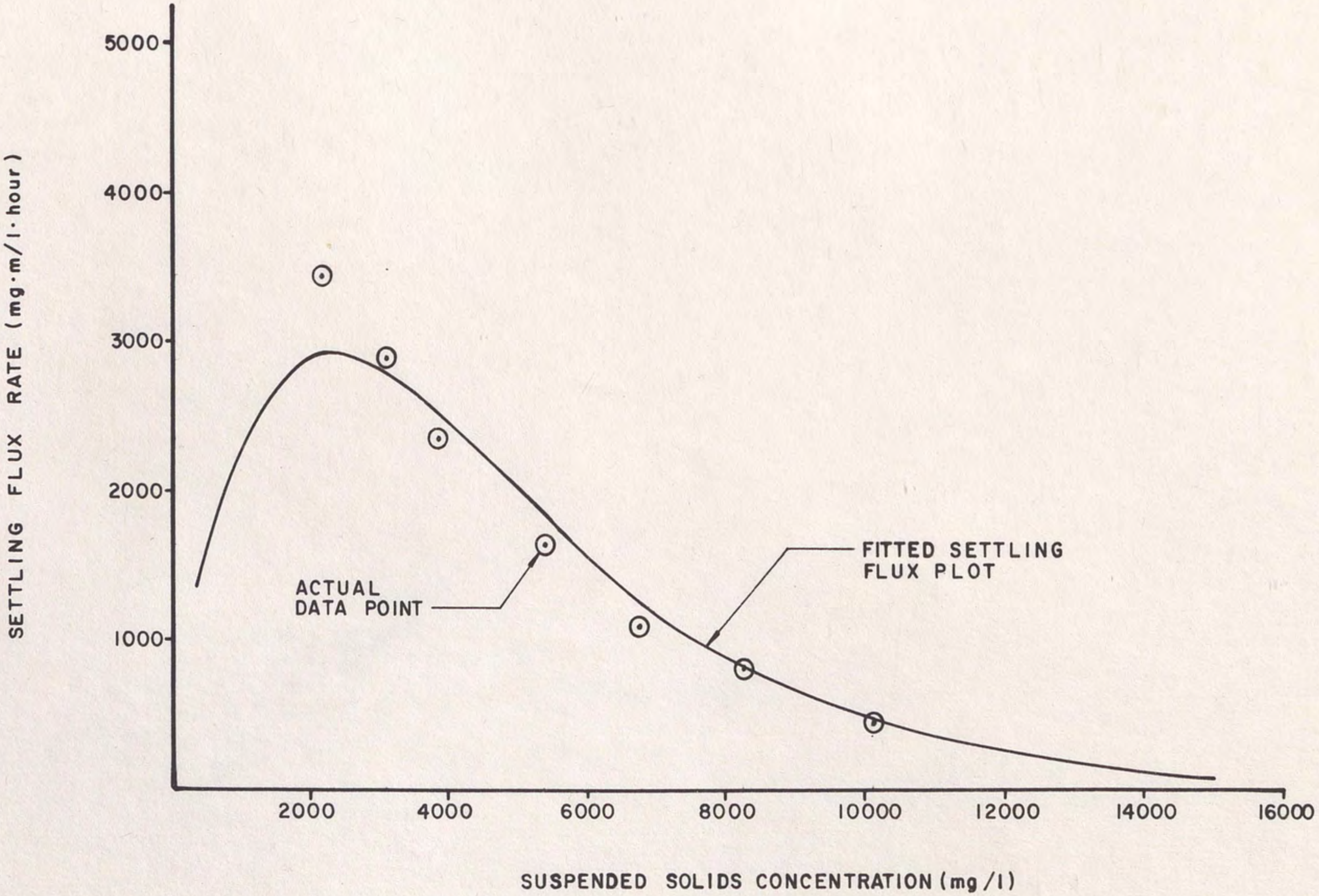

Figure 18: Settling Flux Plot Using Clemson Data

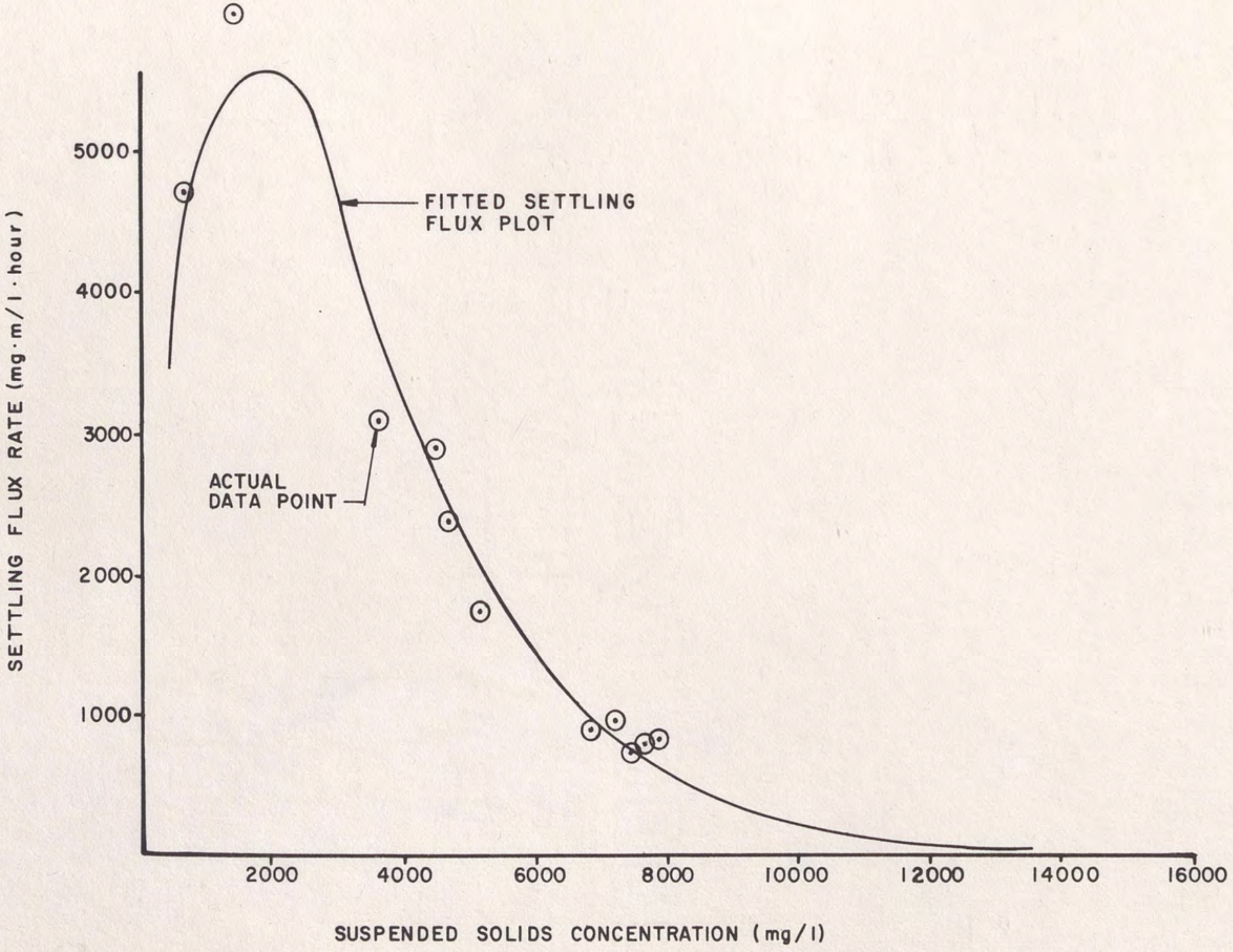

Figure 19: Settling Flux Plot Using Gaffney Data

Simulations

Parameters which were varied for the sensitivity analyses include maximum cell yield, average daily flow rate, influent substrate concentration, mean solids residence time, minimum underflow concentration, and effluent suspended solids concentration. Parameters were varied over the range of values characteristic of municipal wastewater treatment applications for complete mix activated sludge plants as presented in Table 13.

TABLE 13

VALUE OF PARAMETERS TO BE VARIED FOR THE SENSITIVITY ANALYSES

Parameter	Values
1) Kinetic Parameters	
a) Maximum cell yield (YMAX)	0.4, 0.6, and 0.8 mg VSS/mg BOD5
2) Wastewater Characteristics	
a) Average daily flow rate (Q)	1, 5, 15, and 45 MGD
b) Influent substrate concentration (S)	150, 200, and 250 mg BOD5/l
3) Process Characteristics	
a) Mean solids residence time (SRT)	5, 7, and 10 days
b) Minimum underflow concentration (MUC)	0.5, 0.7, 0.9, 1.1, 1.3, and 1.5% solids
4) Effluent Quality	
a) Effluent suspended solids concentration (XE)	10, 15, 20, and 30 mg BOD5/l

CHAPTER VI

RESULTS AND DISCUSSION

Results of the control simulations and the remaining sensitivity analysis simulations are discussed in this section. Results of all simulations are presented by variable in Appendix A. Results of the control simulations using Clemson and Gaffney municipal treatment plant settling data respectively are also presented for comparison.

Control Optimum Solutions

The control optimum solutions using Clemson and Gaffney municipal treatment plant settling data are presented in Table 14. The resulting configurations are almost identical. Both optimum solutions have MLSS concentrations in the middle two thousands (mg/l), return pumping rates are 35 and 37 percent of the average daily inflow, settling basin detention times are also very close at 3.67 and 3.80 hours, and settling basin overflow rates are identical.

Sensitivity Analysis Results

Results of the sensitivity analysis will follow. Parameters which were varied include maximum cell yield, average daily flow rate, influent substrate concentration, mean cell residence time, minimum underflow concentration, and effluent suspended solids concentration. In all cases,

TABLE 14

CONTROL OPTIMUM SOLUTIONS USING THE CLEMSON AND GAFFNEY MUNICIPAL TREATMENT PLANT SETTLING DATA

	Settling Characteristics	
	Clemson Data	Gaffney Data
1) Aeration basins		
MLSS concentration (mg/l)	2,617	2,519
Number of tanks	6	6
Total volume ($ft^3 x 10^6$)	.558	.580
Individual aerator horsepower (hp)	75	75
Number of aerators per tank	2	2
Hydraulic detention time (hrs.)	6.68	6.94
2) Settling basins		
Basin diameter (feet)	100	100
Depth (feet)	13.5	13.0
Overflow rate (gpd/ft^2)	637	637
Underflow concentration (mg/l)	10,095	9,304
Number of basins	3	3
Detention time (hours)	3.80	3.67
3) Pumping facilities		
Recycle rate (MGD)	5.25	5.57
Number of pumps	5	5
Individual motor horsepower (hp)	15	15
4) Total annual equivalent cost ($\$x10^6$/year)	1.162	1.167

results using the Clemson data and the Gaffney data were very similar despite radical differences in settling characteristics.

MAXIMUM CELL YIELD

Variation of the maximum cell yield (YMAX) has a noticeable impact on the optimum system configuration. Optimum system solutions for various maximum cell yield values are presented in tables 17 and 18 in Appendix A. Variation of YMAX impacts the aeration basin costs for each MLSS concentration (see Figure 20). Settling basin and return pumping costs for each MLSS concentration are unaffected by variations in YMAX. The total system cost at each MLSS concentration reflects the changes in the aeration basin costs.

The aeration basin costs can be broken down into aerator costs and basin costs. An increase in the value of YMAX results in an increase in the required aeration basin detention time and a decrease in the aeration energy requirements. Aeration energy requirements decrease due to a net decrease in endogenous respiration. When YMAX increases, the aeration basin detention time (or volume) increases in proportion to the increase in YMAX. Consequently, a greater increase in aeration basin volume and cost takes place at lower MLSS concentrations (i.e., higher hydraulic detention times). On the other hand,

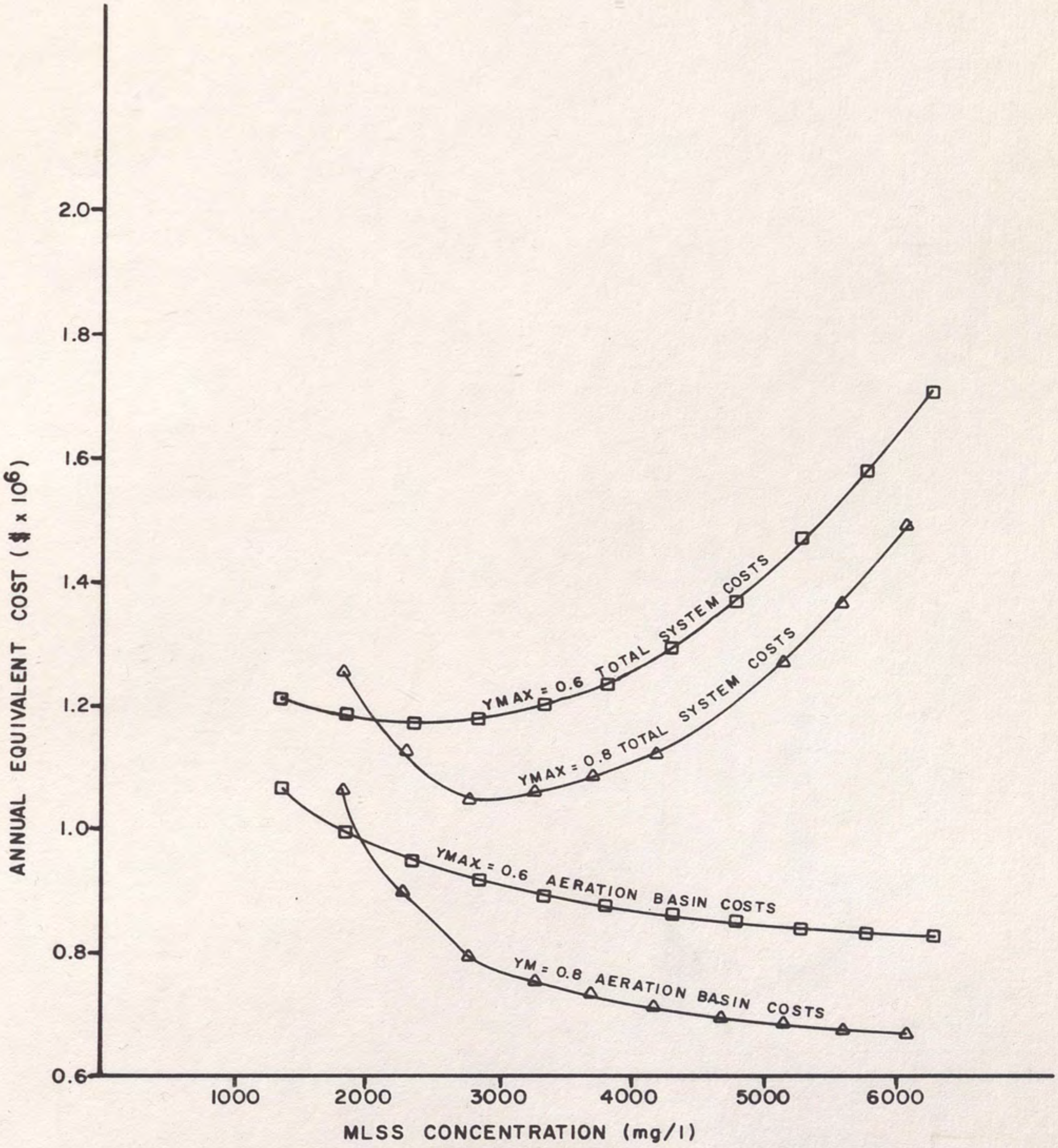

Figure 20: Effect of Increased Maximum Cell Yield On Aeration Basin Cost and Total System Cost

aeration requirements and costs decrease by a constant amount at each MLSS concentration. The resulting cost functions are presented in Figure 20. One result of increasing the value of YMAX is to shift the optimum system to a higher MLSS concentration. Despite the increase in MLSS concentration, the aeration basin hydraulic detention time for the optimum system increases. The increase in detention time is caused by the increase in YMAX. Since mechanical aerators are used, energy requirements for the aerators are usually determined by oxygen demand rather than mixing. Therefore, as YMAX increases aeration energy requirements usually decrease. The settling basin and return sludge pumping costs and designs for each particular MLSS concentration remain constant. However, the shift of the optimum system to a higher MLSS concentration results in different optimum settling basin and return sludge pumping configurations. The settling basin detention time and the return sludge pumping rate increase in response to an increase in MLSS concentration. The underflow concentration tends to decrease with an increase in MLSS concentration.

Average Daily Flow Rate

Variation of the average daily flow rate (Q) resulted in changes in system scale and some interesting changes in system configuration. Optimum system solutions for various average daily flow rates are presented in tables 19 and 20 in Appendix A. Impacts to the optimum system configuration, with the exception of scale differences, appear to be due to the incremental availability of certain equipment (i.e., clarifier mechanisms, mechanical aerators, and pumps). The effects of incremental clarifier mechanism sizes on system design are the most predominant.

The number of settling basins increases as the average daily flow rate increases. Since settling basins are available in incremental diameters to match the clarifier mechanism sizes, the chances of producing an overflow rate close to the maximum overflow rate for a particular MLSS concentration increases as flow rate increases. More data points are required to verify trends shown during variation of the average daily flow rate.

Influent Substrate Concentration

Variation of the influent substrate concentration (S) has a noticeable impact on the optimum system configuration. Optimum system solutions for various influent substrate concentration values are presented in tables 21 and 22 in Appendix A. Variation of the influent substrate concentration impacts the aeration basin cost for each MLSS concentration (see Figure 21). Settling basin and return pumping costs for each MLSS concentration are unaffected by variations in the influent substrate

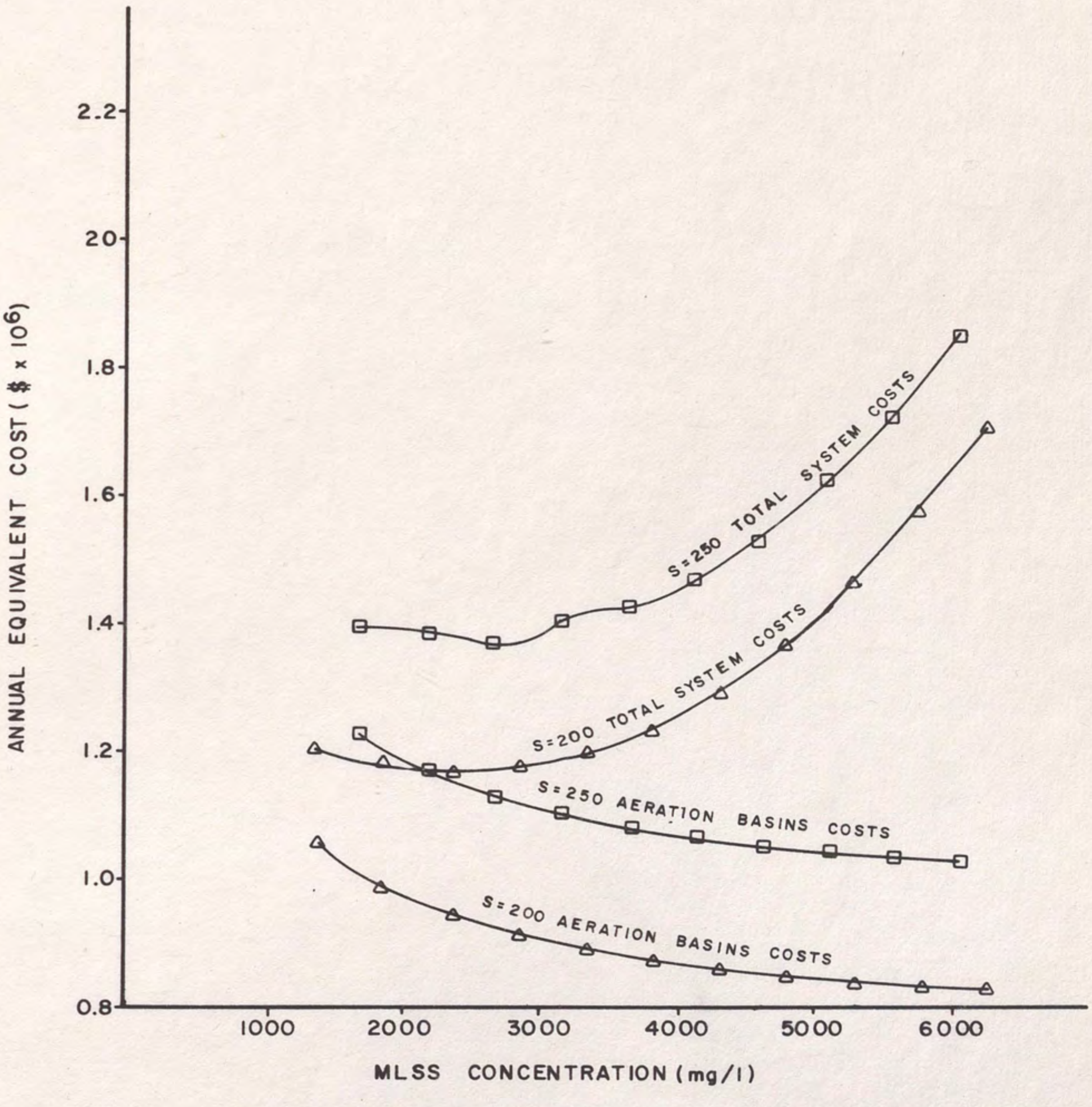

Figure 21: Effect of Increased Influent Substrate Concentration on Aeration Basin Cost and Total System Cost

concentration. The total system cost at each MLSS concentration reflects the changes in aeration basin costs.

An increase in the influent substrate concentration results in an increase in both the aeration energy requirements and the aeration basin detention time. When the influent substrate increases, the aeration basin detention time (or volume) increases in proportion to the increase in the influent substrate concentration minus the effluent substrate concentration. Consequently, a greater increase in the aeration basin volume and cost takes place at lower MLSS concentrations (i.e., higher hydraulic detention times). On the other hand, aeration requirements and costs increase by a constant amount regardless of MLSS concentration. The resulting cost functions are presented in Figure 21.

One result of increasing the value of the influent substrate concentration is to shift the optimum system to a higher MLSS concentration. Despite the increase in MLSS concentration, the aeration basin hydraulic detention time for the optimum system increases. The increase in detention time is caused by the increase in the influent substrate concentration. Since mechanical aerators are used, energy requirements for the aerators are usually determined by oxygen demand rather than mixing. Therefore, as the influent substrate concentration increases, aeration energy requirements usually increase. The settling basin and return sludge pumping costs and designs for each particular MLSS concentration remain constant. However, the shift of the optimum system to a higher MLSS concentration results in different optimum settling basin and return sludge pumping configurations. The settling basin detention time and return sludge pumping rate increase slightly in response to an increase in MLSS concentration. The underflow concentration tends to decrease with an increase in MLSS concentration.

Mean Solids Residence Time

Variation of the mean solids residence time (SRT) has a noticeable impact on the aeration basin system. Optimum system solutions for various mean solids residence time values are presented in tables 23 and 24 in Appendix A. Variation of the SRT impacts the aeration basin costs for each MLSS concentration (see Figure 22). Settling basin and return sludge pumping costs at each MLSS concentration are unaffected by variations in the SRT. However, the selection of the optimum settling basin and return pumping facilities is affected by a change in the optimum MLSS concentration. The total system cost at each MLSS concentration reflects the changes in the aeration basin costs.

An increase in the SRT results in an increase in the required aeration basin detention time and the aeration

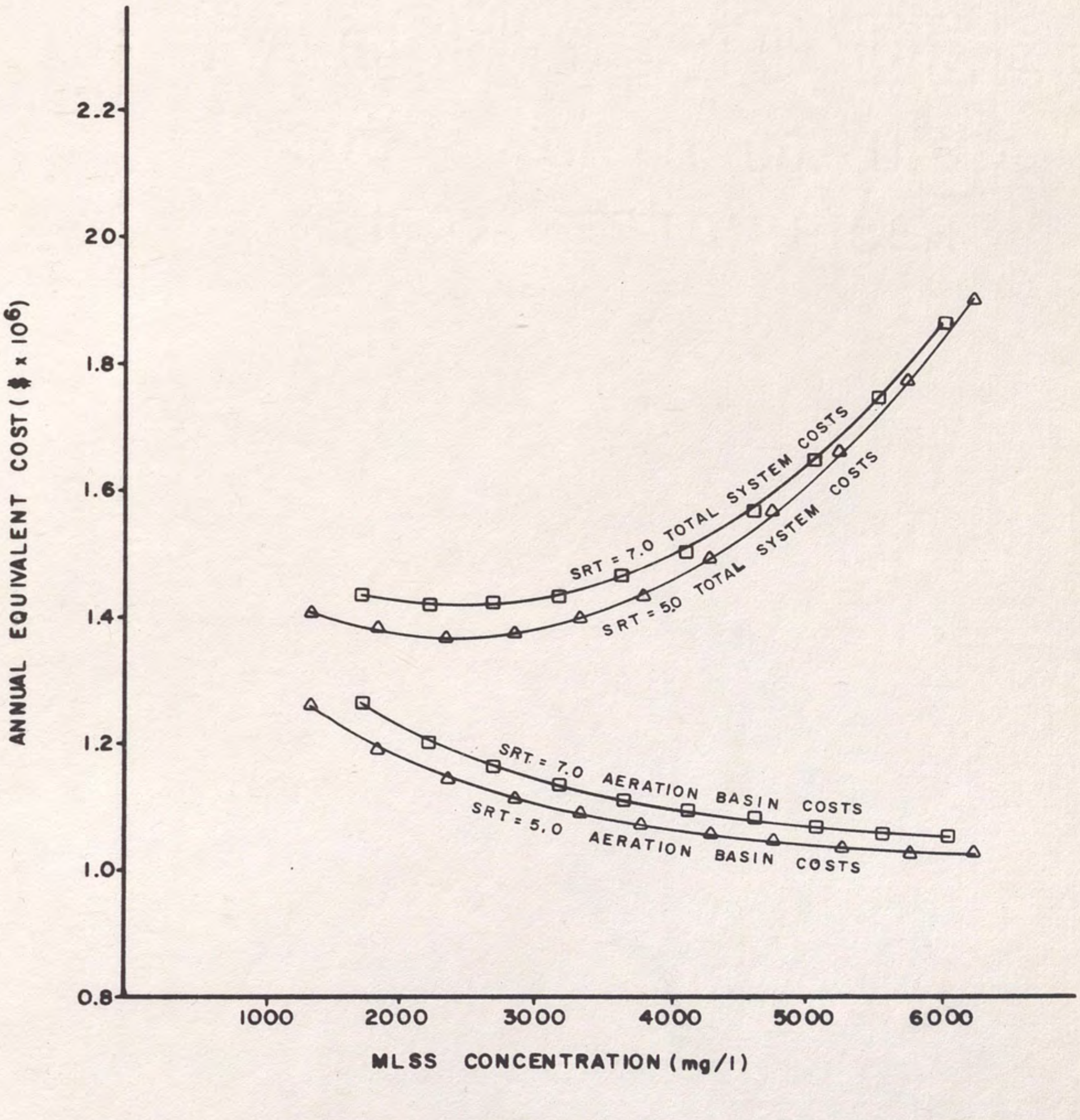

Figure 22: Effect of Increased Solids Residence Time on Aeration Basin Cost and Total System Cost

energy requirements. The increase in aeration energy requirements is insignificant. Change in the mean solids residence time may shift the optimum system to a slightly higher or lower MLSS concentration. The response is not well-behaved. The settling basin and pumping facilities configurations for the optimum system do not show substantial change. Overall changes are slight with variation of the SRT value.

Minimum Underflow Concentration

Variation of the minimum underflow concentration (MUC) has a substantial impact on the optimum system configuration. Optimum system solutions for various minimum underflow concentration values are presented in tables 25 and 26 in Appendix A. Variation of the MUC impacts the settling basin costs and the return sludge pumping costs for each MLSS concentration (see Figure 23). Aeration basin costs at each MLSS concentration are unaffected by variations in the minimum underflow concentration. The total system cost at each MLSS concentration reflects changes in the settling basin and return sludge pumping facilities costs. Changes in the pumping cost are relatively insignificant as compared to changes in the settling basin costs.

In general, as the minimum underflow concentration increases, the maximum obtainable recycle sludge pumping rate decreases, and the maximum obtainable overflow rates at most

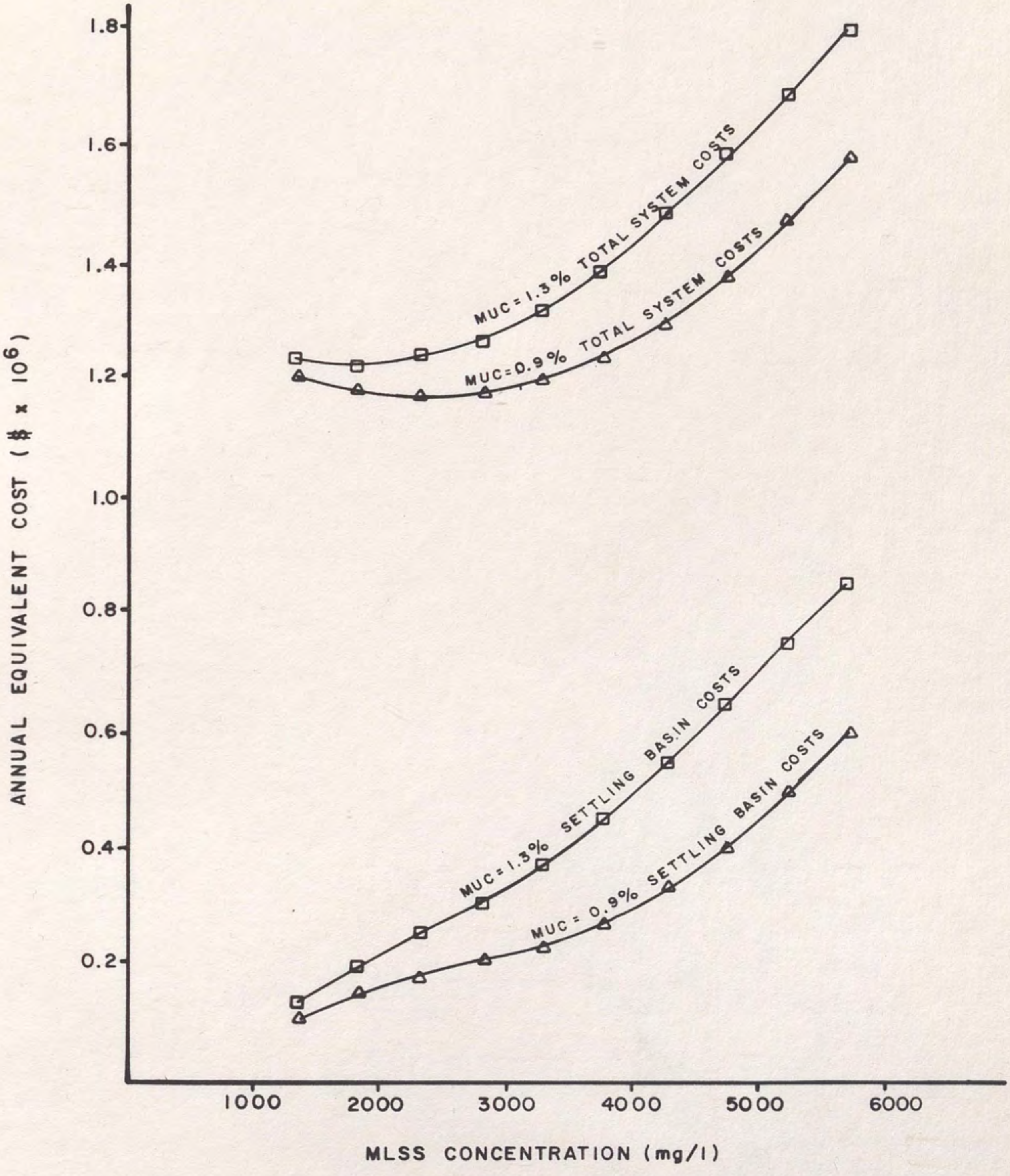

Figure 23: Effects of an Increase in the Minimum Underflow Concentration on Settling Basin Cost and Total System Cost

MLSS concentrations decreases. Associated with a decrease in the maximum obtainable overflow rate is an increase in the required settling basin surface area. As the recycle rate decreases, overflow rates for higher MLSS concentrations are decreased more severely than those for lower MLSS concentrations. Consequently, settling basin costs increase more substantially for higher MLSS concentrations. As a result, the optimum cost system is pushed toward lower MLSS concentrations.

Larger settling basin surface areas are required to produce higher minimum underflow concentrations. Lower overflow rates result from increasing the settling basin surface area. Due to a decrease in overflow rate, a lower detention time is required to meet effluent quality standards. The shift of the optimum system towards lower MLSS concentrations results in increased aeration basin detention times for the optimum system.

Effluent Suspended Solids Concentration

Variation of the effluent suspended solids concentration (XE) results in noticeable changes to the optimum settling basin system. Optimum system solutions for various effluent suspended solids concentration values are presented in tables 27 and 28 in Appendix A. Variation of XE impacts the settling basin costs for each MLSS concentration (see Figure 24). Aeration basin costs for

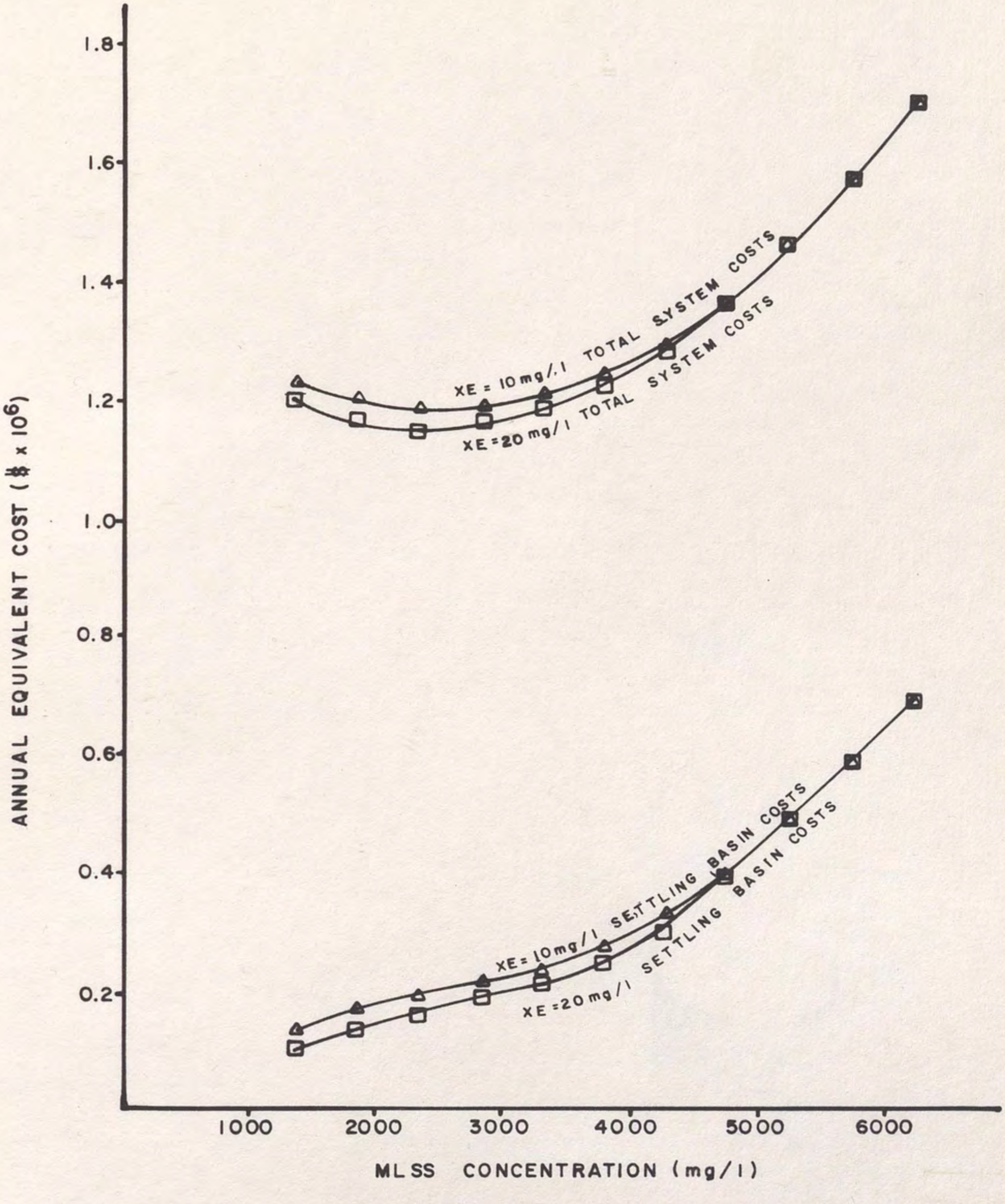

Figure 24: Effects of an Increase in the Effluent Suspended Solids Concentration on Settling Basin Cost and Total System Cost

each MLSS concentration are unaffected by variations in XE. The total system cost at each MLSS concentration reflects the changes in settling basin costs.

For a particular state point on the settling flux plot, an increase in the effluent suspended solids concentration requires a decrease in the settling basin detention time. The required decrease in settling basin detention time becomes less pronounced as the MLSS concentration increases due to the characteristics of the settling basin performance model. With an increase in effluent suspended solids concentration, settling basin detention time decreases resulting in a decrease in settling basin depth.

Optimum System Characteristics

Optimum system characteristics were established using simulations for various influent flow rates as presented in tables 19 and 20. Optimum system characteristics established using the Clemson and the Gaffney Municipal Treatment Plant settling data show excellent correlation despite differences in settling characteristics. A description of system characteristics and a comparison with current acceptable design values for these characteristics is included in this section. System characteristics discussed include MLSS concentration, aeration basin hydraulic detention time, settling basin overflow rate, settling basin depth, settling basin detention time, and return sludge pumping ratio.

MLSS Concentration

Optimum system MLSS concentrations ranged from 2030 mg/l to 2911 mg/l. Metcalf and Eddy (1979) report a typical range of MLSS concentrations for the complete mix activated sludge system as 3000 mg/l to 6000 mg/l. This divergence from the accepted design practice appears to be due to the cost impact of high MLSS concentrations on the settling basin system. Larger MLSS concentrations require larger areas for thickening and larger settling basin detention times to meet clarification constraints.

Aeration Basin Hydraulic Detention Time

Optimum system hydraulic detention times range from 6.0 to 8.6 hours. Metcalf and Eddy (1979) report a typical range of aeration basin hydraulic detention times for the complete mix activated sludge system as 3 to 5 hours. The divergence of the results from these values is not surprising considering the relationship between MLSS concentration and aeration basin hydraulic detention time.

Settling Basin Overflow Rate

Optimum system settling basin overflow rates ranged from 566 gpd/ft^2 to 819 gpd/ft^2. These values are well within the range of values commonly used in current design practice.

Settling Basin Depth

Optimum system settling basin depths ranged from 12.1 to 16.9 feet. This depth represents the settling basin clear zone depth. Additional depth would be required for sludge storage. The WPCF Manual of Practice FD-8 (1985) states:

> "Depth required for sludge storage is dependent on flowrate variations, changes in settling characteristics of the sludge, and changes in operating parameters of the biological process such as solids residence time. An estimate of this value is facility-dependent but probably about 3 feet."

Thus, total side water depths of 15.1 to 19.9 feet are indicated. The WPCF Manual of Practice Number 8 (1977) recommends side water depths from 11 to 13 feet for settling basins up to 100 feet in diameter.

Settling Basin Detention Time

Optimum system settling basin clear zone detention times ranged from 3.33 hours to 4.04 hours. Settling basin detention times calculated using the range of overflow rates and depths suggested in the WPCF Manual of Practice Number 8 (1977) varied from 2.5 hours to 3.9 hours (see Table 4). Settling basin detention times suggested by this research appear to fall at the upper end of those inferred by design guidelines. However, detention times suggested by this research are clear zone detention times, while those calculated from WPCF guidelines consider the entire settling basin volume. Therefore, clear zone detention times indicated by this research are greater than those typically used in design practice. Detention times for this research were calculated using a settling basin performance model. The model indicates that detention times commonly used are insufficient to achieve optimal clarification efficiency.

Return Sludge Pumping Recycle Ratio

Optimum system return sludge pumping ratios varied from 24 to 47 percent of the influent flow rate. Metcalf and Eddy (1979) report a typical range of 25 to 100 percent for the return sludge pumping ratios for complete mix facilities. The optimum recycle ratios are on the low end of values used in design practice. However, the Metcalf and Eddy recycle ratios are for systems which operate at MLSS concentrations from 3000 to 6000 mg/l. The optimum recycle ratios are very reasonable for the operating MLSS concentrations indicated for the optimum systems.

CHAPTER VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

A FORTRAN computer program was written to define an optimum complete mix activated sludge system for given wastewater characteristics and effluent quality constraints. The optimization routine considers capital, operation, and maintenance costs for the aeration basins, the settling basins and the return sludge pumping system. Sensitivity analyses were performed to identify those variables to which the optimum complete mix activated sludge system is particularly sensitive. In addition, results were analyzed to identify the characteristics of an optimum complete mix activated sludge system as defined by this model.

Sensitivity Analysis

The cost and configuration of the optimum complete mix activated sludge system exhibited some degree of sensitivity to all the variables examined in the sensitivity analysis. The optimum system was least sensitive to variations in the mean solids residence time. The optimum system was more sensitive to variations in the remaining variables.

Variation of the maximum cell yield (YMAX), the mean solids residence time (SRT) or the influent substrate concentration (S) directly impacts the configuration and cost of the aeration basin systems at each MLSS concentration. The configuration and cost for the settling basin and the return pumping systems at individual MLSS concentrations are not affected by variations in YMAX, SRT or S. However, selection of the optimum MLSS concentration and thus selection of the optimum settling basin and return pumping systems are affected by changes in the aeration basin system cost. On the other hand, variations in the minimum underflow concentration (MUC) or the effluent suspended solids concentration (XE) directly impacts the configuration and cost of the settling basin and the return pumping systems at each MLSS concentration. An increase in the MUC results in an increase in the optimum system settling basin surface area and a resultant decrease in settling basin depth. An increase in the XE results in a decrease in the optimum system settling basin depth. The configuration and cost for the aeration basin system at individual MLSS concentrations is not affected by variations in MUC or XE.

Optimum System Characteristics

Several system parameters have been selected to characterize the optimum complete mix activated sludge system. These parameters are: 1) the mixed liquor suspended solids concentration (MLSS); 2) the aeration basin hydraulic detention time (HDT_{AB}); 3) the settling basin overflow rate (ORA); 4) the settling basin detention time (HDT_{SB}); 5) the settling basin depth (DEPTH); and 6) the recycle pumping ratio (QR/Q). Table 15 presents a summary of the range of optimum system values for these six system parameters. In addition, Table 15 presents a range of typical current design values for each of the system characteristics for comparison to the optimum system values.

Conclusions

Limitations of The Optimization Model

The general applicability of the optimization model for the complete mix activated sludge system is dependent on the reliability of the settling basin performance model and the settling flux model for the particular treatment application. Settling basin performance models and settling flux data must be developed for a specific application. Therefore, the use of these models for other applications may lead to unreliable results.

The settling basin performance model used in this study was developed using a pilot plant with synthetic wastewater. The performance model is sensitive to settling basin detention time, settling basin overflow rate and mixed liquor suspended solids concentration. Although the optimization model does not have widespread applicability, the results are felt to be significant in identifying optimum system trends.

TABLE 15

COMPARISON OF VALUES FOR OPTIMUM SYSTEM CHARACTERISTICS TO VALUES USED IN CURRENT DESIGN PRACTICE

System Characteristic	Optimum System Values	Current Design Practice Values
1) MLSS	2030 - 2911 mg/l	3000 - 6000 mg/l *
2) HDT_{AB}	6.0 - 8.6 hours	3 - 5 hours *
3) ORA	566 - 819 gpd/ft^2	$\geq$ 800 gpd/ft^2 **
4) HDT_{SB}	3.33 - 4.04 hours (Clear zone detention time)	2.5 to 3.9 hours ** (Total detention time)
5) DEPTH (Total depth)	15.1 - 19.9 feet	11 - 13 feet **
6) QR/Q	24 - 47 percent	25- 100 percent *

* Source: Metcalf and Eddy (1979)

** Source: WPCF Manual of Practice Number 8 (1977)

Design Implications of Results

The results of this study suggest that the following modifications to current design practice would produce improved treatment and more cost effective designs for the complete mix activated sludge system:

1) Lower MLSS concentrations
2) Greater aeration basin hydraulic detention times
3) Greater clear zone detention times for the settling basin
4) Larger settling basin side water depths
5) Smaller recycle pumping rate ratios

The use of slightly lower MLSS concentrations and slightly larger aeration basin hydraulic detention times are indicated by simulation results. The aeration basin hydraulic detention time and the MLSS concentration are inversely related. MLSS concentrations in the range of 2000 to 3000 mg/l and detention times of 6.0 to 8.5 hours are suggested by simulation results.

Greater settling basin clear zone detention times than are commonly used in current practice are indicated. Clear zone detention times of 3.3 to 4.0 hours are indicated. The most economical method of providing an increase in settling basin detention time is to increase the depth, as indicated by simulation results. Depths of 13 to 17 feet were calculated for optimum systems. These depths are clear zone depths, therefore several feet would be added to obtain actual side water depths. These depths were calculated for an effluent suspended solids level of 15 mg/l. Less stringent effluent standards produce smaller clear zone depths. Partially due to decrease in the optimum MLSS concentrations, recycle pumping ratios decreased. Values of 24 to 47 percent recycle pumping to influent flow are indicated by simulation results.

Recommendations

The following recommendations are made for additional research:

1) The optimization routine used for this study considers the interactions of the aeration basin system, the settling basin system and the return sludge pumping facilities in design and economic analysis. However, the underflow concentration produced by the activated sludge settling basin is an important cost consideration in sludge treatment costs. Additional studies are suggested to determine the impact of sludge treatment costs on the optimum system configuration.

2) The performance models which were employed in the simulations are not sensitive to all variables which are suspected to influence clarifier efficiency. Maximum constraints were not imposed on the design for recycle flow rate and detention

period, despite speculation that adverse effects may be associated with extreme values for these variables. Additional experimental studies are warranted to assess the impact of turbulence associated with elevated recycle flow rates. Experimental studies are also necessary to identify potential rising sludge problems associated with extended sludge retention and attendant denitrification.

3) Simulations were executed using two very different settling flux data. The sensitivity of results to the settling data appears to be small. Additional simulations using various settling data are recommended to determine the importance of the settling flux data to selection of the optimum system. In addition, the effects of varying the settling basin performance model should be studied.

APPENDIX A

COMPILATION OF SIMULATION RESULTS

TABLE 16

CONTROL OPTIMUM SOLUTIONS USING THE CLEMSON AND GAFFNEY MUNICIPAL TREATMENT PLANT SETTLING DATA

	Settling Characteristics	
	Clemson Data	Gaffney Data
1) Aeration basins		
MLSS concentration (mg/l)	2,617	2,519
Number of tanks	6	6
Total volume ($ft^3 x 10^6$)	.558	.580
Individual aerator horsepower (hp)	75	75
Number of aerators per tank	2	2
Hydraulic detention time (hrs.)	6.68	6.94
2) Settling basins		
Basin diameter (feet)	100	100
Depth (feet)	13.5	13.0
Overflow rate (gpd/ft^2)	637	637
Underflow concentration (mg/l)	10,095	9,304
Number of basins	3	3
Detention time (hours)	3.80	3.67
3) Pumping facilities		
Recycle rate (MGD)	5.25	5.57
Number of pumps	5	5
Individual motor horsepower (hp)	15	15
4) Total annual equivalent cost ($\$x10^6$/year)	1.162	1.167

TABLE 17

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MAXIMUM CELL YIELD VALUES - CLEMSON DATA

	Maximum Cell Yield (mg VSS/mg BOD5)		
	0.4	0.6	0.8
1) Aeration basins			
MLSS concentration (mg/l)	2,204	2,617	2,846
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.434	.558	.690
Individual aerator horsepower (hp)	100	75	50
Number of aerators per tank	2	2	2
Hydraulic detention time (hours)	5.20	6.68	8.26
2) Settling basins			
Basin diameter (feet)	95	100	90
Depth (feet)	13.2	13.5	13.0
Overflow rate (gpd/ft^2)	705	637	589
Underflow concentration (mg/l)	10,833	10,095	9,802
Number of basins	3	3	4
Detention time (hours)	3.37	3.8	3.97
3) Pumping facilities			
Recycle rate (MGD)	3.830	5.248	6.136
Number of pumps	4	5	5
Individual motor horsepower (hp)	15	15	20
4) Total annual equivalent cost ($\$ x 10^6$/year)	1.282	1.162	1.045

TABLE 18

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MAXIMUM CELL YIELD VALUES - GAFFNEY DATA

	Maximum Cell Yield (mg VSS/mg BOD5)		
	0.4	0.6	0.8
1) Aeration basins			
MLSS concentration (mg/l)	1,940	2,519	2,563
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.494	.580	.766
Individual aerator horsepower (hp)	100	75	50
Number of aerators per tank	2	2	2
Hydraulic detention time (hours)	5.91	6.94	9.17
2) Settling basins			
Basin diameter (feet)	100	100	100
Depth (feet)	18.6	13.0	13.2
Overflow rate (gpd/ft^2)	955	637	637
Underflow concentration (mg/l)	9,117	9,304	9,231
Number of basins	2	3	3
Detention time (hours)	3.49	3.67	3.73
3) Pumping facilities			
Recycle rate (MGD)	4.053	5.568	5.764
Number of pumps	4	5	5
Individual motor horsepower (hp)	15	15	20
4) Total annual equivalent cost ($\$ x 10^6$/year)	1.274	1.167	1.040

TABLE 19

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS AVERAGE DAILY FLOW RATES - CLEMSON DATA

	Average Daily Flow Rate (MGD)			
	1.0	5.0	15.0	45.0
1) Aeration basins				
MLSS concentration (mg/l)	2,324	2,715	2,617	2,030
Number of tanks	2	4	6	12
Total volume ($ft^3 x 10^6$)	.042	.179	.558	2.159
Individual aerator horsepower (hp)	30	75	75	75
Number of aerators per tank	1	1	2	3
Hydraulic detention time (hours)	7.53	6.44	6.68	8.61
2) Settling basins				
Basin Diameter (feet)	30	75	100	100
Depth (feet)	14.1	12.1	13.5	15.2
Overflow rate (gpd/ft^2)	707	566	637	819
Underflow concentration (mg/l)	10,429	10,542	10,095	10,574
Number of basins	2	2	3	7
Detention time (hours)	3.57	3.83	3.80	3.33
3) Pumping facilities				
Recycle rate (MGD)	.286	1.733	5.248	10.690
Number of pumps	2	2	5	20
Individual motor horsepower (hp)	3	25	15	15
4) Total annual equivalent cost ($\$x10^6$/year)	.160	.472	1.162	3.225

TABLE 20

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS AVERAGE DAILY FLOW RATES - GAFFNEY DATA

	Average Daily Flow Rate (MGD)			
	1.0	5.0	15.0	45.0
1) Aeration basins				
MLSS concentration (mg/l)	2,324	2,911	2,516	2,226
Number of tanks	2	4	6	12
Total volume ($ft^3 x 10^6$)	.041	.167	.580	1.970
Individual aerator horsepower (hp)	30	75	75	75
Number of aerators per tank	1	1	2	3
Hydraulic detention time (hours)	7.53	6.01	6.94	7.86
2) Settling basins				
Basin diameter (feet)	30	75	100	100
Depth (feet)	14.1	12.7	13.0	16.9
Overflow rate (gpd/ft^2)	707	566	637	819
Underflow concentration (mg/l)	9,316	9,025	9,304	9,042
Number of basins	2	2	3	7
Detention time (hours)	3.57	4.04	3.67	3.70
3) Pumping facility				
Recycle rate (MGD)	.332	2.380	5.568	14.692
Number of pumps	2	3	5	45
Individual motor horsepower (hp)	5	10	15	15
4) Total annual equivalent cost ($\$ x 10^6$/year)	.161	.474	1.167	3.235

TABLE 21

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS INFLUENT SUBSTRATE CONCENTRATION VALUES - CLEMSON DATA

	Influent Substrate Concentration (mg/l)		
	150	200	250
1) Aeration basins			
MLSS concentration (mg/l)	2,498	2,617	2,656
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.434	.558	.692
Individual aerator horsepower (hp)	50	75	100
Number of aerators per tank	2	2	2
Hydraulic detention time (hours)	5.20	6.68	8.28
2) Settling basins			
Basin diameter (feet)	100	100	100
Depth (feet)	12.9	13.5	13.7
Overflow rate (gpd/ft^2)	637	637	637
Underflow concentration (mg/l)	10,499	10,095	9,947
Number of basins	3	3	3
Detention time (hours)	3.64	3.80	3.85
3) Pumping facilities			
Recycle rate (MGD)	4.681	5.248	5.465
Number of pumps	5	5	5
Individual motor horsepower (hp)	10	15	15
4) Total annual equivalent cost ($\$x10^6$/year)	.932	1.162	1.375

TABLE 22

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS INFLUENT SUBSTRATE CONCENTRATION VALUES - GAFFNEY DATA

	Influent Substrate Concentration (mg/l)		
	150	200	250
1) Aeration basins			
MLSS concentration (mg/l)	2,497	2,519	2,560
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.434	.580	.718
Individual aerator horsepower (hp)	50	75	100
Number of aerators per tank	2	2	2
Hydraulic detention time (hours)	5.20	6.94	8.59
2) Settling basins			
Basin diameter (feet)	100	100	100
Depth (feet)	12.9	13.0	13.2
Overflow rate (gpd/ft^2)	637	637	637
Underflow concentration (mg/l)	9,340	9,304	9,236
Number of basins	3	3	3
Detention time (hours)	3.64	3.67	3.73
3) Pumping facilities			
Recycle rate (MGD)	5.474	5.568	5.751
Number of pumps	5	5	5
Individual motor horsepower (hp)	15	15	20
4) Total annual equivalent cost ($\$x10^6$/year)	.937	1.167	1.383

TABLE 23

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MEAN SOLIDS RETENTION TIME VALUES - CLEMSON DATA

	Mean Solids Retention Time (days)		
	5.0	7.0	10.0
1) Aeration basins			
MLSS Concentration (mg/l)	2,617	2,310	2,595
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.558	.816	.925
Individual aerator horsepower (hp)	75	75	75
Number of aerators per tanks	2	2	2
Hydraulic detention time (hours)	6.68	9.77	11.08
2) Settling basins			
Basin diameter (feet)	100	100	100
Depth (feet)	13.5	11.9	13.4
Overflow rate (gpd/ft^2)	637	637	637
Underflow concentration (mg/l)	10,095	11,070	10,173
Number of basins	3	3	3
Detention time (hours)	3.80	3.36	3.78
3) Pumping facilities			
Recycle rate (MGD)	5.248	3.955	5.136
Number of pumps	5	4	5
Individual motor horsepower (hp)	15	15	15
4) Total annual equivalent cost ($\$ x 10^6$/year)	1.161	1.216	1.259

TABLE 24

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MEAN SOLIDS RETENTION TIME VALUES - GAFFNEY DATA

	Mean Solids Retention Time (days)		
	5.0	7.0	10.0
1) Aeration basins			
MLSS concentration (mg/l)	2,519	2,597	2,595
Number of tanks	6	6	6
Total volume ($ft^3 x 10^6$)	.580	.726	.926
Individual aerator horsepower (hp)	75	75	75
Number of aerators per tanks	2	2	2
Hydraulic detention time (hours)	6.94	8.69	11.08
2) Settling basins			
Basin diameter (feet)	100	100	100
Depth (feet)	13.0	13.4	13.4
Overflow rate (gpd/ft^2)	637	637	637
Underflow concentration (mg/l)	9,304	9,172	9,172
Number of basins	3	3	3
Detention time (hours)	3.67	3.78	3.78
3) Pumping facilities			
Recycle rate (MGD)	5.568	5.925	5.914
Number of pumps	5	5	5
Individual motor horsepower (hp)	15	20	20
4) Total annual equivalent cost ($\$ x 10^6$/year)	1.1677	1.212	1.264

TABLE 25

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MINIMUM UNDERFLOW CONCENTRATION VALUES - CLEMSON DATA

		Minimum Underflow Concentration (% Solids)					
		0.5	0.7	0.9	1.1	1.3	1.5
1)	Aeration basins						
	MLSS concentration (mg/l)	2617	2617	2617	2324	1737	1443
	Number of tanks	6	6	6	6	6	6
	Total volume (ft³ x 10⁶	.558	.558	.558	.629	.841	1.013
	Individual aerator horsepower (hp)	75	75	75	75	75	75
	Number of aerators per tank	2	2	2	2	2	2
	Hydraulic detention time (hours)	6.68	6.68	6.68	7.53	10.07	12.12
2)	Settling basins						
	Basin diameter (feet)	100	100	100	100	90	95
	Depth (feet)	13.5	13.5	13.5	12.0	8.0	8.0
	Overflow rate (gpd/ft²)	637	637	637	637	589	423
	Underflow concentration (mg/l)	10,095	10,095	10,095	11,030	13,003	15,081
	Number of basins	3	3	3	3	4	5
	Detention time (hours)	3.80	3.80	3.80	3.38	2.44	3.39
3)	Pumping facilities						
	Recycle rate (MGD)	5.248	5.248	5.248	4.002	2.312	1.587
	Number of pumps	5	5	5	5	3	2
	Individual motor horsepower (hp)	15	15	15	15	10	20
4)	Total annual equivalent Cost ($ x 10⁶/year)	1.162	1.162	1.162	1.167	1.219	1.313

TABLE 26

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS MINIMUM UNDERFLOW CONCENTRATION VALUES - GAFFNEY DATA

		Minimum Underflow Concentration (% Solids)				
		0.5	0.7	0.9	1.1	1.3
1)	Aeration basins					
	MLSS concentration (mg/l)	2226	2226	2519	1932	1345
	Number of tanks	6	6	6	6	6
	Total volume (ft^3 x 10^6)	.657	.657	.580	.756	1.086
	Individual aerator horsepower (hp)	75	75	75	75	75
	Number of aerators per tank	2	2	2	2	2
	Hydraulic detention time (hours)	7.86	7.86	6.94	9.05	13.0
2)	Settling basins					
	Basin diameter (feet)	100	100	100	100	100
	Depth (feet)	21.6	21.6	13.0	8.0	8.0
	Overflow rate (gpd/ft^2)	955	955	637	477	318
	Underflow concentration (mg/l)	8,538	8,538	9,304	11,049	13,042
	Number of basins	2	2	3	4	6
	Detention time (hours)	4.07	4.07	3.67	3.01	4.51
3)	Pumping facilities					
	Recycle rate (MGD)	5.288	5.288	5.568	3.178	1.725
	Number of pumps	5	5	5	3	2
	Individual motor horsepower (hp)	15	15	15	25	25
4)	Total annual equivalent Cost ($ x 10^6/year)	1.162	1.162	1.167	1.229	1.396

TABLE 27

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS EFFLUENT SUSPENDED SOLIDS CONCENTRATION VALUES - CLEMSON DATA

	Effluent Suspended Solids Concentration (mg/l)			
	10	15	20	30
1) Aeration basins				
MLSS concentration (mg/l)	2421	2617	2617	2421
Number of tanks	6	6	6	6
Total volume ($ft^3 \times 10^6$)	.603	.558	.558	.603
Individual aerator horsepower (hp)	75	75	75	75
Number of aerators per tank	2	2	2	2
Hydraulic detention time (hours)	7.22	6.68	6.68	7.22
2) Settling basins				
Basin diameter (feet)	100	100	100	95
Depth (feet)	15.5	13.5	10.8	8.0
Overflow rate (gpd/ft^2)	637	637	637	705
Underflow concentration (mg/l)	10,738	10,095	10,095	10,101
Number of basins	3	3	3	3
Detention time (hours)	4.37	3.80	3.03	2.04
3) Pumping facilities				
Recycle rate (MGD)	4.367	5.248	5.248	4.729
Number of pumps	4	5	5	5
Individual motor horsepower (hp)	2	15	15	10
4) Total annual equivalent Cost ($\$ \times 10^6$/year)	1.179	1.162	1.150	1.139

TABLE 28

OPTIMUM SYSTEM SOLUTIONS FOR VARIOUS EFFLUENT SUSPENDED SOLIDS CONCENTRATION VALUES - GAFFNEY DATA

	Effluent Suspended Solids Concentration (mg/l)			
	10	15	20	30
1) Aeration basins				
MLSS concentration (mg/l)	2421	2519	1932	1932
Number of tanks	6	6	6	6
Total volume (ft^3 x 10^6)	.603	.580	.756	.756
Individual aerator horsepower (hp)	75	75	75	75
Number of aerators per tank	2	2	2	2
Hydraulic detention time (hours)	7.22	6.94	9.05	9.05
2) Settling basins				
Basin diameter (feet)	100	100	100	100
Depth (feet)	15.5	13.0	12.9	8.0
Overflow rate (gpd/ft^2)	637	637	955	955
Underflow concentration (mg/l)	9,468	9,304	9,132	9,132
Number of basins	3	3	2	2
Detention time (hours)	4.37	3.67	2.43	1.50
3) Pumping facilities				
Recycle rate (MGD)	5.153	5.568	4.025	4.025
Number of pumps	5	5	4	4
Individual motor horsepower (hp)	15	15	15	15
4) Total annual equivalent Cost ($ x 10^6/year)	1.183	1.167	1.151	1.137

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