COMPLETION REPORT

TO

OPERATIONAL CONTROL OPTIMIZATION OF WASTEWATER TREATMENT

E-017

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Summary

This research has examined wastewater treatment costs from an operational perspective. An operational model of the activated sludge treatment process was developed. The model is used to transform certain specified system parameters of an existing treatment facility into biological and flow output specifications. This results in a complete description of the operating system. An economic evaluation of this system is then preformed. This evaluation utilizes traditional engineering economic analysis to derive the equivalent uniform annual cost of facility operation.

The entire analysis package has been developed on a Radio Shack TRS-80 microcomputer. This was judged to be an important step in enhancing the ultimate usefulness of this type of analysis.

Introduction

Throughout Oklahoma, and the world, wastewater treatment is an ongoing exercise. It is a necessary practice in order to protect our environment from the undesirable side-effects of untreated waste. Of major concern is treating the wastewater in the most economical manner.

Earlier research in this regard resulted in the development of a model to determine the least-cost design for the activated sludge precess (Kincannon and Koelling, No. EN 082-R-78-W). This prior research concerned treatment facility design. However, many more plants are currently operating than are being designed. A great savings potential exists in these operating facilities. The objective of this research was to develop an operational and economic model of an existing treatment plant as a first step in optimizing the system subject to environmental shocks.

The activated sludge process, one of the major wastewater treatment processes, was used as the modeled system. The major components of the activated sludge process are shown in Figure 1. Sludge treatment costs must also be considered. There are several alternatives in this regard, one of which is presented in Figure 2.

Objectives of Research

The objectives of this research were two-fold. The initial effort centered on the development of a model of the activated sludge process in the operational mode. This model should be capable of specifying sludge treatment operational parameters for any particular system environment encountered. It is necessary to integrate this model with the concepts of engineering economic analysis to derive an economic model of treatment operation, reflecting annual costs related to operation, maintenance, and energy consumption.

The second major objective of the research emphasized practicality and applicability of the model. This objective was to develop the appropriate software to

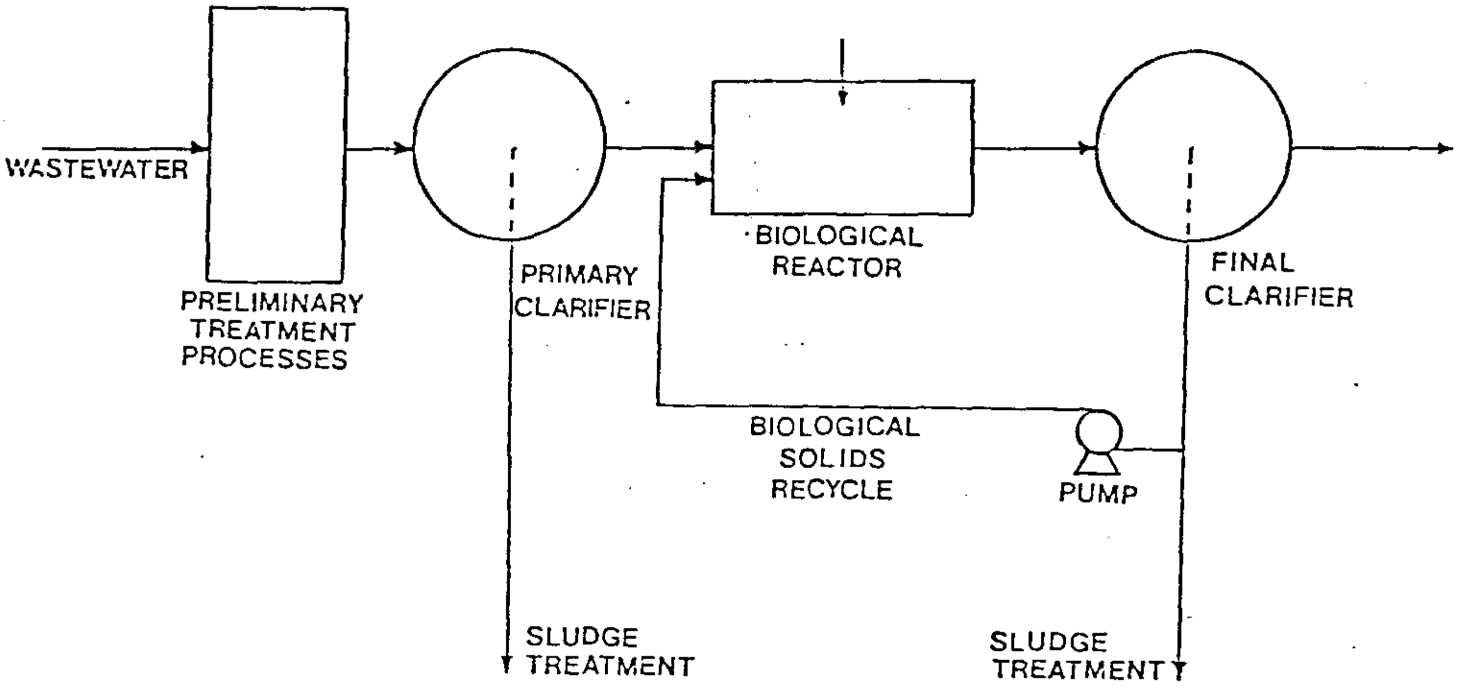

Figure 1. Flow diagram of activated sludge process.

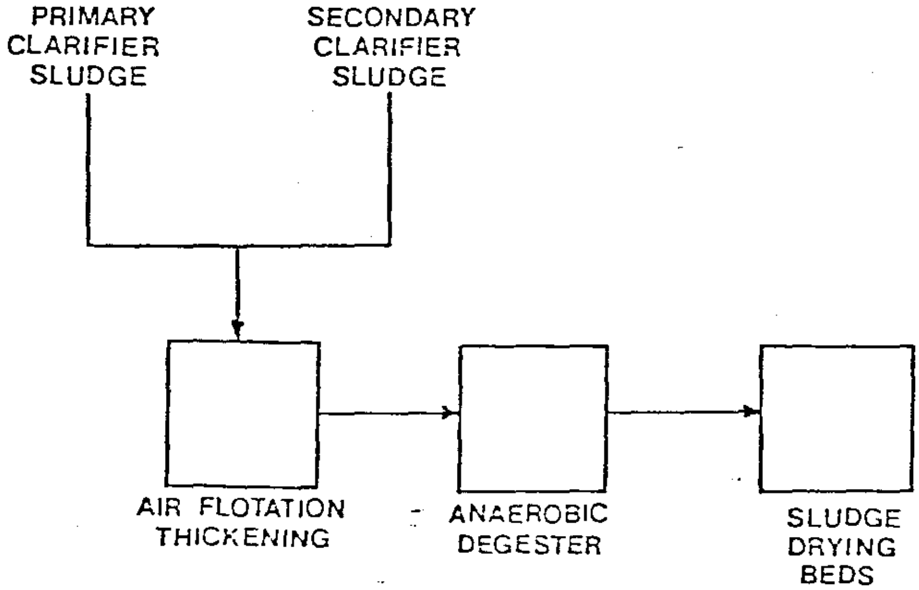

Figure 2. Flow diagram of sludge treatment process.

allow the model to be implemented on a microcomputer. This software should include both a stand-alone operational model and the economic model. It should produce a complete economic analysis and generate operational specifications for the treatment facility.

Variable Definition

Listed below are the variables which are used throughout this report. Notice that they are categorized as either input or output variables. Input variables represent inputs to the computer program to derive operational specifications (output varaiables). In essence, they represent current system parameters.

VARIABLE DEFINITIONS

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1) INPUT VARIALBES

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A. GENERAL

VARIABLE	DEFINITION	UNITS
BS	BOD-5 EFFLUENT STANDARD	MG/L
XE	SUSPENDED SOLID EFFLUENT STANDARD	MG/L
K1	BOD-5 RATIO OF SUSPENDED SOLIDS	NONE
SO	SOLUBLE INFLUENT BOD-5	MG/L
F	FLOW	MGD
APC	AREA OF PRIMARY CLARIFIER	SQ. FT.
XO	INFLUENT SUSPENDED SOLIDS	MG/L
V	VOLUME OF BIOLOGICAL REACTOR	MGAL
UM	U-MAX BIOKINETIC CONSTANT	LB/DAY/LB

KB	K-B BIOKINETIC CONSTANT	LB/DAY/LB
KD	K-D BIOKINETIC CONSTANT	DAY $^{-1}$
YT	Y-T BIOKINETIC CONSTANT	LB/LB
A	A SETTLEABILITY CONSTANT	FT/MIN
N	N SETTLEABILITY CONSTANT	NONE
AFC	AREA OF FINAL CLARIFIER	SQ.FT
MXR	MAXM. POSSIBLE XR	MG/L

B. MECHANICAL AERATION

NO	OXYGEN RATING OF AERATOR	LB/HP/HR
B	SALINITY-SURFACE TENSION CORRECTION FACTOR	NONE
CW	OXYGEN SATURATION CONCENTRATION FOR WASTE	MG/L
CL	DISSOLVED OXYGEN CONCENTRATION	MG/L
TW	TEMPERATURE OF WASTE WATER	DEG. C
AW	OXYGEN TRANSFER CORRECTION FACTOR	NONE

C. DIFFUSED AERATION

AE	TRANSFER EFFICIENCY OF AERATION	NONE
PI	ABSOLUTE INLET PRESSURE	PSIA
PO	ABSOLUTE OUTLET PRESSURE	PSIA
TP	TEMPERATURE OF WASTE WATER	DEG. C
E	COMPRESSOR EFFICIENCY	NONE

D. PUMPING

H1	PRIMARY CLARIFIER SLUDGE PUMP HEAD	FT
H2	FINAL CLARIFIER SLUDGE PUMP HEAD	FT
H3	RECYCLE PUMP HEAD	FT
EC	ELECTRICAL POWER COST	$/KWH
LC	LABOR COST	$/HR
LO	SOLIDS LOADING TO AIR FLOTATION	LB/DAY/SQ.FT
ED	EFFICIENCY OF ANAEROBIC DIGESTOR	NONE
LD	SOLIDS LOADING TO DIGESTORS	LB/DAY
FS	SOLIDS FRACTION OF PRIMARY SLUDGE	NONE

2) OUTPUT VARIABLES

****

VARIABLE	DEFINITION	UNITS
SE	SOLUBLE EFFLUENT BOD-5	MG/L
SI	SOLUBLE INFLUENT AFTER PRIMARY CLARIFIER	MG/L
XI	INFLUENT S.S. AFTER PRIMARY CLARIFIER	MG/L
PS	SLUDGE PRODUCED FROM PRIMARY CLARIFIER	LB/DAY

X	SUSPENDED SOLIDS IN BIOLOGICAL REACTOR	MG/L
AP	ALPHA-RECYCLE FLOW FRACTION	NONE
XR	SUSPENDED SOLIDS OF WASTE FLOW	MG/L
FW	WASTE FLOW FROM FINAL CLARIFIER	MGD
SFC	SLUDGE PRODUCED FROM FINAL CLARIFIER	LB/DAY

B. MECHANICAL AERATION

POH	POUNDS OF OXYGEN PER HOUR	LB(0_2)/HR
NI	OXYGEN RATING FOR PLANT CONDITIONS	MG/L
HP	HORSE-POWER	HP

C. DIFFUSED AREATION

POD	POUNDS OF OXYGEN PER DAY	LB(0_2)/DAY
PAS	POUNDS OF AIR PER SECOND	LB/SEC
HP	HORSE-POWER	HP
MHP	MIXING HORSE-POWER	HP

METHODS

Two basic components had to be developed for complete system representation. These were an operational model specifying complete system parameters and an economic model used to derive system cost.

OPERATIONAL MODEL

In order to adequately represent the operation of the waste treatment facility it was necessary to develop a comprehensive model of the operational activiated sludge process. This consists of a series of mathematical equations relating the parameters of the system. Mathematical models for some unit processes have been developed previously. However, it was necessary in this research to formulate models for additional unit processes. Figure 3 depicts each process and the mathematical models utilized in each case.

ECONOMIC MODEL

The economic model utilizes standard engineeing economic analysis to derive annual operating and maintenance costs for the system parameters specified in the operational model. Costs equations were formulated and used for this purpose. The cost equations used are presented in Figure 4. A computer program was written and merged with the operational model program to compute system cost.

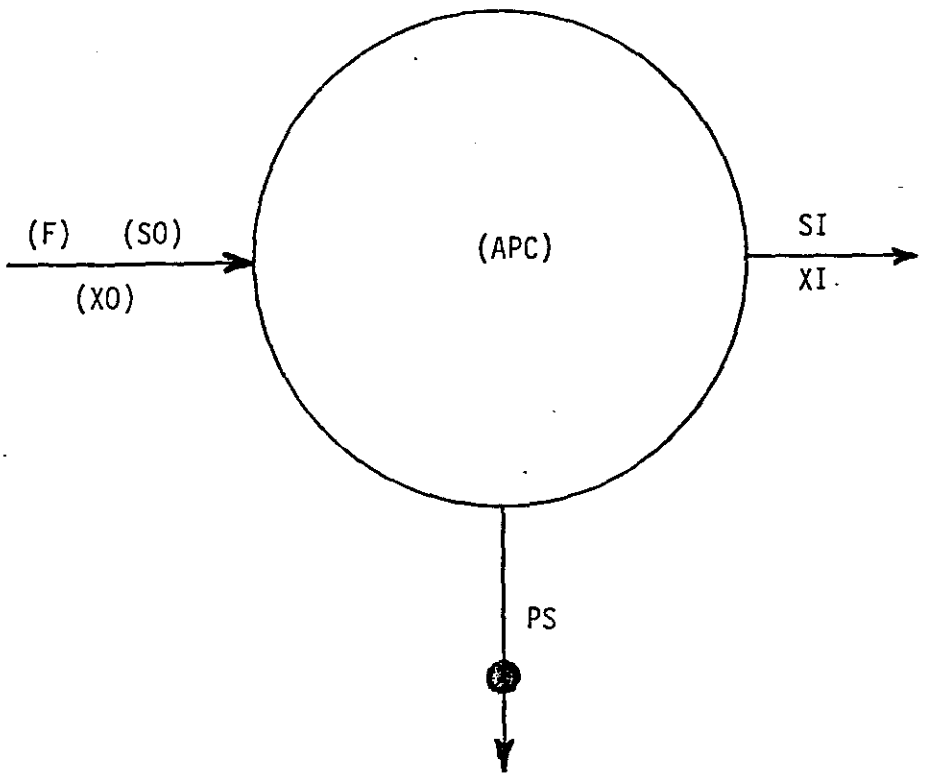
COMPUTER PROGRAM

This program computes the total annual cost of operation and maintenance of a wastewater treatment plant. The total consists of the following cost components:

1) Operation and maintenance costs,
2) Maintenance labor costs,
3) Operation labor costs,
4) Electric power costs,
5) Material and Supply costs.

These costs are dependent on some system parameters and output variables. The output variables are again dependent on the system parameters. The program is of the interactive type and the input parameters are entered through the Keyboard of the TRS-

Primary Clarifier Specifications



$$SE=BS-(KI)(XE)$$

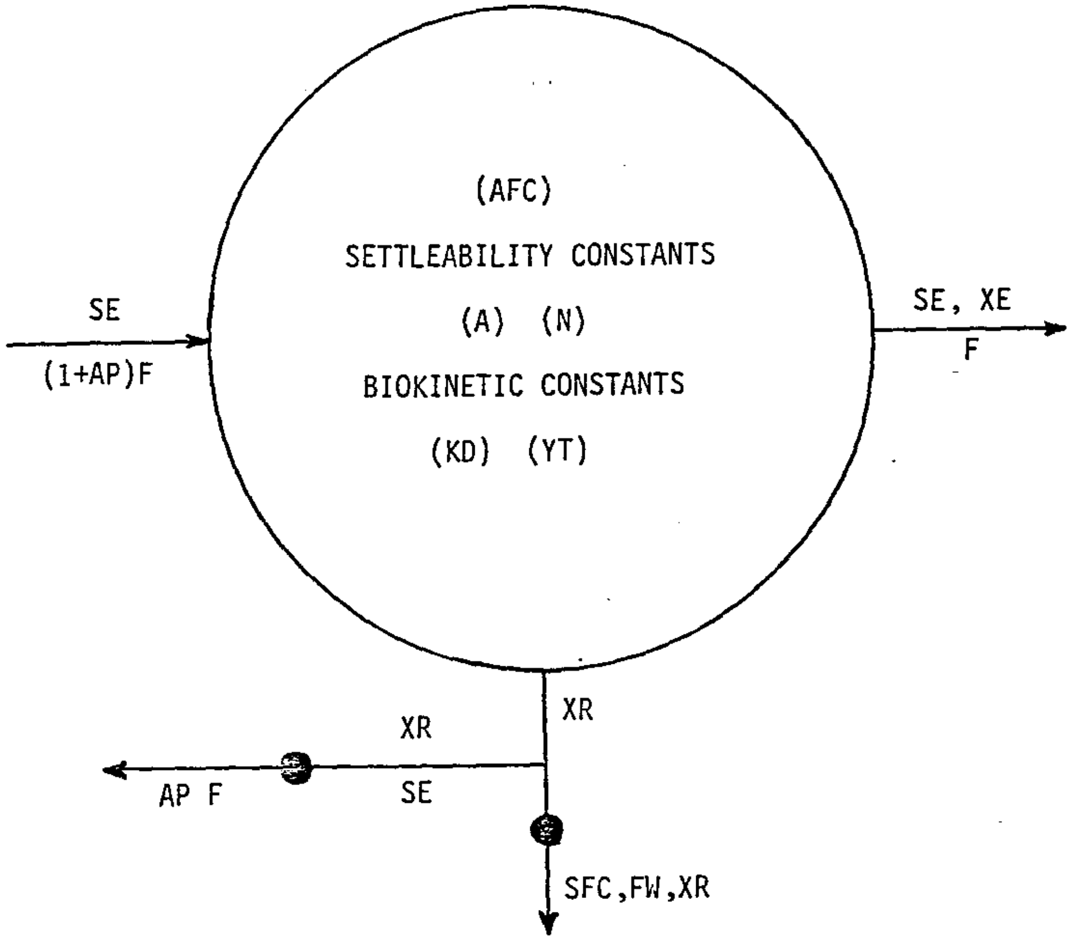
$$XI=X0-X0\left(0.711-\frac{474F}{APC}\right)$$

$$SI=S0+(KI)(XI)$$

$$PS=(F)(X0)8.34\left(0.711-\frac{474F}{APC}\right)$$

FIGURE 3 UNIT PROCESS MODELS

Final Clarifier Specifications



$$\frac{AP^{n-1}}{(1+AP)^{n}} = \frac{F(1.0036E-06)^{n}}{0.01077(AFC)(A)(n-1)\left(\frac{n}{n-1}\right)^{n}} \qquad \text{(solve for AP)}$$

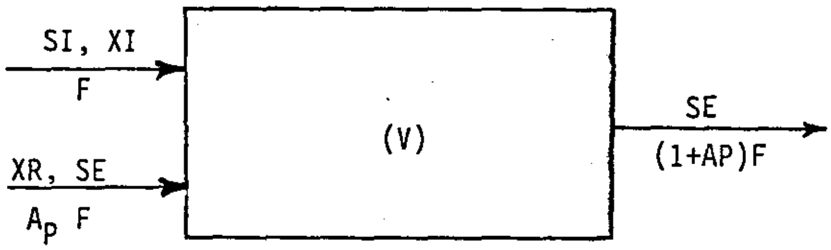
$$XR = \frac{\frac{(KD)(X)(V)}{F} + (1+AP)X + \frac{(YT)(UM)(SI)}{KB + \frac{(F)(SI)}{(X)(V)}}}{AP}$$

$$FW = \frac{(1+AP)(X)(F) - (AP)(F)(XR) - (F)(XE)}{XR-XE}$$

$$SFC = 8.34(XR)(FW)$$

FIGURE 3 (CONT.)

Activated Sludge Specifications



$$X = \frac{8.34F \; \frac{SI}{V}}{\frac{(SI)(UM)}{SI-SE} - KB}$$

FIGURE 3 (CONT.)

COST EQUATIONS

CLARIFIERS

OPERATION LABOR

$\$/YR=4.99(A)^{0.577}\ LC$

MAINTENANCE LABOR

$\$/YR=1.936(A)^{0.618}\ LC$

MATERIAL & SUPPLY COSTS

$\$/YR=4.47(A)^{0.758}$

DIFFUSED AIR SYSTEM

OPERATION LABOR

$\$/YR=(27.3)(LC)(CFM)^{0.504}$

MAINTENANCE LABOR

$\$/YR=(9.89)(LC)(CFM)^{0.557}$

ELECTRIC POWER

$\$/YR= HP(24)(.7457)EC(365)$

MECHANICAL AERATION

OPERATION LABOR

$\$/YR=110.8\ {\frac{V\ X\ 10^{6}}{7480}}^{0.518}\ LC$

COST EQUATIONS

FIGURE 4

MAINTENANCE LABOR

$$\$/YR=57.513\ \frac{V\ X\ 10^{6}}{7480}^{0.562}\ LC$$

ELECTRIC POWER

$$\$/YR=(24)(365)(.7457)(HP)(EC)$$

DISSOLVED AIR FLOTATION

TOTAL 0 + M

$$\$/YR=2.52\ \frac{0.0024(PS+SFC)}{L0\ X\ 10^{-6}}^{0.54}$$

LABOR

$$\$/YR=14.14\ \frac{0.0024(PS+SFC)}{L0\ X\ 10^{-6}}^{0.40}$$

POWER

$$\$/YR=0.0031\ \frac{0.0024(PS+SFC)}{L0\ X\ 10^{-6}}^{0.40}\ EC$$

MATERIAL

$$\$/YR=855\ \frac{0.0024(PS+SFS)}{L0\ X\ 10^{-6}}^{0.12}$$

FIGURE 4 (CONT.)

ANAEROBIC DIGESTER

TOTAL O + M

$$\$/YR=96.6 \quad \frac{PS+SFC}{.0019}^{1.3}$$

POWER

$$\$/YR=0.16 \times 10^{-5}(EC) \quad \frac{PS+SFC}{.0019}^{1.3}$$

LABOR

$$\$/YR=57.7 \quad \frac{PS+SFC}{.0019}^{.36}$$

MATERIAL

$$\$/YR=33.4 \quad \frac{PS+SFC}{.0019}^{.35}$$

SLUDGE DRYING BEDS

TOTAL 0+M

$$\$/YR=1.22 \quad \frac{.022\ ED\ (PS+SFC)}{LD \times 10^{-6}}^{0.65}$$

LABOR

$$\$/YR=1.85 \quad \frac{.022\ ED\ (PS+SFC)}{LD \times 10^{-6}}^{0.40}$$

FIGURE 4 (CONT.)

MATERIAL

$$\$/YR=0.37 \times 10^{-3} \left(\frac{.022\ ED\ (PS+SFC)}{LD \times 10^{-6}} \right)^{1.06}$$

PUMPING

OPERATION LABOR

$$\$/YR=(148.39)(LC) \sum_{i=1}^{3} (F_i)^{0.636}$$

MAINTENANCE LABOR

$$\$/YR=(122.45)(LC) \sum_{i=1}^{3} (F_i)^{0.636}$$

ELECTRIC COSTS

$$\$/YR=(0.7454)(24)(365)(62.4)(EC) \sum_{i=1}^{3} (F_i \times H_i)$$

OTHER MATERIAL & SUPPLY

$$\$/YR=(900) \sum_{i=1}^{3} (F_i)^{0.79}$$

FIGURE 4 (CONT.)

80 computer terminal. Within the program there is a provision for computing and comparing the total costs for the mechanical aeration and the diffused aeration. The program is very simple in structure and its flow diagram is shown in Figure 5. The program listing may be found in the appendix.

Results

The results of this research generally consist of the operational and economic models, as described earlier, and their representation in the computer program. For each set of system specifications, a total annual operating and maintenance cost can be derived. This is illustrated in Figure 6 for two different aeration options on otherwise identical system specification.

Research Benefits

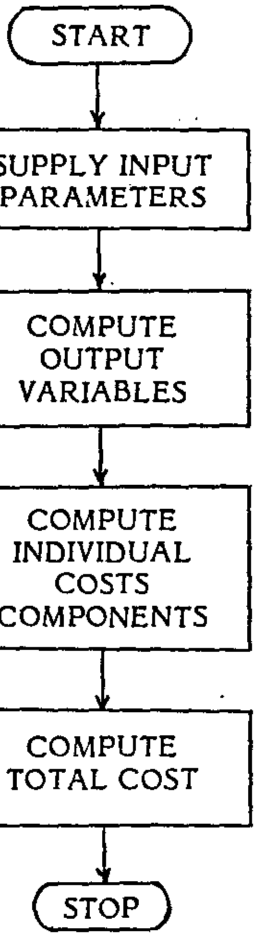
This research has the potential to benefit all local governments which are currently operating wastewater treatment plants. Providing a way in which to evaluate (analytically) annual costs, engineers should be able to reduce that cost by altering system parameters.

This research contributes to the growing field of wastewater treatment cost examination by providing a viable model of current plant operation and including an economic evaluation.

Meetings and Publications

Koelling, C.P. and D.F. Kinncannon, "Cost Minimization of the Wastewater Treatment Process," paper presented at ORSA/TIMS 1982 Joint National Meeting, San Deigo, CA, October 1982.

Koelling, C.P. "Wastewater Treatment: Design Optimization and Its Implication for Federal and Local Governments". Preceedings, Institute of Industrial Engineers, 1983 Annual Industrial Engineers Confernece, May 1983. (reprint attached)



FLOW DIAGRAM OF THE PROGRAM

FIGURE 5

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                         SUMMARY OF VARIABLES

1) INPUT VARIABLES :

  A. GENERAL

   BS= 30 Mg/l         Xe= 30 Mg/l         K1= .5                 Ss= 0 Mg/l
   F= 10 MGD           APC= 10000 SQ.FT.   Xo= 200 Mg/l           V= 8.95 MG
   Um= 16 #/DA/#       Kb= 15.9 #/DA/#     Kd= .07 1/DA           YT= .63 LB/LB
   a= 2.62E-07 FT/MIN                      n= 1.7

  B. MECHANICAL AERATION

   No= 2 #/HP/HR       B= 1                Cw= 9.2 Mg/l           Cl= 2 Mg/l
   TEMP= 25 DEG. C                         AW= .8

  C. DIFFUSED AERATION

   NONE

  D. MISCELLANEOUS

   H1= 20 FT           H2= 20 FT           H3= 20 FT              EC= .05 $/KWH
   LC= 5 $/HR          LO= 25 #/DA/SQ.FT.    ED= .7               FS= .5
   LD= 500 LB/DA


2) OUTPUT VARIABLES

  A. GENERAL

   Se= 15 Mg/L         Si= 156.3 Mg/l      Xi= 152.6 Mg/l         PS= 3953.16 LB/D
   X= 809.82 Mg/l  ALPHA= .556498          Xr= 2180.52 Mg/l       Fw= .0791764 MGD
   SFC= 1439.87 LB/DA

  B. MECHANICAL AERATION

   POH= 58.7566 LB(O2)/HR                  N1= 1.41443 Mg/l   Hp= 671.25 HP

  C. DIFFUSED AERATION

   NONE

  D. MISCELLANEOUS

   F1= 9.48E-04 MGD  F2= .0791764 MGD         F3= 5.56498 MGD



   TOTAL OP + MNT. COST 23607.2
   TOTAL MAINT. LABOR COST 15876
   TOTAL OPER. LABOR COST 39236
   TOTAL ELEC. POWER COST 223445
   TOTAL MAT. + SUPL. COST 10330.6
   TOTAL COST/YR. 312495
```

FIGURE 6 MODEL RESULTS

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                         SUMMARY OF VARIABLES

1) INPUT VARIABLES :

  A. GENERAL

   BS= 30 Mg/l       Xe= 30 Mg/l          K1= .5              Ss= 0 Mg/l
   F= 10 MGD         APC= 10000 SQ.FT.    Xo= 200 Mg/l        V= 8.95 MG
   Um= 16 #/DA/#     Kb= 15.9 #/DA/#      Kd= .07 1/DA        YI= .63 LB/LB
   a= 2.62E-07 FT/MIN                     n= 1.7

  B. MECHANICAL AERATION

   NONE

  C. DIFFUSED AERATION

   AE= .08           Pi= 35 PSIA          Po= 23 PSIA         TEMP= 77 DEG. F
   e= .8

  D. MISCELLANEOUS

   H1= 20 FT         H2= 20 FT            H3= 20 FT           EC= .05 $/KWH
   LC= 5 $/HR        LO= 25 #/DA/SQ.FT.     ED= .7            FS= .5
   LD= 500 LB/DA


2) OUTPUT VARIABLES

  A. GENERAL

   Se= 15 Mg/L       Si= 156.3 Mg/l       Xi= 152.6 Mg/l      PS= 3953.16 LB/D
   X= 809.82 Mg/l    ALPHA= .556498       Xr= 2180.52 Mg/l    Fw= .0791764 MGD
   SFC= 1439.87 LB/DA

  B. MECHANICAL AERATION

   NONE

  C. DIFFUSED AERATION

   POD= 23 LB(O2)/DA      PAS= .0143429 LB/SEC                HP= 671.25 HP
   MHP= 671.25 HP

  D. MISCELLANEOUS

   F1= 9.48E-04 MGD  F2= .0791764 MGD          F3= 5.56498 MGD




   TOTAL OP + MNT. COST 23607.2
   TOTAL MAINT. LABOR COST 1901.75
   TOTAL OPER. LABOR COST 17768.7
   TOTAL ELEC. POWER COST 223445
   TOTAL MNT. + SUPL. COST 10330.6
   TOTAL COST/YR. 277053
```

FIGURE 6 (CONT.)

Appendix

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10 CLEAR 1000:DEFINT I:DEFSTR W,Z
15 ZA=CHR$(128):ZB=CHR$(140):ZC=CHR$(160):ZD=CHR$(176):ZE=CHR$(144):ZF=CHR$(18
20 ZG=CHR$(133):ZH=CHR$(138):ZI=CHR$(180):ZJ=CHR$(173):ZK=CHR$(158):ZL=CHR$(13
25 ZM=CHR$(134):ZN=CHR$(149):ZO=CHR$(170):ZP=CHR$(131):ZQ=CHR$(179):ZU=CHR$(141
:ZZ="SLUDGE"
30 WA=ZC+ZD+ZB+ZB+ZB+ZB+ZD+ZE:WW=STRING$(22,140):WB=STRING$(6,128):WD=ZF+ZG:WE=
H+ZI
35 WH=ZA+ZA+ZA+ZA+ZA:WC=STRING$(11,176):WG="ACTIVATED":WI=STRING$(5,131):WJ=STR
NG$(6,128)
37 W8=" P.C. ":W9=" F.C. "
40 WZ=STRING$(11,131):WM=STRING$(4,128):WL=ZL+ZB+ZD+ZD+ZD+ZD+ZB+ZM:ZZ="SLUDGE"
K=ZA+ZA
90 GOSUB 4000
100 REM **PRIMARY CLARIFIER**
110 CLS:INPUT"BOD EFFLUENT STANDARD =";BS
120 INPUT"S.S. EFFLUENT STANDARD =";XE
130 INPUT"INFLUENT SUSPENDED SOLIDS (MG/L) =";XO
140 INPUT"BOD RATIO OF S.S. <K1> =";K1
150 INPUT"SOLUBLE INFLUENT BOD (MG/L) =";SO
160 INPUT"FLOW (MGD) =";F
170 INPUT"AREA OF PRIMARY CLARIFIER (SQ.FT.) =";APC
180 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O ";T1$
190 IFLEFT$(T1$,1)="N"THEN110
200 SE=BS-(K1*XE):XI=XO-(XO*(.711-((4.74*F*100)/APC)))
210 SI=SO+(K1*XI):PS=F*XO*(.711-((4.74*F*100)/APC))*8.34
220 REM**ACTIVATED SLUDGE**
230 CLS:INPUT"VOLUME OF REACTOR (MG) =";V
240 PRINTTAB(20)"BIOKINECTIC CONSTANTS"
250 INPUT"U MAX =";UM
260 INPUT"KB =";KB
270 REM**FINAL CLARIFIER**
280 INPUT"DECAY COEFFICIENT (1/DAY) =";KD
290 INPUT"SLUDGE YEILD <YT> =";YT
300 PRINTTAB(20)"SETTLEABILITY CONSTANTS"
310 INPUT"A =";A
320 INPUT"N =";N
330 INPUT"AREA OF FINAL CLARIFIER (SQ.FT.) =";AFC
335 INPUT"MAXIMUM POSSIBLE XR (MG/L) =";MXR
340 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O ";T2$
350 IFLEFT$(T2$,1)="N"THEN230
360 CLS:X=(8.34*F*SI/V)/((UM*SI/(SI-SE))-KB)
390 KA=F*((1.0036*10[-6*X)[N)
400 KA=KA/(AFC*1.077*.01*A):KA=KA/(N-1):KA=KA/((N/(N-1))[N)
410 FORC=1TO6
420  FORC1=0TO10
430   AA=(C1*10[-C)+AC
440   CA=(AA[(N-1))/((1+AA)[N)
450 IFCA>=KATHEN480
460 NEXTC1
470 IF AL>=1 THEN CLS:PRINT"AREA FINAL CLARIFIER IS TOO SMALL":END
480 AL=AC+((C1-1)*10[-C):AC=AL
490 NEXTC
510 XR=((KD*X*V/F)+((1+AL)*X)-(YT*UM*SI/(KB+(F*SI/(X*V)))))/AL
512 IFXR<MXRTHEN 520
513 XR=MXR:E1=-1
514 AL=((((KD*X*V/F)-(YT*UM*SI/(KB+(F*SI/(X*V)))))/XR)+(X/XR))/(1-(X/XR))
520 FW=(((1+AL)*X*F)-(AL*XR*F)-(F*XE))/(XR-XE)
522 IFFW>0THEN 530
524 FW=0:XR=X-((XE-X)/AL):E1=-1
525 IFXR<MXR THEN 530
527 XR=MXR:AL=(XE-X)/(X-XR)
530 SFC=FW*XR*8.34
540 CLS:PRINT"ENTER TYPE OF AERATION DEVICE : (1) MECHANICAL
550 INPUT"
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570 POH=((SI-SE)*F/16.32)-((((1+AL)*F*X)-(AL*F*XR))*1.42/24)
580 CLS:PRINTTAB(15)"MECHANICAL AERATION"
590 INPUT"OXGYEN RATING OF AERATOR <NO>";NO
600 PRINT:PRINT"SALINITY-SURFACE TENSION CORRECTION"
610 INPUT"FACTOR , USUALLY 1";B
620 PRINT:PRINT"OXYGEN-SATURATION CONCENTRATION FOR WASTE AT GIVEN"
630 INPUT"TEMPERATURE AND ALTITUDE <CW>";CW
640 PRINT:INPUT"D.O. CONCENTRATION";CL
650 PRINT:INPUT"TEMPERATURE (CENTIGRADE)";TW
660 PRINT:INPUT"OXYGEN-TRANSFER CORRECTION FACTOR FOR WASTE";AW
670 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T5$
680 IFLEFT$(T5$,1)="N"THEN580
690 N1=NO*AW*((B*CW)-CL)*(1.024[(TW-20))/9.17
700 HP=POH/N1:GOTO830
710 CLS:PRINTTAB(15)"DIFFUSED AERATION"
720 POD=((SI-SE)*F/.68)-((((1+AP)*X)-(AP*XR))*F*1.42)
730 INPUT"TRANSFER EFFICIENCY OF AERATOR";AE
740 INPUT"ABSOLUTE INLET PRESSURE (PSIA)";PI
750 INPUT"ABSOLUTE OUTLET PRESSURE (PSIA)";PO
760 INPUT"TEMPERATURE (CENTIGRADE)";TP
770 INPUT"COMPRESSOR EFFICIENCY";E
780 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T6$
790 IFLEFT$(T6$,1)="N"THEN710
800 PAS=POD/(20044.8*AE)
805 DE=(.6659*(TP+273))/PI
806 CFM=DE*PAS*60
810 TP=(1.8*TP)+32
820 HP=53.5*PAS*(460+TP)*(((PO/PI)[.283)-1)/(550*.283*E)
830 MHP=V*75
840 IFMHP>HPTHENHP=MHP
850 CLS:INPUT"PRIMARY SLUDGE PUMP HEAD (FT)";H1
860 INPUT"FINAL SLUDGE PUMP HEAD (FT)";H2
870 INPUT"RECYCLE PUMP HEAD (FT)";H3
880 INPUT"ELECTRIC POWER COST ($/KWH)";EC
890 INPUT"LABOR COST ($/HR)";LC
900 INPUT"SOLIDS LOADING TO AIR FLOTATION (LBS/DAY SQ.FT.)";LO
910 INPUT"SOLIDS LOADING TO ANAEROBIC DIGESTER (LBS/DAY)";LD
920 INPUT"EFFICIENCY OF ANAEROBIC DIGESTER";ED
930 INPUT"SOILD FRACTION OF PRIMARY SLUDGE";FS
940 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T7$
950 IFLEFT$(T7$,1)="N"THEN850
960 F1=(PS/(8.34*FS))/(10[6):F2=(SFC/(8.34*XR/(10[6)))/(10[6):F3=AL*F
1000 CLS:INPUT"DO YOU WANT A HARD PRINT (Y) OR (N) ";Q1$
1010 IFLEFT$(Q1$,1)="N" THEN 1400
1020 CLS:PRINT"SET PRINTER , PRESS ENTER."
1030 IF INKEY$=""THEN1030
1040 LPRINT:LPRINT:LPRINTTAB(30)"SUMMARY OF VARIABLES"
1050 LPRINT:LPRINTTAB(5)"1) INPUT VARIABLES :"
1060 LPRINT:LPRINTTAB(7)"A. GENERAL"
1070 LPRINT:LPRINTTAB(8)"BS=";BS;"Mg/l";TAB(24)"Xe=";XE;"Mg/l";TAB(43)"K1=";K1;
AB(62)"Ss=";SS;"Mg/l"
1080 LPRINTTAB(8)"F=";F;"MGD";TAB(24)"APC=";APC;"SQ.FT.";TAB(43)"Xo=";XO;"Mg/l"
TAB(62)"V=";V;"MG"
1090 LPRINTTAB(8)"Um=";UM;"#/DA/#";TAB(24)"Kb=";KB;"#/DA/#";TAB(43)"Kd=";KD;"1/
A";TAB(62)"YT=";YT;"LB/LB"
1100 LPRINTTAB(8)"a=";A;"FT/MIN";TAB(43)"n=";N
1110 ON T4GOTO 1120,1165
1120 LPRINT:LPRINTTAB(7)"B. MECHHANICAL AERATION"
1130 LPRINT:LPRINTTAB(8)"No=";NO;"#/HP/HR";TAB(26)"B=";BTAB(43);"Cw=";CW;"Mg/l"
TAB(62)"Cl=";CL;"Mg/l"
1140 LPRINTTAB(8)"TEMP=";TW;"DEG. C";TAB(43)"AW=";AW
1150 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1160 LPRINT:LPRINTTAB(8)"NONE":GOTO 1200
1165 LPRINT:LPRINTTAB(7)"B. MECHHANICAL AERATION":LPRINT:LPRINTTAB(8)"NONE"
1170 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
```

```
AB(62)"TEMP=";TP;"DEG. F"
1190 LPRINTTAB(8)"e=";E
1200 LPRINT:LPRINTTAB(7)"D. MISCELLANEOUS"
1210 LPRINT:LPRINTTAB(8)"H1=";H1;"FT";TAB(24)"H2=";H2;"FT";TAB(43)"H3=";H3;"FT
TAB(62)"EC=";EC;"$/KWH"
1220 LPRINTTAB(8)"LC=";LC;"$/HR";TAB(24)"LO=";LO;"#/DA/SQ.FT.";TAB(45)"ED=";ED;
AB(62)"FS=";FS
1230 LPRINTTAB(8)"LD=";LD;"LB/DA"
1240 LPRINT:LPRINT:LPRINTTAB(5)"2) OUTPUT VARIABLES"
1250 LPRINT:LPRINTTAB(7)"A. GENERAL"
1260 LPRINT:LPRINTTAB(8)"Se=";SE;"Mg/L";TAB(24)"Si=";SI;"Mg/l";TAB(43)"Xi=";XI;
Mg/l";TAB(62)"PS=";PS;"LB/DA"
1270 LPRINTTAB(8)"X=";X"Mg/l";TAB(24)"ALPHA=";AL;TAB(43)"Xr=";XR;"Mg/l";TAB(62
Fw=";FW;"MGD"
1275 IFE1<>-1THEN1280
1276 LPRINTTAB(8)"WARNING: MAXIMUN Xr WAS USED !!"
1280 LPRINTTAB(8)"SFC=";SFC;"LB/DA"
1290 ON T4GOTO 1300,1340
1300 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION"
1310 LPRINT:LPRINTTAB(8)"PUH=";PUH;"LB(O2)/HR";TAB(43)"N1=";N1;"Mg/l";TAB(62)"
=";HP;"Hp"
1320 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1330 LPRINT:LPRINTTAB(8)"NONE":GOTO 1380
1340 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION"
1350 LPRINT:LPRINTTAB(8)"NONE"
1360 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1370 LPRINT:LPRINTTAB(8)"POD=";POD;"LB(O2)/DA";TAB(30)"PAS=";PAS;"LB/SEC";TAB(
);"HP=";HP;"Hp":LPRINTTAB(8)"MHP=";MHP;"Hp"
1380 LPRINT:LPRINTTAB(7)"D. MISCELLANEOUS"
1390 LPRINT:LPRINTTAB(8)"F1=";F1;"MGD";TAB(26)"F2=";F2;"MGD";TAB(50)"F3=";F3;"
D"
1400 INPUT"DO YOU WANT COST";Q2$
1410 IFLEFT$(Q2$,1)="N" THEN END
1420 CLS:PRINT"SET PRINTER, PRESS ENTER"
1430 IFINKEY$=""THEN1430
1440 GOSUB 5000
1450 END
4000 CLS
4010 PRINT@64," F,SO,XO                SI,XI      ";STRING$(2,92);"O2";STRING$(2,92);"
   SE               F,SE,XE"
4020 PRINT@139,WA+WB+WC+WB+WA
4030 PRINT@202,WD+WB+WE+WH+ZN+WG+ZO+WH+WD+WB+WE
4040 PRINT@261,WI+ZJ+ZE+W8+ZC+ZK+ZP+ZP+ZP+ZQ+ZQ+ZN+WK+ZZ+ZA+ZO+WI+ZJ+ZE+W9+ZC+Z
+WI
4050 PRINT@331,WL+WM+ZN+ZA+WZ+WJ+WL
4060 PRINT@398,ZO+ZA+ZA+ZH+ZH+ZA+ZA+ZA+ZA+ZU+WW+ZN
4070 PRINT@448,"                ";STRING$(2,92);"SLUDGE";STRING$(2,92);"      RECYCLE
LOW      ";STRING$(2,92);"SLUDGE";STRING$(2,92)
4080 PRINT:PRINT:PRINT"PRESS SPACE BAR TO CONTINUE"
4090 IFINKEY$=""THEN4090
4100 RETURN
5000 REM
5010 REM COST COMPUTATIONS
5012 REM   CA(I) = MAT. + SUPL. COST
5013 REM   CE(I) = (ELECTRICAL) POWER COST
5014 REM   CM(I) = MAINT. LABOR COST
5016 REM   COM(I)= TOTAL OPER. + MAINT. COST
5017 REM   CP(I) = OPER. LABOR COST
5018 REM   CM & CM ARE NOT INCLUDED IN COM
5020 DIM CA(10),CE(10),CM(10),COM(10),CP(10)
5030 CP(1) = 4.999*(A[0.577)*LC
5040 CM(1) = 1.936*(A[0.618)*LC
5050 CA(1) = 4.470*(A[0.758)
5060 IF T4 = 1 THEN 5110
```

```
5090 CE(1) = HP*0.7457*EC*24*365
5100 GOTO 5160
5110 QT = V*10[6/7480
5120 CP(2) = 110.8*(QT[0.518)*LC
5130 CM(2) = 52.513*(QT[0.562)*LC
5140 CE(1) = 24*365*0.7457*HP*EC
5150 REM
5160 QT = 0.0024*(PS+SFC)/(LO*10[-6)
5170 COM(1) = 2.52*QT[0.54
5180 CP(3) = 14.14*QT[0.4
5190 CE(2) = 0.0031*QT[0.4*EC
5200 CA(2) = 855.0*QT[0.12
5210 REM
5220 QT = (PS+SFC)/0.0019
5230 COM(2) = 96.6*QT[0.35
5240 CE(3) = 0.16*(10[-5)*EC*QT[1.3
5250 CP(4) = 57.7*QT[0.36
5260 CA(3) = 33.4*QT[0.35
5270 REM
5280 QT = 0.022*ED*(PS+SFC)/(LD*10[-6)
5290 COM(3) = 1.22*QT[0.65
5300 CP(5) = 1.85*QT[0.4
5310 CA(4) = 0.37*(10[-3)*QT[1.06
5320 REM
5330 CP(6) = 148.39*LC*(F1[0.636+F2[0.636+F3[0.636)
5340 CM(3) = 122.45*LC*(F1[0.569+F2[0.569+F3[0.569)
5350 CE(4) = (F1*H1+F2*H2+F3*H3)
5360 CE(4) = CE(4)*EC*62.4*0.7457*24*365/550
5365 CA(5) = 900*(F1[.79+F2[.79+F3[.79)
5370 REM
5380 C1 = COM(1)+COM(2)+COM(3)
5390 LPRINTTAB(8)"TOTAL OP + MNT. COST";C1
5400 C2 = CM(1)+CM(2)+CM(3)
5410 LPRINTTAB(8)"TOTAL MAINT. LABOR COST";C2
5420 C3 = CP(1)+CP(2)+CP(3)+CP(4)+CP(5)+CP(6)
5430 LPRINTTAB(8)"TOTAL OPER. LABOR COST";C3
5440 C4 = CE(1)+CE(2)+CE(3)+CE(4)
5450 LPRINTTAB(8)"TOTAL ELEC. POWER COST";C4
5460 C5 = CA(1)+CA(2)+CA(3)+CA(4)
5470 LPRINTTAB(8)"TOTAL MAT. + SUPL. COST";C5
5480 REM
5490 CC = C1+C2+C3+C4+C5
5500 LPRINTTAB(8)"TOTAL COST/YR.";CC
5510 RETURN
```

WASTEWATER TREATMENT: DESIGN OPTIMIZATION AND ITS IMPLICATIONS FOR FEDERAL AND LOCAL GOVERNMENTS

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Abstract

The wastewater treatment design problem is addressed with an objective of minimizing costs over the life of the facility. The model developed utilizes the treatment design equations to generate an annual cost expression. Through the use of simple nonlinear optimization techniques, the treatment design which results in the lowest cost is found. An analysis of the model's performance reveals its potential impact on facility costs. Also examined is the impact with respect to costs at both the federal level and local level.

Introduction

During the past few years, millions of dollars have been spent in constructing wastewater treatment plants. The American taxpayer is faced with additional large expenditures for wastewater treatment facilities. Inflation will add to the cost of constructing these treatment plants as well as increasing the operation and maintenance costs. Even so, very little has been done by the design engineer in regards to selecting the most cost effective design. The objective of this research was to develop an optimization technique for selecting the most cost effective design for the activated sludge wastewater treatment process.

The current design process consists largely of picking treatment components which result in a desired effluent quality. For the activated sludge process, one of the major wastewater treatment processes, the typical components are illustrated in Figure 1. The design of the biological reactor, final clarifier, recycle pump, and recycle pipeline are dependent upon each other. Many different combinations of these components can result in the same quality effluent. Thus, a particular effluent quality can be achieved through a number of designs. It is desirable to choose that design which meets the required effluent at the least possible cost.

Additional questions arise regarding the precise definition of minimum cost. Wastewater treatment costs are shared by the federal and local government. The federal government funds a percentage (in general, 75%) of the construction costs while local governments are responsible for all operating and maintenance costs. Since the design chosen dictates construction and operating and maintenance costs, the federal government would be interested in selecting a design which results in low construction costs. Local government would want low operating and maintenance costs. Thus, finding the design which presents the least-cost to the federal government may not be the same design which presents the least cost to the local government. This issue will be examined further later in this paper.

This paper presents a decision model for choosing the least-cost wastewater treatment design. This consists of system equations specifying the relevant design, an economic model relating each design to an annual cost, and an optimization model to find the design yielding the least cost. An analysis of model test results is also included.

Assumptions

There are several assumptions which were made during the development of this treatment model. These relate primarily to the treatment process and the economic model used.

Of the many different types of wastewater treatment processes, the process modelled is the activated sludge treatment process which is described in Figure 1. This is extended in Figure 2 to consider treatment of sludge. Further, later on the sludge treatment activity is included in the design model. The particular sludge treatment process considered is presented in Figure 3.

Assumptions were also required for the economic model. Government specifications were included in the creation of the model. These included such things as handling interest charges during construction and special charges for "yard work" (laying pipelines, other charges not specifically allocated to other construction). One specification not rigidly followed was the discount or interest rate used. An interest rate was chosen to reflect current financial conditions.

The lives of assets included in the analysis are also based upon government specifications. In cases where salvage values were not dictated, expert opinion was used to determine these values.

Finally, inflation is not explicitly considered in the analysis. This would also include changes in energy costs over the years of life of the treatment facility. This

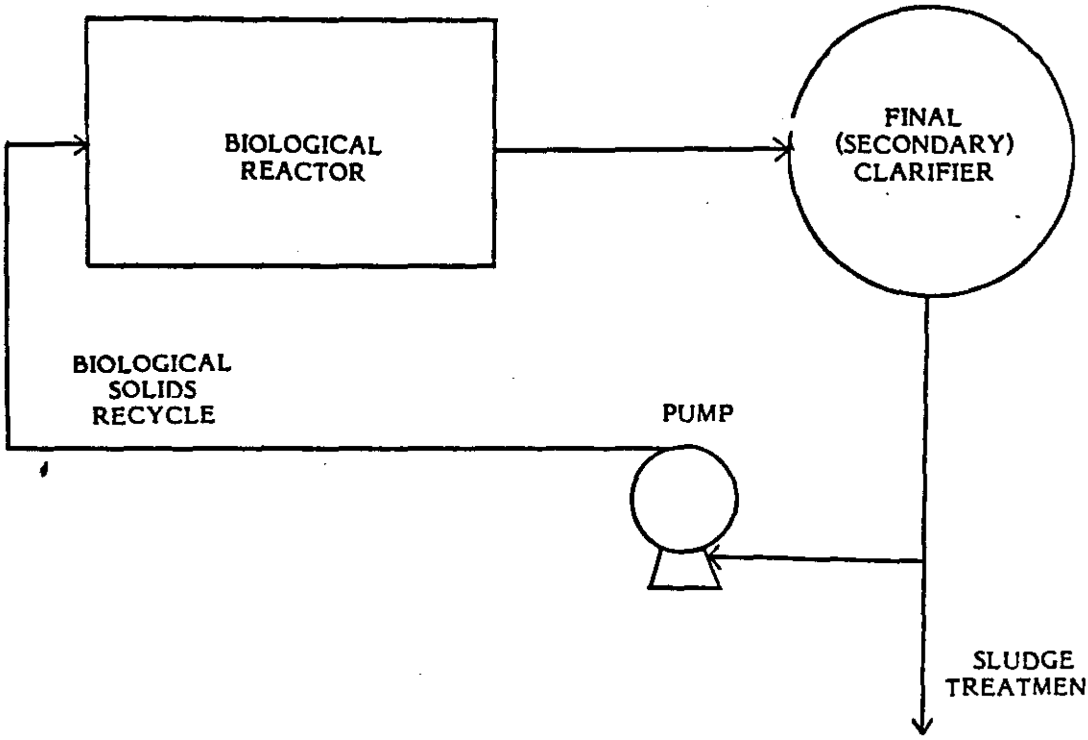

Figure 1. Basic Activated Sludge Process

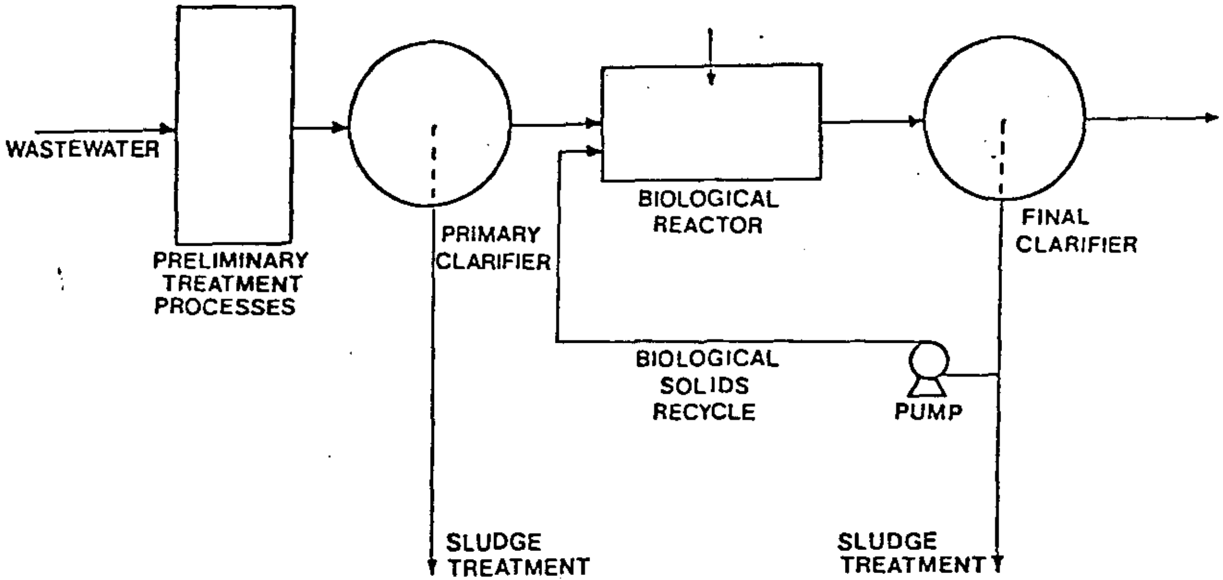

Figure 2. Flow Diagram of Activated Sludge Process

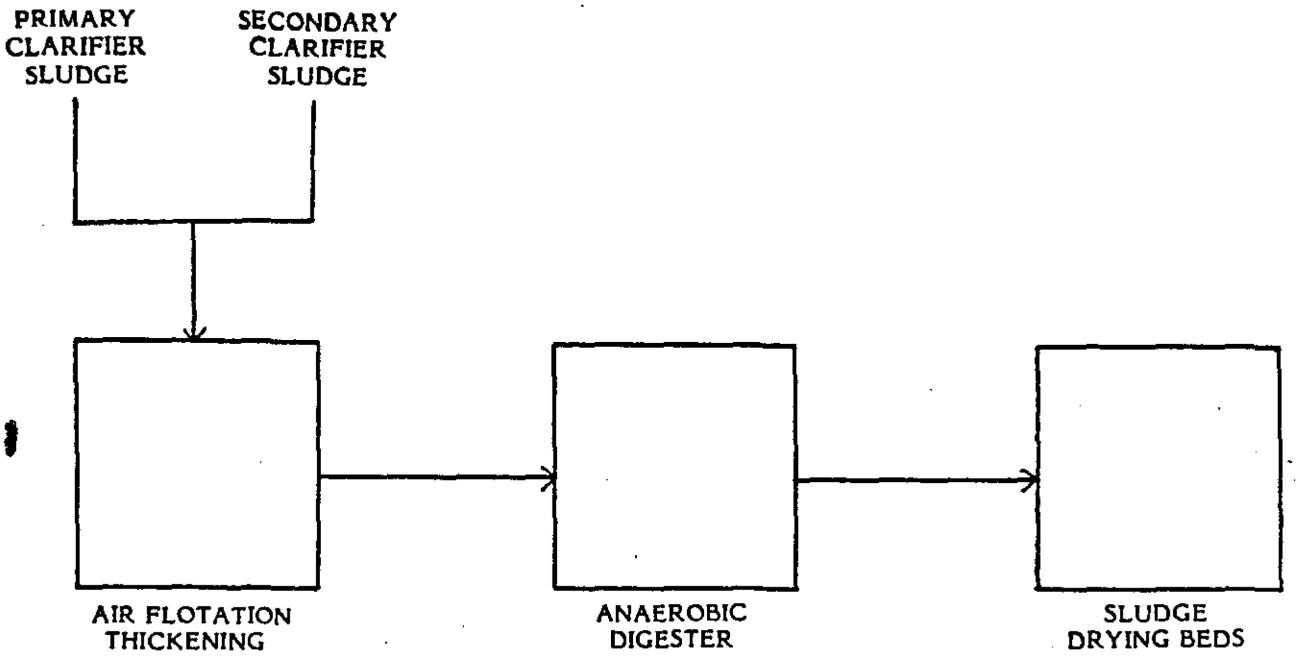

Figure 3. Flow Diagram of the Sludge Treatment Process

would be a desired extension of the current model. The anticipated impact of these considerations will be addressed later in the paper.

Activated Sludge Model

The activated sludge process is but one of several wastewater treatment processes in use today. Because it is one of the most popular processes, it was chosen for analysis. The activated sludge process is depicted in Figure 2.

In this paper there is no reason to detail the biological activity of the activated sludge treatment process. What is of concern are the appropriate treatment components, their relationships, and the resultant decision variables.

The major components of interest, from Figure 2, are related as follows. The influent, after passing through any preliminary treatment processes, enters the primary clarifier. At this point a certain amount is routed directly to sludge treatment. This amount is determined by the overflow-rate, F_{OF}. The overflow rate, in combination with the influent flow rate, F, dictates the rate of flow into the activated sludge process.

The first component of the activated sludge process is the biological reactor where the waste is treated biologically. An aeration process is also included. The size of the biological reactor is specified as a volume.

The only cost, other than construction, associated with the biological reactor, is related to the aeration process. Two different aeration processes were considered: diffused and mechanical.

The second component of the activated sludge process is the secondary, or final, clarifier. In this clarifier biological solids settle to the bottom, being either recycled or sent to sludge treatment. The effluent is taken from the top of the clarifier. Of course the desire is that the effluent meet quality specifications. The size of the clarifier is specified as an area.

A prescribed amount of the biological solids are sent to sludge treatment. A prescribed amount is also recycled through the activated sludge process. This recycling is actually the third major component of the process. The amount of recycling is controllable, and as will be shown later, has a significant impact on the overall design of the system. As shown in Figure 2, the solids are recycled to the biological reactor. The variable α specifies the fraction of biological solids which are recycled.

The sludge treatment process is depicted in Figure 3. Sludge may arrive from either the primary clarifier or secondary clarifier. There is a trade-off between treatment within the activated sludge process and sludge treatment.That is, more of one implies less of the other. Sludge treatment represents the last stage of the treatment process.

The specification of system components must be made via system design equations. These equations relate biological constants and input parameters to system operation, including specification of system components; volume of the biological reactor and area of the final clarifier.

Design models are available for the biological reactor, final clarifier, and recycle flow rates. Appropriate models from the literature were selected, [3]. There are no models available for the primary clarifier and sludge treatment processes. For these processes, data was taken from the literature and a mathematical relationship was developed. Before presenting the design equations, it is necessary to present the definition of symbols used. These definitions are given below.

a = Sludge settling velocity constant

A = Surface area of a clarifier (square feet)

E = Fraction of suspended solids removed in the primary clarifier

F = Wastewater flow rate (million gallons per day)

F_{C12} = Solids flow rate from air flotation unit

F_{OF} = Overflow rate (gallons per day per ft^2)

k_d = Decay coefficient (day^{-1})

k_s = Biological constant

L_D = Solids loading to digester (pounds per day)

L_o = Solids loading to air flotation (pounds per day ft^2)

n = Sludge settling velocity constant

S_e = Organic material concentration (effluent, milligrams per liter)

S_i = Organic material concentration (total from primary clarifier, milligrams per liter)

S_s = Soluble organic material concentration (influent, milligrams per liter)

V = Volume of the biological reactor (million gallons)

X = Biological population (milligrams per liter)

X_o = Suspended solids in influent (milligrams per liter)

X_R = Final clarifier underflow solids concentration (milligrams per liter)

Y_t = Sludge yield

α = Recycle flow rate

μ_{max} = Maximum growth rate (day^{-1})

μ_n = Net specific growth rate (day^{-1})

Based upon these definitions, the pertinent design equations are presented in Table 1. These are the relationships used in the system model. Notice that there is interdependence among the components. A specification of the system seems difficult from these complex interrelationships. However, they can be reduced to a form which allows straightforward analysis. This is detailed in the optimization discussion.

Each particular treatment design results in a specific treatment cost, consisting of construction and operation and maintenance costs. The determination, and comparison, of these costs is accomplished through an engineering economy model of the system. The development and operation of this model is presented in the next section.

Economic Model

The purpose of the research was to determine the activated sludge treatment design resulting in the minimum cost. In order to accomplish this it was necessary to develop a precise definition of cost.

Because the costs of constructing and operating a waste treatment facility do not all occur at once, it is important to perform an analysis which accounts for the time value of money. In order to compare designs based upon this, a standard analysis was established. In this case, due to the unequal lives of the assets, the comparison was based upon equivalent uniform annual costs.

Maintenance and operating cost information was available on an annual basis. Other costs however, were available only on a present worth basis. These consisted of construction and related costs. The related costs were "yard work" (site preparation) and interest during construction. Yard work is assumed to be 14 percent of the total construction cost. A specific formula is used for specifying the interest during construction. This formula is:

$$\text{Interest during construction} = \text{discount rate} \times \text{construction period(yrs)} \times \text{total capital expenditures}$$

In the analysis, a construction period of two years was used.

The cost equations used were developed from cost curves available in the literature ([1] and [5]). They were revised to reflect current economic conditions. Table 2 presents the cost equations applicable to this study. Notice that each component has an initial capital cost plus annual operation and maintenance costs. The diffused air and mechanical aeration systems are subsets of the biological reactor system (only one of the two aeration systems will be used). The clarifier cost equation is the same regardless of type (primary or final).

Besides cost, additional data was required concerning the useful lives of equipment, terminal salvage values, and the appropriate discount rate. The Environmental Protection Agency provides a set of guidelines in [4] which are to be used regarding these attributes. This information was used as a base, with a revision of the discount rate based upon current levels. The discount rate used in this case was 12 percent.

Given the appropriate cost information, each

TABLE 1

DESIGN EQUATIONS

Treatment Process	Design Equation
Biological Reactor	$V = \frac{Y_t F[S_i - (1 + \alpha)S_e] + \alpha X_R F}{k_d X} - \frac{(1 + \alpha)F}{k_d}$
Biological solids	$X = \frac{\frac{Y_t[S_i - (1 + \alpha)S_e]}{1 + k_d/\mu_n} + \alpha X_R}{1 + \alpha}$
Growth rate	$\mu_n = \mu_{max} \frac{S_e}{K_s + S_e} - k_d$
Final clarifier	$A = \frac{F(1.0036 \times 10^{-6} X)^n (1 + \alpha)^n 10^6}{1.077 \times 10^4 \left[a(n-1)(\frac{n}{n-1})^n (\alpha)^{n-1}\right]}$
Primary clarifier	$S_i = S_s + 0.5\ X_o\ (1 - E)$
	$E = 0.711 - 0.000474\ F_{oF}$
	$A = \frac{F \times 10^6}{F_{oF}}$
Air flotation	$F_{c12} = \left[\frac{0.02\ (X_o EF + VX\mu_n)}{L_o \times 10^{-6}}\right]$

particular treatment structure resulted in a particular system cost. This is true not only for designs which resulted in different effluent quality, but also designs which resulted in the same effluent. That is, given a set of treatment parameters and a desired effluent, a number (essentially infinite) of designs is possible. However, each of these designs results in a particular (equivalent uniform annual) cost. The system cost equations are summarized below.

Total cost = cost of construction (A/P) + cost of operation and maintenance + cost of electric power supply + cost of material and supply - salvage value (A/F)

where,

Total cost of construction = construction cost for plant + yard work cost + interest during construction

Cost of operation and maintenance = O & M cost for diffused air system (or mechanical aeration) + O & M cost for clarifiers + O & M cost for pumping + O & M cost for dissolved air flotation + labor cost for anaerobic digester + labor cost for sludge drying beds

Cost of electric power supply = EL. cost for diffused air-system (or mechanical aeration) + EL. cost for pumping + EL. cost for dissolved air flotation + EL. cost for anaerobic digester

Cost of material and supply = material cost for clarifiers + material cost for pumping + material cost for dissolved air flotation + materials cost for anaerobic digester + material cost for sludge drying beds

This leads to the objective of the research, which was to develop a model to determine the wastewater

TABLE 2

COMPONENT COST EQUATIONS

Component	Capital Costs	O & M Costs
Activated sludge aeration basin	$\$ = 68.341\left[\frac{V \times 10^6}{7.48}\right]^{0.753}$	
Diffused air system	$\$ = 1859.3\left[\frac{25\ V \times 10^6}{1000 + 7.48}\right]^{0.673}$	Operation Labor $\$/yr = 27.3\ (CFM)^{0.504}\ C_1$ Maintenance Labor $\$/yr = 9.89\ CFM)^{0.557}\ C_1$ Electric $\$/yr = 4454.34\ C_2(F)^{0.868}$
Mechanical aeration	$\$ = 18.808\left[\frac{V \times 10^6}{1000 \times 7.48}\right]^{0.803}$	Operation Labor $\$/yr = 110.8\left(\frac{V \times 10^6}{1000 \times 7.48}\right)^{0.518} C_1$ Maintenance Labor $\$/yr = 52.513\left(\frac{V \times 10^{-6}}{1000 \times 7.48}\right)^{0.562} C_1$ Electric Power $\$/yr = 4020.65\ (F)^{0.8215}\ C_2$
Clarifiers	$\$ = 446.3\ (A)^{0.739}$	Operation Labor $\$/yr = 4.999\ (A)^{0.577}\ C_1$ Maintenance Labor $\$/yr = 1.936\ (A)^{0.618}\ C_1$ Material & supply costs $\$/yr = 4.47\ (A)^{0.758}$
Pumping	$\$ = 560.305\ (F)^{0.702}$	Operation Labor $\$/yr = 148.39(F)^{0.636}\ C_1$ Maintenance Labor $\$/yr = 122.45(F)^{0.569}\ C_1$ Electric Power $\$/yr = 873.49(F)^{0.837}\ C_2$ Other Material & Supply $\$/yr = 900(F)^{0.791}$

TABLE 2 (cont.)

Component	Capital Costs	O & M Costs
Anaerobic digester	$\$ = 94.4\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.57}$	Total $\$/yr = 96.6\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.35}$ Power $\$/yr = 0.16 \times 10^{-5} C_2\left[\frac{8.34(X_oEF+VX\mu_n)}{1900 \times 10^{-6}}\right]^{136}$ Labor $\$/yr = 57.7\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.36}$ Material $\$/yr = 33.4\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.35}$
Sludge drying beds	$\$ = 45.9\left[\frac{0.185\ E_o(X_oEF + UX\mu_n)}{L_D \times 10^{-6}}\right]^{0.56}$	Total $\$/yr = 1.22\left[\frac{0.185E_D(X_oEF + VX\mu_n)}{L_D \times 10^{-6}}\right]^{0.65}$ Labor $\$/yr = 1.85\left[\frac{0.185E_D(X_oEF + VX\mu_n)}{L_D \times 10^{-6}}\right]^{0.40}$ Material $\$/yr = 0.37 \times 10^{-3}\left[\frac{0.185E_D(X_oEF+VX\mu_n)}{L_D \times 10^{-6}}\right]^{1.06}$
Dissolved air flotation	$\$ = 18.68\left[\frac{0.02(X_oE\ F + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.29}$	Total O & M $\$/yr = 2.52\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.54}$ Labor $\$/yr = 14.14\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.40}$ Power $\$/yr = 0.0031\ C_2\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.40}$ Material $\$/yr = 855\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.12}$

treatment design which results in the lowest annual cost. The optimization model to perform this task is presented in the next section.

Before discussing the optimization procedure, there is an important aspect of the engineering economy model which must be addressed. The costs can be partitioned into two types; those incurred by the federal government and those incurred locally. Under the current funding structure, the federal government funds 75 percent of all facility construction costs, with the local government funding the remainder of the construction cost and all annual operating and maintenance costs. Therefore, not only does each treatment structure result in a particular level of annual costs, but this cost can also be divided into federal and local contributions This allows an examination of each design on three levels: federal, local, and combined. The value of this delineation is discussed in the optimization section.

Optimization Model

The optimum treatment design is that which results in the lowest equivalent uniform annual cost of construction and operation and maintenance. Thus, the optimization process considers values of decision variables in the activated sludge process which specify a treatment design. These decision variables were presented earlier in Table 1. Each design yields specific values of the decision variables. These, in turn, result in a specific equivalent annual cost.

A function was developed relating the design/decision variables to equivalent uniform annual cost. The design-cost relationships in Table 2 constituted the bulk of the equation. Annual operation and maintenance costs were included directly. Capital costs, including such items as yard work and interest during construction, were converted to equivalent annual costs using the capital recovery factor. The resulting function was nonlinear in several variables. This posed problems in terms of finding a global optimal solution.

The design/decision variables of interest are highly interdependent. There is literally an infinite number of combinations of these variables. However, upon close examination of the existing relationships, it was determined that a specification of the recycling of biological solids resulted in a generation of unique values for the other variables. In this way, a complete treatment design could be specified entirely by the single decision variable α . By rearranging the annual cost function to reflect this, the result was a nonlinear function of one variable.

Reduction of the multi-variable design problem to a single-variable problem significantly reduced the effort involved in optimization. A specification of α yields particular design variables, which in turn yield an annual cost figure. Thus, for each α an equivalent uniform annual cost is found. The problem becomes one of optimizing a function of one variable.

The total annual cost function in terms of α is highly nonlinear, which made straightforward methods using the calculus inappropriate. A nonlinear search procedure was deemed most useful. The problem in using this type of technique is the behavior of the objective function. For a strictly convex objective function an optimal solution is guaranteed. If the function is not convex, a false optimum may be found. Therefore, in the initial stages of this research a quasi-enumerative search procedure was used. This approach allowed a complete examination of the behavior of the annual cost function.

Results of this original investigation of the cost function revealed that it was a well-behaved, convex function. Computational effort could be significantly reduced by utilizing an efficient search procedure. In order to find the optimal solution, the Fibonacci search procedure was used (see, for example, [2]).

The extensive computations involved required the development of a computer program. The program, written in FORTRAN, was run on a Hewlett-Packard Model 3000 minicomputer. This use of the small computer was initiated as a steppingstone process leading to a microcomputer application in the future.

For analysis purposes, the computer program displayed many design and cost characteristics for each of many values of α . An example of the analysis output is given in Table 3.

By examining one variable at a time, the level of α that resulted in the "best" value for that variable could be determined. For example, the value of α could be found that yielded the lowest total annual costs. The result was the major objective of the research (although more easily found via the Fibonacci search).

The model to this point only considered the activated sludge process. The inclusion of sludge treatment in the model resulted in additional considerations. This required the addition of the sludge treatment process (Figure 2) and the primary clarifier to the activated sludge process. Their design variables and cost specifications are presented in Tables 1 and 2, respectively.

The cost of sludge treatment, and the activated sludge process as well, is dependent on the sludge removed at the primary clarifier. This is determined by the overflow rate, F_{OF}. Therefore, an additional decision variable was needed for the annual cost function.

With this extension, the cost function became nonlinear in two variables. Optimization of this type of model was somewhat more complex than the single-variable case. For analysis purposes, a quasi-enumerative approach was taken. For a minimum-cost determination only, a combination quasi-enumerative and Fibonacci search process was used. For a particular overflow rate, a Fibonacci search was used to determine the minimum-cost value of α . This was repeated for eight values of the overflow rate, covering the entire range of possible values. The eight costs found were then compared to obtain the overall minimum-cost system design.

Analysis of Test Results

Several tests were conducted to assess the impact of on the design specifications and annual cost of the system. The joint impact of α and F_{OF} was also examined.

Figure 4 expresses the effect of α on clarifier area, aeration tank volume (biological reactor), and annual

TABLE 3

SAMPLE PROGRAM OUTPUT

ALPHA	CLAR. AREA	REACTOR VOLUME	TOTAL COST	CONST. COST	LABOR $	POWER + MAT	LOCAL GOVT.	FEDERAL GOVT.	SLUDGE COST
.10	4902.58	7.6344	919974.63	529167.25	26005.66	6321.18	187390.19	465190.06	266378.38
.30	13868.74	3.0945	683493.13	325386.00	21122.03	14876.90	131347.69	286046.25	265991.25
.50	22838.93	2.1444	653107.50	293411.25	21286.88	22280.49	129546.48	257937.34	265603.50
.70	31809.64	1.7307	656904.88	290352.31	22259.88	29103.57	136446.22	255248.25	265215.31

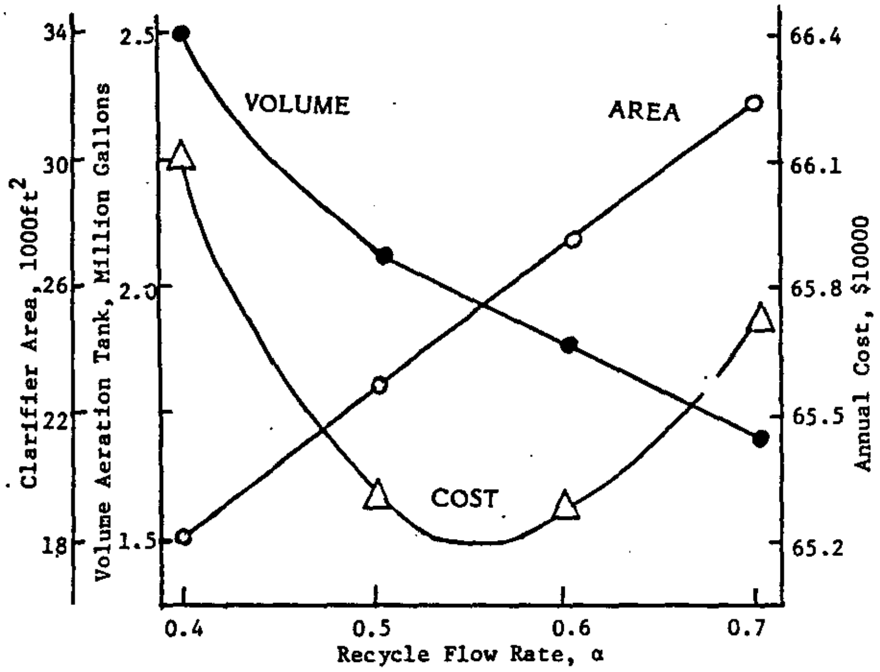

Figure 4. General Cost Minimization

cost. It was found that there was a direct linear relationship between α and the area of the clarifier. Volume of the aeration tank decreases at a decreasing rate as α increases. Finally, Figure 4 illustrates that there is indeed a particular recycle flow rate, α, that results in the lowest annual cost. This same pattern was evident in all situations examined.

An analysis of the impact of the overflow rate, F_{OF}, on sludge treatment cost and total annual cost is presented in Figure 5. This also measures the impact of α, since for each overflow rate the costs shown are the minimum possible; found by optimizing with respect to α. Notice that there is indeed an overflow rate that yields a minimum cost for sludge treatment. However, an overflow rate that yields a minimum total cost is not shown on the graph. It is evident from the cost curves that this will not continue much below $F_{OF} = 500$, as the sludge treatment cost increases dramatically. The precise minimum value has not been investigated at this stage.

The effect of the overflow rate on other treatment variables is illustrated in Table 4 for both the diffused air aeration system and mechanical aerators. For the same overflow rate, the optimal α is lower, as is the total annual cost for mechanical aerators. Sludge treatment costs are only slightly higher, due to increased sludge from the activated sludge process.

Finally, within each decision variable, the cost-range does not appear very large. For instance, for the overflow range in Table 4, the total cost differs by only five percent for diffused air and four percent for mechanical aerators. Figure 4 shows a range of total cost of only about five percent (and this does not reflect the total possible range of α). These indeed reflect tens of thousands of dollars per year, but the impact is not fully represented.

Most important is the joint impact of α and F_{OF} on total annual cost. When considered in unison, the impact is significantly increased. For instance, a poor (non-optimal) choice of α for a poor (non-optimal) choice of F_{OF} can result in costs that are twenty percent or more above minimum annual costs. In this light, the value of the optimization approach is apparent.

The analysis could also be performed for any subset of the total annual costs. This led to an evaluation at both the federal and local government levels. The results of this analysis are presented in the next section.

Impact on Federal and Local Governments

By partitioning the total annual cost into that portion for which the federal government is responsible (75% of construction costs) and that portion for which the local government is responsible, an analysis was performed to determine the least-cost system design for each. For the federal government, this is essentially minimizing capital costs, while for the local government this is a trade-off between construction cost and annual operation and maintenance costs.

Figure 6 illustrates the cost-minimization dilemma. The federal government naturally wants to spend less money, and there is a recycle flow rate which minimizes the federal governments annual cost. The same is true for local governments.

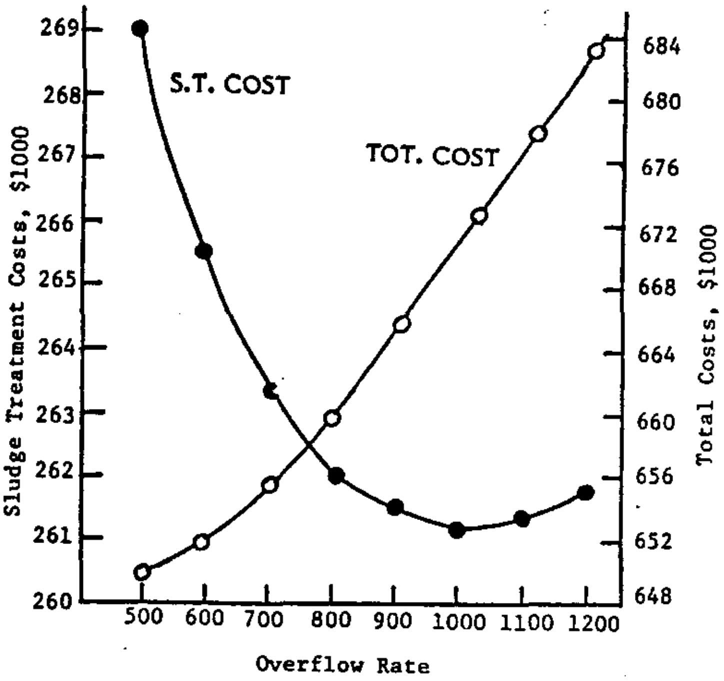

Figure 5. Effect of Overflow Rate on Treatment Costs

TABLE 4

EFFECT OF OVERFLOW RATE ON TREATMENT VARIABLES

#	α	A	V	FOF	E	SI	Sludge Cost	Total Cost 'T COST'
Diffused Air								
1	0,54	24,618,41	1.9647	500	0.474	165.750	269,026.19	649,731.13*
2	0.55	25,081.54	2.0133	600	0.4266	171,675	265,506.44	652,287.25
3	0,56	25,544.79	2,0611	700	0.3792	177.600	263,325.25	656,094.75
4	0.57	26,007.96	2.1081	800	0.3318	183.525	262,041.91	660,699.0
5	0.58	26,471.16	2.1544	900	0.2844	189.450	261,384.88	665,834.00
6	0.59	26,934.4	2.1999	1000	0.23700	195.375	261.183.25*	671,335.00
7	0.59	26,948.94	2.2687	1100	0.18960	201.3	261.341.75	677,087.38
8	0.60	27,412.21	2.3128	1200	0.1422	207.225	261,744.38	683,015.50
Mechanical Aerators								
1	0.37	16,993.5	2.5535	500	0.474	165.750	269,378.4	534,998.13*
2	0.38	17,456.68	2.5967	600	0.4266	171.675	265,836.19	535,612.13
3	0.39	17,919.86	2.639	700	0.3792	177.60	263,652.25	537,520.63
4	0.39	17,934.6	2.7923	800	0.3318	183,525	262,385.	540,252.75
5	0.40	18,397.77	2.7691	900	0.2844	189.45	261.725.4	543,538.63
6	0.41	18,861.0	2.8081	1000	0.23700	195,375	261,521.06*	547,229.0
7	0.41	18,875.72	2.8952	1100	0.18960	201.3	261,677.03	551,181.25
8	0.42	19,338.92	2.9321	1200	0.1422	207.225	262.077.0	555,350.75

The problem is that neither recycle flow rate "best" for federal or local governments corresponds to the recycle flow rate that yields the minimum annual cost for the entire system. In general, the minimum-cost point for the federal government will be at a higher recycle flow rate, since this represents lower capital cost requirements.

Thus, minimization of wastewater treatment costs may be dependent upon whose view is taken. It also means that each funding level must be willing to given a little in order to achive the minimum system cost.

At the present time, wastewater treatment cost may not be at a minimum level from any viewpoint. A federal funding policy, recognizing that a minimum cost design can indeed by specified, should be considered.

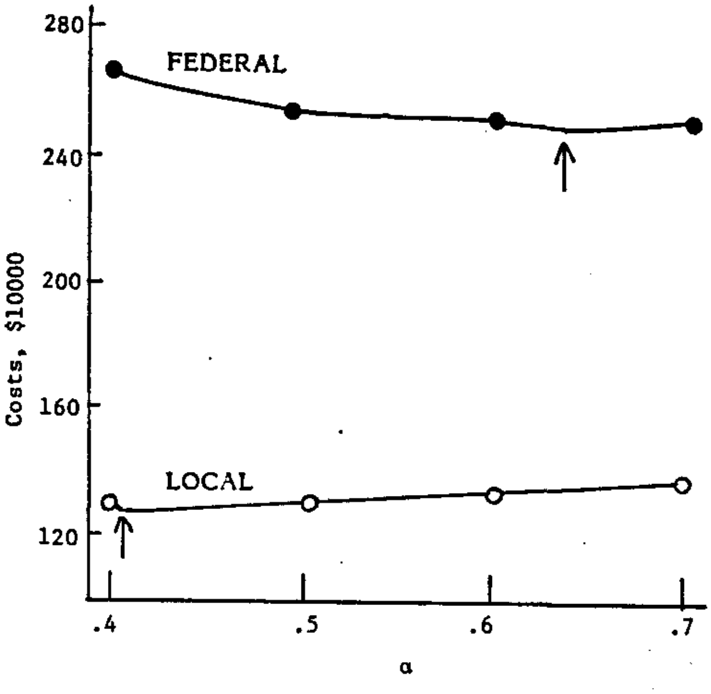

Figure 6. Comparison of Federal and Local Costs

Summary

This paper has presented a general procedure for developing the least-cost wastewater treatment design for the activated sludge process and the sludge treatment process suggested. The system was represented as a group of treatment design variables. Based upon the cost of each particular design component, an economic model was developed which specified an equivalent uniform annual cost for each particular design. In this manner, the specification of design variables resulted in a specific annual cost.

The equivalent uniform annual cost function was used as the objective function in a cost minimization model. This function was reduced to a function of one variable, the recycle flow rate . It was determined that a single-variable search technique could be used to find the minimum-cost design. When sludge treatment was added to the activated sludge process, the function became one consisting of two variables. For minimization a combined quasi-enumerative, single-variable search was used.

Analysis of test results revealed the appropriateness of this approach. Savings of from five to twenty percent, maybe more, are evident in the use of the model. It was also shown that relationhips existed between the overflow rate and the optimal value of the recycle flow rate, and the optimal recycle flow rate and the type of aeration utilized. These relationships, and others, should prove valuable to design engineers.

Finally, it was shown that the minimum-cost system design does not correspond to the federal governments minimum-cost design or the local governments minimum-cost design. It was suggested that the current federal funding policy be examined with the minimization of tax-payer cost in mind.

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WASTEWATER TREATMENT: DESIGN OPTIMIZATION AND ITS IMPLICATIONS FOR FEDERAL AND LOCAL GOVERNMENTS

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Abstract

The wastewater treatment design problem is addressed with an objective of minimizing costs over the life of the facility. The model developed utilizes the treatment design equations to generate an annual cost expression. Through the use of simple nonlinear optimization techniques, the treatment design which results in the lowest cost is found. An analysis of the model's performance reveals its potential impact on facility costs. Also examined is the impact with respect to costs at both the federal level and local level.

Introduction

During the past few years, millions of dollars have been spent in constructing wastewater treatment plants. The American taxpayer is faced with additional large expenditures for wastewater treatment facilities. Inflation will add to the cost of constructing these treatment plants as well as increasing the operation and maintenance costs. Even so, very little has been done by the design engineer in regards to selecting the most cost effective design. The objective of this research was to develop an optimization technique for selecting the most cost effective design for the activated sludge wastewater treatment process.

The current design process consists largely of picking treatment components which result in a desired effluent quality. For the activated sludge process, one of the major wastewater treatment processes, the typical components are illustrated in Figure 1. The design of the biological reactor, final clarifier, recycle pump, and recycle pipeline are dependent upon each other. Many different combinations of these components can result in the same quality effluent. Thus, a particular effluent quality can be achieved through a number of designs. It is desirable to choose that design which meets the required effluent at the least possible cost.

Additional questions arise regarding the precise definition of minimum cost. Wastewater treatment costs are shared by the federal and local government. The federal government funds a percentage (in general, 75%) of the construction costs while local governments are responsible for all operating and maintenance costs. Since the design chosen dictates construction and operating and maintenance costs, the federal government would be interested in selecting a design which results in low construction costs. Local government would want low operating and maintenance costs. Thus, finding the design which presents the least-cost to the federal government may not be the same design which presents the least cost to the local government. This issue will be examined further later in this paper.

This paper presents a decision model for choosing the least-cost wastewater treatment design. This consists of system equations specifying the relevant design, an economic model relating each design to an annual cost, and an optimization model to find the design yielding the least cost. An analysis of model test results is also included.

Assumptions

There are several assumptions which were made during the development of this treatment model. These relate primarily to the treatment process and the economic model used.

Of the many different types of wastewater treatment processes, the process modelled is the activated sludge treatment process which is described in Figure 1. This is extended in Figure 2 to consider treatment of sludge. Further, later on the sludge treatment activity is included in the design model. The particular sludge treatment process considered is presented in Figure 3.

Assumptions were also required for the economic model. Government specifications were included in the creation of the model. These included such things as handling interest charges during construction and special charges for "yard work" (laying pipelines, other charges not specifically allocated to other construction). One specification not rigidly followed was the discount or interest rate used. An interest rate was chosen to reflect current financial conditions.

The lives of assets included in the analysis are also based upon government specifications. In cases where salvage values were not dictated, expert opinion was used to determine these values.

Finally, inflation is not explicitly considered in the analysis. This would also include changes in energy costs over the years of life of the treatment facility. This

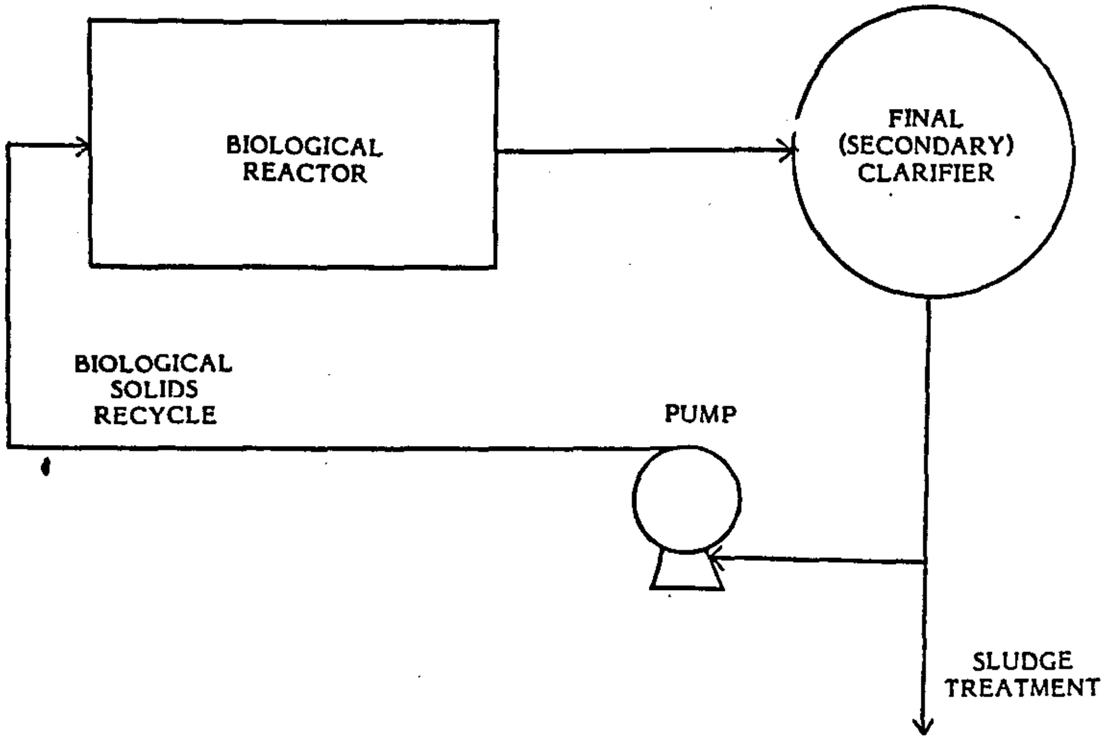

Figure 1. Basic Activated Sludge Process

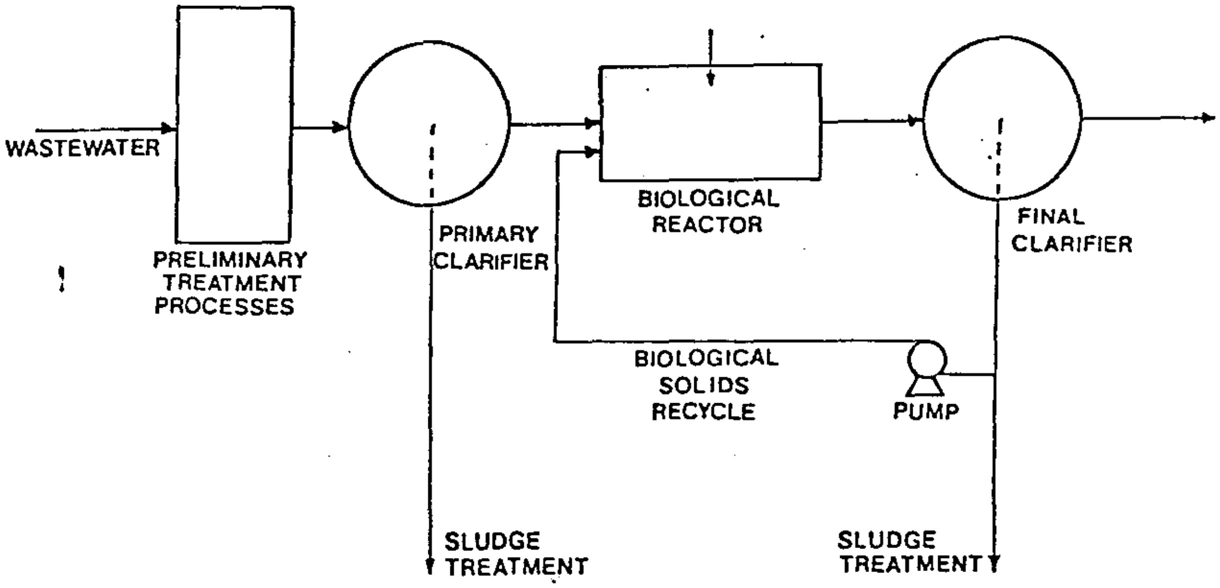

Figure 2. Flow Diagram of Activated Sludge Process

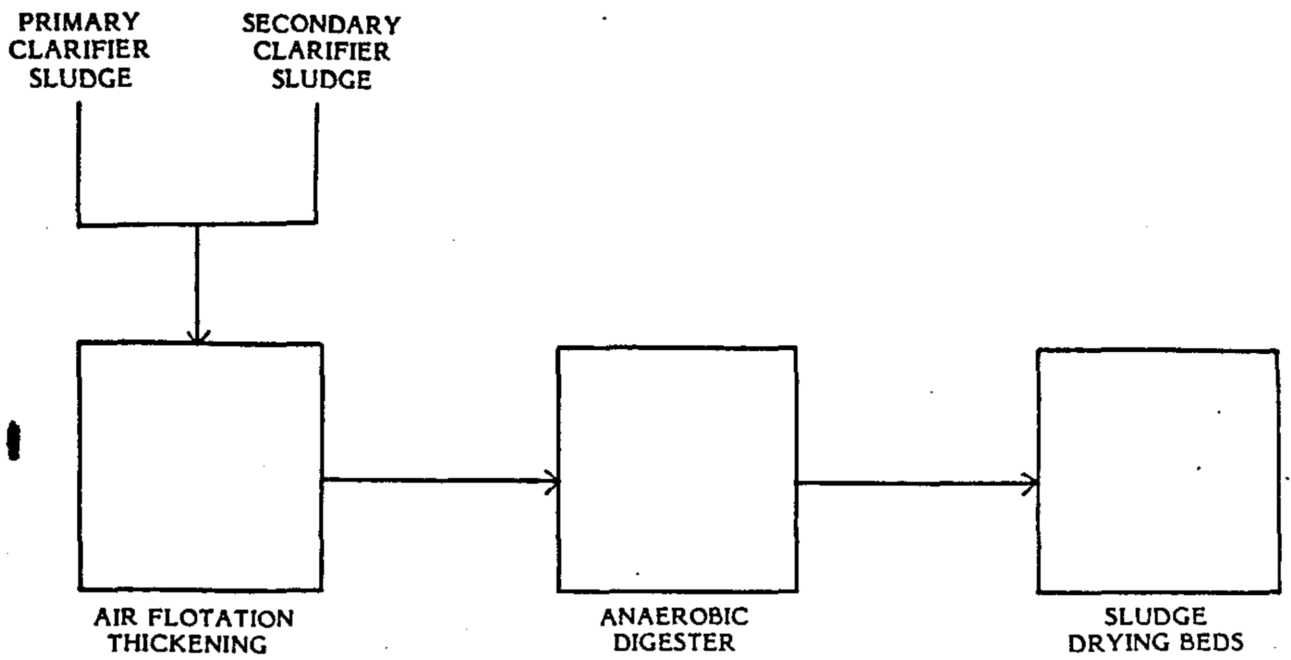

Figure 3. Flow Diagram of the Sludge Treatment Process

would be a desired extension of the current model. The anticipated impact of these considerations will be addressed later in the paper.

Activated Sludge Model

The activated sludge process is but one of several wastewater treatment processes in use today. Because it is one of the most popular processes, it was chosen for analysis. The activated sludge process is depicted in Figure 2.

In this paper there is no reason to detail the biological activity of the activated sludge treatment process. What is of concern are the appropriate treatment components, their relationships, and the resultant decision variables.

The major components of interest, from Figure 2, are related as follows. The influent, after passing through any preliminary treatment processes, enters the primary clarifier. At this point a certain amount is routed directly to sludge treatment. This amount is determined by the overflow-rate, F_{OF}. The overflow rate, in combination with the influent flow rate, F, dictates the rate of flow into the activated sludge process.

The first component of the activated sludge process is the biological reactor where the waste is treated biologically. An aeration process is also included. The size of the biological reactor is specified as a volume.

The only cost, other than construction, associated with the biological reactor, is related to the aeration process. Two different aeration processes were considered: diffused and mechanical.

The second component of the activated sludge process is the secondary, or final, clarifier. In this clarifier biological solids settle to the bottom, being either recycled or sent to sludge treatment. The effluent is taken from the top of the clarifier. Of course the desire is that the effluent meet quality specifications. The size of the clarifier is specified as an area.

A prescribed amount of the biological solids are sent to sludge treatment. A prescribed amount is also recycled through the activated sludge process. This recycling is actually the third major component of the process. The amount of recycling is controllable, and as will be shown later, has a significant impact on the overall design of the system. As shown in Figure 2, the solids are recycled to the biological reactor. The variable α specifies the fraction of biological solids which are recycled.

The sludge treatment process is depicted in Figure 3. Sludge may arrive from either the primary clarifier or secondary clarifier. There is a trade-off between treatment within the activated sludge process and sludge treatment. That is, more of one implies less of the other. Sludge treatment represents the last stage of the treatment process.

The specification of system components must be made via system design equations. These equations relate biological constants and input parameters to system operation, including specification of system components; volume of the biological reactor and area of the final clarifier.

Design models are available for the biological reactor, final clarifier, and recycle flow rates. Appropriate models from the literature were selected, [3]. There are no models available for the primary clarifier and sludge treatment processes. For these processes, data was taken from the literature and a mathematical relationship was developed. Before presenting the design equations, it is necessary to present the definition of symbols used. These definitions are given below.

a = Sludge settling velocity constant

A = Surface area of a clarifier (square feet)

E = Fraction of suspended solids removed in the primary clarifier

F = Wastewater flow rate (million gallons per day)

F_{C12} = Solids flow rate from air flotation unit

F_{OF} = Overflow rate (gallons per day per ft^2)

k_d = Decay coefficient (day^{-1})

k_s = Biological constant

L_D = Solids loading to digester (pounds per day)

L_o = Solids loading to air flotation (pounds per day ft^2)

n = Sludge settling velocity constant

S_e = Organic material concentration (effluent, milligrams per liter)

S_i = Organic material concentration (total from primary clarifier, milligrams per liter)

S_s = Soluble organic material concentration (influent, milligrams per liter)

V = Volume of the biological reactor (million gallons)

X = Biological population (milligrams per liter)

X_o = Suspended solids in influent (milligrams per liter)

X_R = Final clarifier underflow solids concentration (milligrams per liter)

Y_t = Sludge yield

α = Recycle flow rate

μ_{max} = Maximum growth rate (day^{-1})

μ_n = Net specific growth rate (day^{-1})

Based upon these definitions, the pertinent design equations are presented in Table 1. These are the relationships used in the system model. Notice that there is interdependence among the components. A specification of the system seems difficult from these complex interrelationships. However, they can be reduced to a form which allows straightforward analysis. This is detailed in the optimization discussion.

Each particular treatment design results in a specific treatment cost, consisting of construction and operation and maintenance costs. The determination, and comparison, of these costs is accomplished through an engineering economy model of the system. The development and operation of this model is presented in the next section.

Economic Model

The purpose of the research was to determine the activated sludge treatment design resulting in the minimum cost. In order to accomplish this it was necessary to develop a precise definition of cost.

Because the costs of constructing and operating a waste treatment facility do not all occur at once, it is important to perform an analysis which accounts for the time value of money. In order to compare designs based upon this, a standard analysis was established. In this case, due to the unequal lives of the assets, the comparison was based upon equivalent uniform annual costs.

Maintenance and operating cost information was available on an annual basis. Other costs however, were available only on a present worth basis. These consisted of construction and related costs. The related costs were "yard work" (site preparation) and interest during construction. Yard work is assumed to be 14 percent of the total construction cost. A specific formula is used for specifying the interest during construction. This formula is:

$$\text{Interest during construction} = \text{discount rate} \times \text{construction period(yrs)} \times \text{total capital expenditures}$$

In the analysis, a construction period of two years was used.

The cost equations used were developed from cost curves available in the literature ([1] and [5]). They were revised to reflect current economic conditions. Table 2 presents the cost equations applicable to this study. Notice that each component has an initial capital cost plus annual operation and maintenance costs. The diffused air and mechanical aeration systems are subsets of the biological reactor system (only one of the two aeration systems will be used). The clarifier cost equation is the same regardless of type (primary or final).

Besides cost, additional data was required concerning the useful lives of equipment, terminal salvage values, and the appropriate discount rate. The Environmental Protection Agency provides a set of guidelines in [4] which are to be used regarding these attributes. This information was used as a base, with a revision of the discount rate based upon current levels. The discount rate used in this case was 12 percent.

Given the appropriate cost information, each

TABLE I

DESIGN EQUATIONS

Treatment Process	Design Equation
Biological Reactor	$V = \frac{Y_t F[S_i - (1+\alpha)S_e] + \alpha X_R F}{k_d X} - \frac{(1+\alpha)F}{k_d}$
Biological solids	$X = \frac{\frac{Y_t[S_i - (1+\alpha)S_e]}{1 + k_d/\mu_n} + \alpha X_R}{1+\alpha}$
Growth rate	$\mu_n = \mu_{max} \frac{S_e}{K_s + S_e} - k_d$
Final clarifier	$A = \frac{F(1.0036 \times 10^{-6} X)^n (1+\alpha)^n 10^6}{1.077 \times 10^4 [a(n-1)(\frac{n}{n-1})^n (\alpha)^{n-1}]}$
Primary clarifier	$S_i = S_s + 0.5 X_o (1 - E)$
	$E = 0.711 - 0.000474 F_{oF}$
	$A = \frac{F \times 10^6}{F_{oF}}$
Air flotation	$F_{c12} = \left[\frac{0.02 (X_o EF + VX\mu_n)}{L_o \times 10^{-6}}\right]$

particular treatment structure resulted in a particular system cost. This is true not only for designs which resulted in different effluent quality, but also designs which resulted in the same effluent. That is, given a set of treatment parameters and a desired effluent, a number (essentially infinite) of designs is possible. However, each of these designs results in a particular (equivalent uniform annual) cost. The system cost equations are summarized below.

Total cost = cost of construction (A/P) + cost of operation and maintenance + cost of electric power supply + cost of material and supply - salvage value (A/F)

where,

Total cost of construction = construction cost for plant + yard work cost + interest during construction

Cost of operation and maintenance = 0 & M cost for diffused air system (or mechanical aeration) + 0 & M cost for clarifiers + 0 & M cost for pumping + 0 & M cost for dissolved air flotation + labor cost for anaerobic digester + labor cost for sludge drying beds

Cost of electric power supply = EL. cost for diffused air-system (or mechanical aeration) + EL. cost for pumping + EL. cost for dissolved air flotation + EL. cost for anaerobic digester

Cost of material and supply = material cost for clarifiers + material cost for pumping + material cost for dissolved air flotation + materials cost for anaerobic digester + material cost for sludge drying beds

This leads to the objective of the research, which was to develop a model to determine the wastewater

TABLE 2

COMPONENT COST EQUATIONS

Component	Capital Costs	O & M Costs
Activated sludge aeration basin	$\$ = 68.341\left[\frac{V \times 10^6}{7.48}\right]^{0.753}$	
Diffused air system	$\$ = 1859.3\left[\frac{25\ V \times 10^6}{1000 + 7.48}\right]^{0.673}$	Operation Labor $\$/yr = 27.3\ (CFM)^{0.504}\ C_1$ Maintenance Labor $\$/yr = 9.89\ CFM)^{0.557}\ C_1$ Electric $\$/yr = 4454.34\ C_2(F)^{0.868}$
Mechanical aeration	$\$ = 18.808\left[\frac{V \times 10^6}{1000 \times 7.48}\right]^{0.803}$	Operation Labor $\$/yr = 110.8\ \left(\frac{V \times 10^6}{1000 \times 7.48}\right)^{0.518} C_1$ Maintenance Labor $\$/yr = 52.513\left(\frac{V \times 10^{-6}}{1000 \times 7.48}\right)^{0.562} C_1$ Electric Power $\$/yr = 4020.65\ (F)^{0.8215}\ C_2$
Clarifiers	$\$ = 446.3\ (A)^{0.739}$	Operation Labor $\$/yr = 4.999\ (A)^{0.577}\ C_1$ Maintenance Labor $\$/yr = 1.936\ (A)^{0.618}\ C_1$ Material & supply costs $\$/yr = 4.47\ (A)^{0.758}$
Pumping	$\$ = 560.305\ (F)^{0.702}$	Operation Labor $\$/yr = 148.39(F)^{0.636}\ C_1$ Maintenance Labor $\$/yr = 122.45(F)^{0.569}\ C_1$ Electric Power $\$/yr = 873.49(F)^{0.837}\ C_2$ Other Material & Supply $\$/yr = 900(F)^{0.791}$

TABLE 2 (cont.)

Component	Capital Costs	O & M Costs
Anaerobic digester	$\$ = 94.4\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.57}$	Total $\$/yr = 96.6\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.35}$
		Power $\$/yr = 0.16 \times 10^{-5}C_2\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{136}$
		Labor $\$/yr = 57.7\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.36}$
		Material $\$/yr = 33.4\left[\frac{8.34(X_oEF + VX\mu_n)}{1900 \times 10^{-6}}\right]^{0.35}$
Sludge drying beds	$\$ = 45.9\left[\frac{0.185\ E_o(X_oEF + UX\mu_n)}{L_D \times 10^{-6}}\right]^{0.56}$	Total $\$/yr = 1.22\left[\frac{0.185E_D(X_oEF + VX\mu_n)}{L_D \times 10^{-6}}\right]^{0.65}$
		Labor $\$/yr = 1.85\left[\frac{0.185E_D(X_oEF + VX\mu_n)}{L_D \times 10^{-6}}\right]^{0.40}$
		Material $\$/yr = 0.37 \times 10^{-3}\left[\frac{0.185E_D(X_oEF + VX\mu_n)}{L_D \times 10^{-6}}\right]^{1.06}$
Dissolved air flotation	$\$ = 18.68\left[\frac{0.02(X_oE\ F + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.29}$	Total O & M $\$/yr = 2.52\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.54}$
		Labor $\$/yr = 14.14\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.40}$
		Power $\$/yr = 0.0031\ C_2\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.4}$
		Material $\$/yr = 855\left[\frac{0.02(X_oEF + VX\mu_n)}{L_o \times 10^{-6}}\right]^{0.12}$

treatment design which results in the lowest annual cost. The optimization model to perform this task is presented in the next section.

Before discussing the optimization procedure, there is an important aspect of the engineering economy model which must be addressed. The costs can be partitioned into two types; those incurred by the federal government and those incurred locally. Under the current funding structure, the federal government funds 75 percent of all facility construction costs, with the local government funding the remainder of the construction cost and all annual operating and maintenance costs. Therefore, not only does each treatment structure result in a particular level of annual costs, but this cost can also be divided into federal and local contributions This allows an examination of each design on three levels: federal, local, and combined. The value of this delineation is discussed in the optimization section.

Optimization Model

The optimum treatment design is that which results in the lowest equivalent uniform annual cost of construction and operation and maintenance. Thus, the optimization process considers values of decision variables in the activated sludge process which specify a treatment design. These decision variables were presented earlier in Table 1. Each design yields specific values of the decision variables. These, in turn, result in a specific equivalent annual cost.

A function was developed relating the design/decision variables to equivalent uniform annual cost. The design-cost relationships in Table 2 constituted the bulk of the equation. Annual operation and maintenance costs were included directly. Capital costs, including such items as yard work and interest during construction, were converted to equivalent annual costs using the capital recovery factor. The resulting function was nonlinear in several variables. This posed problems in terms of finding a global optimal solution.

The design/decision variables of interest are highly interdependent. There is literally an infinite number of combinations of these variables. However, upon close examination of the existing relationships, it was determined that a specification of the recycling of biological solids resulted in a generation of unique values for the other variables. In this way, a complete treatment design could be specified entirely by the single decision variable α . By rearranging the annual cost function to reflect this, the result was a nonlinear function of one variable.

Reduction of the multi-variable design problem to a single-variable problem significantly reduced the effort involved in optimization. A specification of α yields particular design variables, which in turn yield an annual cost figure. Thus, for each α an equivalent uniform annual cost is found. The problem becomes one of optimizing a function of one variable.

The total annual cost function in terms of α is highly nonlinear, which made straightforward methods using the calculus inappropriate. A nonlinear search procedure was deemed most useful. The problem in using this type of technique is the behavior of the objective function. For a strictly convex objective function an optimal solution is guaranteed. If the function is not convex, a false optimum may be found. Therefore, in the initial stages of this research a quasi-enumerative search procedure was used. This approach allowed a complete examination of the behavior of the annual cost function.

Results of this original investigation of the cost function revealed that it was a well-behaved, convex function. Computational effort could be significantly reduced by utilizing an efficient search procedure. In order to find the optimal solution, the Fibonacci search procedure was used (see, for example, [2]).

The extensive computations involved required the development of a computer program. The program, written in FORTRAN, was run on a Hewlett-Packard Model 3000 minicomputer. This use of the small computer was initiated as a steppingstone process leading to a microcomputer application in the future.

For analysis purposes, the computer program displayed many design and cost characteristics for each of many values of α . An example of the analysis output is given in Table 3.

By examining one variable at a time, the level of α that resulted in the "best" value for that variable could be determined. For example, the value of α could be found that yielded the lowest total annual costs. The result was the major objective of the research (although more easily found via the Fibonacci search).

The model to this point only considered the activated sludge process. The inclusion of sludge treatment in the model resulted in additional considerations. This required the addition of the sludge treatment process (Figure 2) and the primary clarifier to the activated sludge process. Their design variables and cost specifications are presented in Tables 1 and 2, respectively.

The cost of sludge treatment, and the activated sludge process as well, is dependent on the sludge removed at the primary clarifier. This is determined by the overflow rate, F_{OF}. Therefore, an additional decision variable was needed for the annual cost function.

With this extension, the cost function became nonlinear in two variables. Optimization of this type of model was somewhat more complex than the single-variable case. For analysis purposes, a quasi-enumerative approach was taken. For a minimum-cost determination only, a combination quasi-enumerative and Fibonacci search process was used. For a particular overflow rate, a Fibonacci search was used to determine the minimum-cost value of α. This was repeated for eight values of the overflow rate, covering the entire range of possible values. The eight costs found were then compared to obtain the overall minimum-cost system design.

Analysis of Test Results

Several tests were conducted to assess the impact of on the design specifications and annual cost of the system. The joint impact of α and F_{OF} was also examined.

Figure 4 expresses the effect of α on clarifier area, aeration tank volume (biological reactor), and annual

TABLE 3

SAMPLE PROGRAM OUTPUT

ALPHA	CLAR. AREA	REACTOR VOLUME	TOTAL COST	CONST. COST	LABOR $	POWER + MAT	LOCAL GOVT.	FEDERAL GOVT.	SLUDGE COST
.10	4902.58	7.6344	919974.63	529167.25	26005.66	6321.18	187390.19	465190.06	266378.38
.30	13868.74	3.0945	683493.13	325386.00	21122.03	14876.90	131347.69	286046.25	265991.25
.50	22838.93	2.1444	653107.50	293411.25	21286.88	22280.49	129546.48	257937.34	265603.50
.70	31809.64	1.7307	656904.88	290352.31	22259.88	29103.57	136446.22	255248.25	265215.31

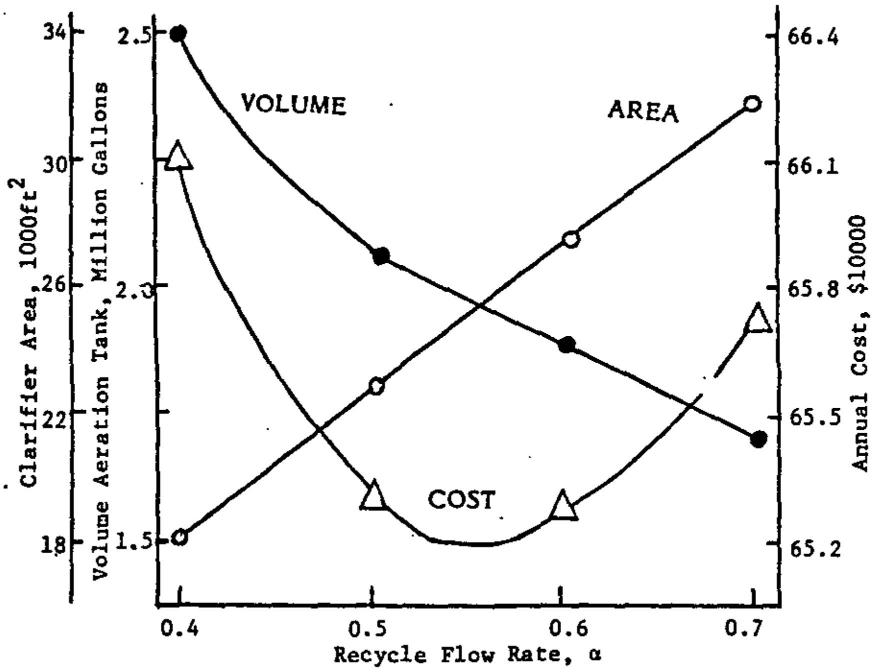

Figure 4. General Cost Minimization

cost. It was found that there was a direct linear relationship between α and the area of the clarifier. Volume of the aeration tank decreases at a decreasing rate as α increases. Finally, Figure 4 illustrates that there is indeed a particular recycle flow rate, α , that results in the lowest annual cost. This same pattern was evident in all situations examined.

An analysis of the impact of the overflow rate, F_{OF}, on sludge treatment cost and total annual cost is presented in Figure 5. This also measures the impact of α, since for each overflow rate the costs shown are the minimum possible; found by optimizing with respect to α . Notice that there is indeed an overflow rate that yields a minimum cost for sludge treatment. However, an overflow rate that yields a minimum total cost is not shown on the graph. It is evident from the cost curves that this will not continue much below $F_{OF} = 500$, as the sludge treatment cost increases dramatically. The precise minimum value has not been investigated at this stage.

The effect of the overflow rate on other treatment variables is illustrated in Table 4 for both the diffused air aeration system and mechanical aerators. For the same overflow rate, the optimal α is lower, as is the total annual cost for mechanical aerators. Sludge treatment costs are only slightly higher, due to increased sludge from the activated sludge process.

Finally, within each decision variable, the cost-range does not appear very large. For instance, for the overflow range in Table 4, the total cost differs by only five percent for diffused air and four percent for mechanical aerators. Figure 4 shows a range of total cost of only about five percent (and this does not reflect the total possible range of α). These indeed reflect tens of thousands of dollars per year, but the impact is not fully represented.

Most important is the joint impact of α and F_{OF} on total annual cost. When considered in unison, the impact is significantly increased. For instance, a poor (non-optimal) choice of α for a poor (non-optimal) choice of F_{OF} can result in costs that are twenty percent or more above minimum annual costs. In this light, the value of the optimization approach is apparent.

The analysis could also be performed for any subset of the total annual costs. This led to an evaluation at both the federal and local government levels. The results of this analysis are presented in the next section.

Impact on Federal and Local Governments

By partitioning the total annual cost into that portion for which the federal government is responsible (75% of construction costs) and that portion for which the local government is responsible, an analysis was performed to determine the least-cost system design for each. For the federal government, this is essentially minimizing capital costs, while for the local government this is a trade-off between construction cost and annual operation and maintenance costs.

Figure 6 illustrates the cost-minimization dilemma. The federal government naturally wants to spend less money, and there is a recycle flow rate which minimizes the federal governments annual cost. The same is true for local governments.

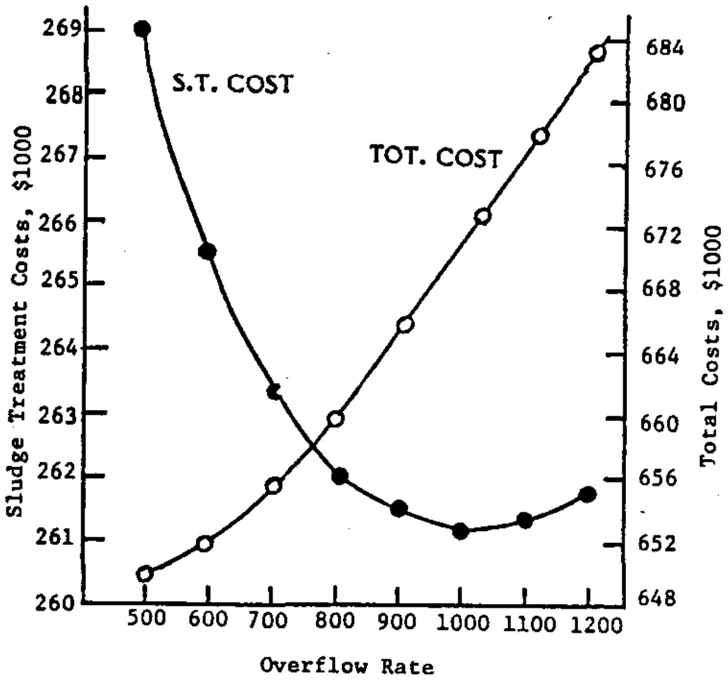

Figure 5. Effect of Overflow Rate on Treatment Costs

TABLE 4

EFFECT OF OVERFLOW RATE ON TREATMENT VARIABLES

Diffused Air

#	α	A	V	FOF	E	SI	Sludge Cost	Total Cost 'T COST'
1	0,54	24,618,41	1.9647	500	0,474	165.750	269,026.19	649,731.13*
2	0.55	25,081,54	2.0133	600	0.4266	171,675	265,506.44	652,287.25
3	0,56	25,544.79	2,0611	700	0.3792	177.600	263,325.25	656,094.75
4	0.57	26,007.96	2.1081	800	0.3318	183.525	262,041.91	660,699.0
5	0.58	26,471.16	2.1544	900	0.2844	189.450	261,384.88	665,834.00
6	0.59	26,934.4	2.1999	1000	0.23700	195.375	261.183.25*	671,335.00
7	0.59	26,948.94	2.2687	1100	0.18960	201.3	261.341.75	677,087.38
8	0,60	27,412.21	2.3128	1200	0.1422	207.225	261,744.38	683,015.50

Mechanical Aerators

#	α	A	V	FOF	E	SI	Sludge Cost	Total Cost 'T COST'
1	0.37	16,993.5	2.5535	500	0.474	165.750	269,378.4	534,998.13*
2	0.38	17,456.68	2.5967	600	0.4266	171,675	265,836.19	535,612.13
3	0.39	17,919.86	2,639	700	0.3792	177.60	263,652.25	537,520.63
4	0.39	17,934.6	2.7923	800	0,3318	183,525	262,385.	540,252.75
5	0,40	18,397,77	2,7691	900	0,2844	189,45	261,725,4	543,538,63
6	0.41	18,861.0	2.8081	1000	0.23700	195,375	261,521.06*	547,229.0
7	0.41	18,875.72	2.8952	1100	0.18960	201.3	261,677.03	551,181.25
8	0.42	19,338.92	2.9321	1200	0.1422	207.225	262.077.0	555,350.75

The problem is that neither recycle flow rate "best" for federal or local governments corresponds to the recycle flow rate that yields the minimum annual cost for the entire system. In general, the minimum-cost point for the federal government will be at a higher recycle flow rate, since this represents lower capital cost requirements.

Thus, minimization of wastewater treatment costs may be dependent upon whose view is taken. It also means that each funding level must be willing to given a little in order to achive the minimum system cost.

At the present time, wastewater treatment cost may not be at a minimum level from any viewpoint. A federal funding policy, recognizing that a minimum cost design can indeed by specified, should be considered.

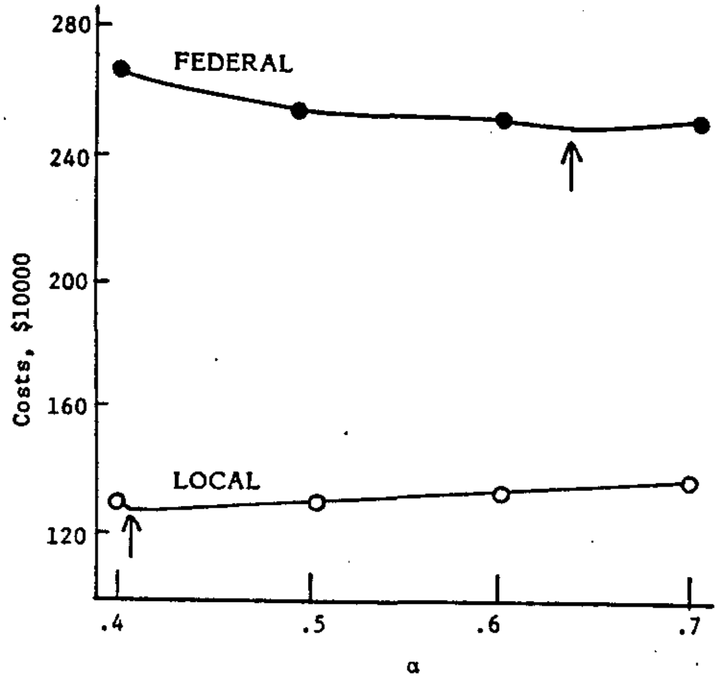

Figure 6. Comparison of Federal and Local Costs

Summary

This paper has presented a general procedure for developing the least-cost wastewater treatment design for the activated sludge process and the sludge treatment process suggested. The system was represented as a group of treatment design variables. Based upon the cost of each particular design component, an economic model was developed which specified an equivalent uniform annual cost for each particular design. In this manner, the specification of design variables resulted in a specific annual cost.

The equivalent uniform annual cost function was used as the objective function in a cost minimization model. This function was reduced to a function of one variable, the recycle flow rate . It was determined that a single-variable search technique could be used to find the minimum-cost design. When sludge treatment was added to the activated sludge process, the function became one consisting of two variables. For minimization a combined quasi-enumerative, single-variable search was used.

Analysis of test results revealed the appropriateness of this approach. Savings of from five to twenty percent, maybe more, are evident in the use of the model. It was also shown that relationhips existed between the overflow rate and the optimal value of the recycle flow rate, and the optimal recycle flow rate and the type of aeration utilized. These relationships, and others, should prove valuable to design engineers.

Finally, it was shown that the minimum-cost system design does not correspond to the federal governments minimum-cost design or the local governments minimum-cost design. It was suggested that the current federal funding policy be examined with the minimization of tax-payer cost in mind.

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