INTEGRATED DYNAMIC MODELS AND CONTROL SYSTEMS FOR WASTEWATER TREATMENT PLANTS

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ABSTRACT

The operation of wastewater treatment plants is still very much an art. This paper discusses how dynamic modeling and computer simulation can be used as tools to develop a "body of theory" for plant operations. A brief progress report on the author's current research is presented. This includes the development of an integrated dynamic model and control system for a typical treatment plant which considers interactions between the different processes and their control loops as well as internal process interactions. A combination of three types of models will be used, these being (a)mechanistic, (b) time-series, and (c) linguistic. An example of a simplified mechanistic model for the step feed activated sludge process is given and simulations of control to prevent process failure by storm flows through change of the wastewater feed point are presented. Suggestions, with references to full scale studies, are given as to how the model might be adapted for use in specific plants.

KEYWORDS

Treatment plant, activated sludge, step feed, mathematical model,dynamic model, plant operation, control system, computer simulation.

INTRODUCTION

During the past few years, the U.S. has expended many billions of dollars on the design and construction of wastewater treatment plants. However, an equivalent amount of attention has not been devoted to plant operations with the result that many plants have difficulties with reliable production of environmentally acceptable effluents at reasonable costs. Plant operation is still very much an art. A "body of theory" for treatment plant operations, equivalent to that which has been developed for plant design, is needed.

The development of theory for treatment plant operations is more difficult than for plant design since more attention must be devoted to dynamic behavior, collection of data to assess performance, and exertion of control for converting unsatisfactory to satisfactory dynamic behavior. In past years, treatment plant operation has been largely empirical since even if quantitative dynamic relationships (dynamic models) could have been established, there were no feasible techniques for solution of most of the resulting equations. This represented a significant bottleneck to the development of theories for plant operations since most engineers, being practical people, are not interested in developing equations (mathematical models) for which solutions are not available.

These equations are, however, solvable by computer. The situation has therefore greatly changed because of the ready availability of inexpensive and powerful computers and user-friendly computer languages oriented toward the solution of dynamic models (computer simulation). The current bottleneck in applying dynamic models to treatment plant operations is thus no longer how to solve the equations but how to set up equations (develop models) that are realistic with respect to their predictions, make maximum use of measurement capabilities, and can be understood and implemented by practioners. A more recent development is that of "expert systems"technology in which the practical knowledge of expert operating engineers, which frequently cannot be expressed mathematically, is translated into computer programs called "linguistic" models.

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This paper will consist of a brief progress report on the author's current research on dynamic models and control systems for wastewater treatment plants. A specific example of a dynamic model for predicting and controlling solids distribution between the aeration tanks and secondary settler of the activated sludge process will then be presented. For a more comprehensive description of both the theoretical and practical applications of dynamic modeling and control systems to treatment plant operations, the reader is referred to the proceedings (Andrews, et al, 1974; Jenkins, 1978 and 1981; Drake, 1985) of four workshops which have been conducted by the International Association on Water Pollution Research and Control(IAWPRC). A 5th workshop is scheduled to be held in Yokohama/Kyoto in 1990.

APPROACH TO PROBLEM

The author and his students have been engaged for more than 20 years in research on the development of dynamic models and control systems for wastewater treatment plants. The major portion of this research has concentrated on models for individual processes such as the anaerobic digestion and activated sludge processes. However, continued attention has also been devoted to integrating the individual process models and control loops into an overall plant model and control system (Bryant, 1972; Busby, 1973; Stenstrom, 1976; Vitasovic, 1986). Such integration is essential for exploration of the interactions between different processes as well as internal interactions in some processes.

Well known examples of internal process interactions are those between the air supply, aeration basins, and secondary settlers in the activated sludge process.As an example of an important interaction between the activated sludge and anaerobic digestion processes, inadequate sludge processing capability or storage limitations can lead to a build-up of solids in the activated sludge process with resultant excessive discharges of solids in the plant effluent. The control system for one process may also influence the performance of anothe process. For example, the on-off cycling of a large influent pump can generate turbulence in the secondary settler thus increasing the solids discharged in the settler effluent (Olsson and Chapman, 1985). A systems engineering approach, which considers all of the plant components, their interactions, and interactions of the plant with other systems, is obviously necessary for development of an integrated control system for wastewater treatment plants.

Objectives

The general objective of the author's current research is to continue work on developing an integrated dynamic model and control system for a typical wastewater treatment plant (Fig. 1). This general objective is being attained through accomplishment of the following specific objectives.

- Critical examination of existing dynamic models and control systems for individual processes with selection of the most appropriate models and control systems for inclusion in an integrated dynamic model and control system for a typical plant.

- Preparation of a computer simulation package for the integrated plant with provision for easy interfacing of the plant model with dynamic models for collection systems, receiving streams, and sludge transport and disposal systems.

- Exploration by computer simulation of integrated control systems for the plant which take advantage of the latest developments in computer control including predictions by dynamic models and the use of expert systems to incorporate the experience of skilled operating engineers.

- Simplification of the integrated model and control system so that they can be implemented on an advanced personal computer such as the IBM PC-AT or equivalent. In this simplification, emphasis will be placed on structuring the model so that it can be easily used, and modified when necessary, by practicing engineers not skilled in advanced programming techniques.

- Preparation of plans for physical experimentation to validate the model and test the most promising control systems at pilot scale and, where appropriate, full scale.

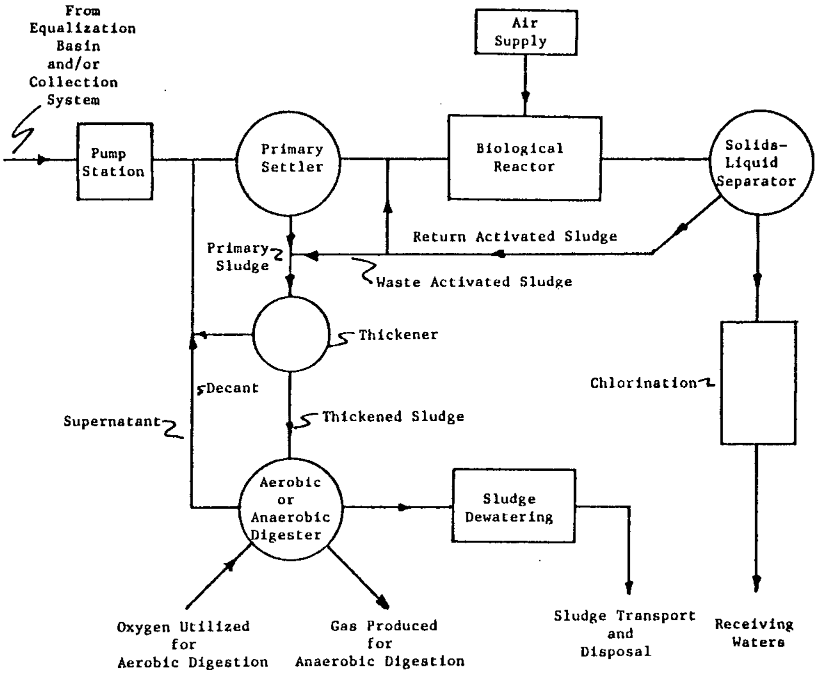


FIGURE 1. FLOW DIAGRAM FOR A TYPICAL WASTEWATER TREATMENT PLANT

The author is acutely aware that accomplishment of the above objectives is an ambitious undertaking for any one group. Exchange of information with other researchers is therefore essential to the success of the research. Moreover, this exchange must be at the international level since only a limited number of researchers are engaged in research oriented toward solution of the problems of plant operations and still fewer are addressing these problems through improving understanding of dynamic behavior and applying computer control.

Types of Models

As discussed by Beck (In press) there are three types of models which hold promise for accomplishing the objectives listed. These are (a) mechanistic, (b) time-series, and (c) linguistic models. From a practical point of view, the purpose of all of these models, as proposed for use in wastewater treatment plant operations, is to predict dynamic behavior and exert control based on these predictions. From the research point of view, the objective is to extend fundamental engineering knowledge of wastewater treatment with ultimate use of this knowledge for improving both plant design and operation.

Mechanistic models are primarily based on fundamental scientific and engineering knowledge about the physical, chemical, and biological phenomena which govern the system being modeled. They usually consist of sets of differential or partial differential equations although difference equations may also be used. When used as a research tool, they may also contain hypothetical knowledge which has not yet been validated. An example of a mechanistic model for the anaerobic digester and its use in computer simulations for exploring process stability and control has been presented by Graef and Andrews (1974) for the anaerobic digester. The emphasis of this type of model is on theory so they are sometimes called theoretical models.

When systems are complex, as are most biological processes used in wastewater treatment, many of the mechanisms may be either unknown or poorly understood and the use of empirical models may be necessary. Such models can be developed by collecting large amounts of data during plant operations and applying the techniques of time-series analysis (Box and Jenkins,1970; Akaike, 1972). They are thus sometimes called "time-series" models. An example of this approach is that of Hiraoka's group (Hiraoka, et al, 1985; Kanaya, et al, 1985; Hiraoka and Tsumura; 1989) which is conducting full scale experiments at the Kawamata plant in Osaka Prefecture.

Linguistic models make use of the practical experience or "mental" models of skilled operating engineers by using the techniques of expert systems which are a class of artificial intelligence programs intended to serve as advisors for decision making or for direct use in automatic control. The emerging field of "Knowledge Engineering" encompasses the job of gathering and codifying the knowledge and experience of human experts. A common type of linguistic model is that based on empirical "if-then" rules in which dynamic behavior and control actions are stated in linguistic terms (Waterman, 1986). An example of research on the application of linguistic modeling to operation of the anaerobic digester is that of Barnett (1989).

Both linguistic and time-series models usually have the potential for more rapid implementation in practice and practicing engineers may thus emphasize the need for the devotion of more immediate effort to development of these types of models. Mechanistic models stress the long-term acquisition of fundamental engineering knowledge and are thus emphasized by many engineering researchers. It is these differences in time scales (short-term vs. long-term) and objectives of modeling (applied vs.fundamental knowledge) that sometimes leads to disagreements between research and practicing engineers as to which type of model is most important. The author is of the opinion that all three types of model can contribute to both short-term practical application and long-term fundamental knowledge acquisition.

The author's experience has been primarily in the area of mechanistic modeling so this type of model is emphasized in his research. However, in the preparation of plans for physical experiments, considerable attention will be devoted to determining how the three types of models can best be combined so as to take advantage of the best features of each in exerting control. The time-series model being developed by Hiraoka's group appears to be an excellent candidate for combining with mechanistic models since data is being collected from a full-scale plant under carefully controlled experimental conditions. Such data has a distinct advantage over data collected during normal operating conditions since the experiments can be designed to force the plant to display the dynamic phenomena of interest. Data collected during normalplant operations may not reflect these phenomena since the objective of operating the plant is to reduce variations in effluent quality. The information needed for validating dynamic models may therefore not be present in this type of data.

Barnett's research provides an example of the combination of a mechanistic model with a linguistic model. His approach differs from the usual expert systems approach in that he used a mechanistic model of the anaerobic digester to develop "if-then" rules for diagnosis of the cause of different types of process failure and the subsequent implementation of control to avoid failure. Additional research will be needed to incorporate rules based on the empirical knowledge of skilled operating engineers before this "expert system" is field tested. Moreover, this field testing should first be accomplished at pilot scale since the purpose of the expert system is to diagnose and prevent process failure. For such testing, it will be necessary to force the digester so that it exhibits the symptoms of a failing digester and then see if the proposed expert system is successful in preventing failure. There is thus a distinct possibility that failure will occur and failure of a pilot digester isgreatly preferred to failure of a full-scale digester.

Computer Simulation

The "model library" approach presented by Olsson, et al (1985) has been adopted for this research. In this approach, modules are prepared for individual processes or subsystems of processes. These modules may then be linked together to form either a process model or a model of the entire plant. The simulation language used by Olsson, SIMNON, has also been adopted. This is a very flexible language in that it can represent either differential equations (which are best for mechanistic models), difference equations (best for digital controllers) and connecting systems which provide a convenient method for linking the individual process models and their control loops into an integrated plant model and control system. An example of the use of SIMNON for simulating control of the step feed version of the activated sludge process will be presented later in this paper.

The version of SIMNON being used is that for the personal computer (PC). This is relatively inexpensive ($675) which means that programs can be prepared and used by practicing engineers at a relatively low cost. An alternate to SIMNON is a program called ACSL which is being used by Patry (In press) in research similar to that described herein.

The time-series analysis techniques proposed for use in this research are those contained in a program called SACCESS which has been developed by Hiraoka's group for their research at the Kawamata plant. They are currently preparing an English manual which describes the application of these techniques to modeling and control of the activated sludge process and have plans to make this available to other researchers. At the appropriate time, the author plans to blend the techniques used in SACCESS with those given in SIMNON so that both mechanistic and time-series models can be utilized for the overall plant model and control system. At this same time, a suitable shell for the application of expert systems techniques will be selected. A short review of some of the shells available for use on PC's is that of Epp (1988).

STEP FEED ACTIVATED SLUDGE PROCESS

In this version of the activated sludge process, influent wastewater can be admitted to any or all of several aeration basins in series as shown in Fig. 2. The value of dynamic modeling and computer simulation for process control will be illustrated by examining the effect of changing the feed point on the solids distribution between the aeration basins and secondary settler when the process is subjected to sudden increases in flow rate as might be caused by storm flows.

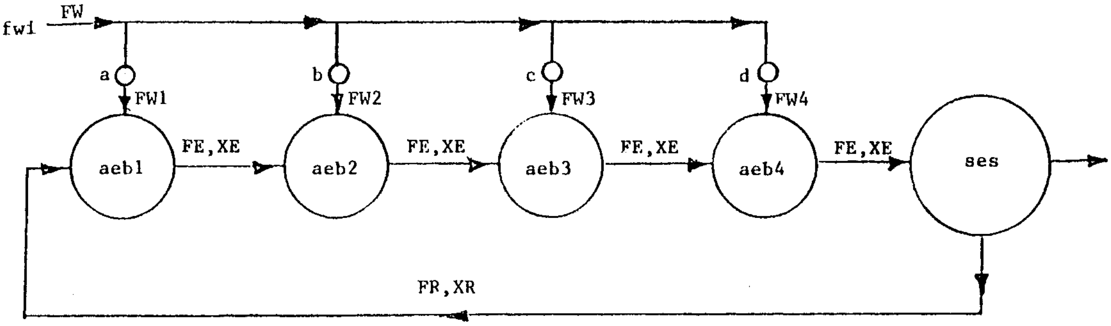


FIGURE 2. FLOW DIAGRAM FOR THE STEP FEED ACTIVATED SLUDGE PROCESS

In order to maintain a constant mass of sludge under aeration, it can be easily shown by algebra that the use of step feed on a continuous basis will substantially reduce the required volume of the aeration basins without requiring an increase in the size of the secondary settler. Thus from a design point of view, the major advantage of the step feed process over the conventional process (in which all of the feed is added to the first aeration basin) is usually considered to be reduction in capital costs. However,from an operational point of view the major advantage of the process is the additional controllability provided by being able to shift the feed point(s). Such control can be used to avoid process failure by either high flow rates or sludge bulking.

It should be noted that the use of step feed for process control is not new. It's use was pioneered by Torpey (1948) at the Bowery Bay plant in New York City.The results reported by Torpey demonstrate the use of step feed to prevent process failure by sludge bulking. However, he also used step feed to prevent process failure by storm flows (1972). Lee and Andrews (1972) used mathematical modeling and computer simulation to explain the theory involved and Buhr (1984) has pointed out some of the practical limitations of this type of control. Hill (1985), in full-scale experiments at the Sagemont plant in Houston, Texas, has demonstrated the use of step feed for reducing the solids loading to secondary settlers. However, the value of changing the feed point(s) for exerting control is still not recognized by many researchers and practicing engineers.

Dynamic Model

A simple dynamic model for illustrating the value of changing the feed point on solids distribution can be obtained by making solids balances for each of four aeration basins in series followed by that for a settler (Fig. 2) with the assumption that the total mass of solids in the process (aeration basins and settler) is constant for the time period being examined. This assumption is valid if sludge is being wasted at the rate at which it is produced which is the usual case. This also means that reaction terms need not be included in the balances and in any case their net effect on the total mass of solids in the process is usually small for short time periods (<24 hours).

In making the solids balances for the aeration tanks, each tank is assumed to have a constant volume and to be completely mixed so that the solids concentration is uniform through the tank volume. A simple model for the settler is obtained by assuming the sludge in the settler to be contained in two layers each with a different solids concentration (Fig. 3). Both layers are assumed to have constant, but different concentrations of solids. The height of the bottom layer is also assumed constant which means that the mass of solids in this layer is constant. The recycled sludge flow rate is also assumed constant resulting in a constant mass flow rate of solids out of the settler. However, the mass flow rate of solids into the settler does vary. The difference between the two mass flow rates is reflected in a change in the amount of sludge stored in the top layer and, since the solids concentration in this layer is constant, a variation in the height of the top layer (sludge blanket level).

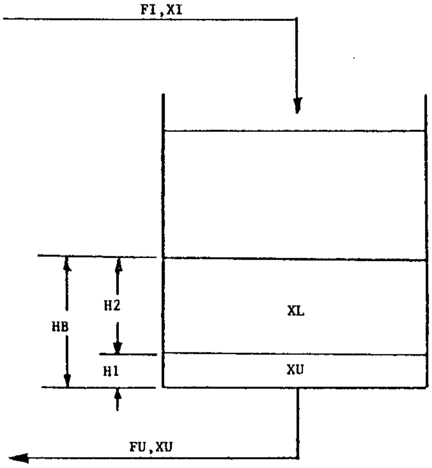


FIGURE 3. SECONDARY SETTLER

Provision for the use of either of two controllers is made in the model. Both are ON-OFF controllers with the manipulated variable being the position (fully open or closed) of the wastewater influent gates to each of the four basins. However, the two controllers use different signals for initiating control with that for the first controller being the influent flow rate to the plant while that for the second controller is the height of the sludge blanket in the settler.

Simulation Program

The SIMNON program for this model is presented in Fig. 4. It consists of the linking of six modules, fwi, aeb1, aeb2, aeb3, aeb4, and ses with a controller module (con1 or con2) by using a connecting system module, cst. Numerical values for parameters and initial conditions for the variables are stored in files called acsp6 or acsp7 (Table I). Definitions of symbols and units used are given in Table II.

The influent flow rate module, fwi, combines a sinusoidal flow rate having a frequency of one cycle per day and maximum and minimum flow rates of 50 and 150 cu m/h, with a pulse flow rate (100 cu m/h), as might be caused by a storm, starting at 1000 hours and lasting until 1400 hours. All of the aeration basin modules (aeb1, aeb2, aeb3, aeb4) consist of the same program with the exception of aeb1 which differs because of the input of recycle sludge from the secondary settler, ses. The two controller modules, either of which may be used, differ in that for con1 the control signal is the influent flow rate while for con2 the signal is the sludge blanket height in the secondary settler.
Both controllers are discrete systems with a sampling time of 0.1 hour.

The connecting system module, cst, serves to link the other modules. For example, the statement "FI[aeb2] = FE[aeb1]" tells the computer that the value for FE (effluent flow rate) contained in module aeb1 will become the value for FI (influent flow rate) in module aeb2. INPUT and OUTPUT statements must also be usedin each module to establish am exchange of information between the different modules. For example, in aeb1 it is stated that FE is an OUTPUT from another moduleand in aeb2 that FW is an INPUT from another module. It should also be noted in Fig. 3, that the cst module for the system containing con2 is slightly different from the module contain con2.

```
DISCRETE SYSTEM con1
"Controller using influent flow rate as signal
INPUT FW
OUTPUT FW1 FW2 FW3 FW4
TIME t
TSAMP ts
y = FW
a = IF y<SP1 THEN 1.0 ELSE 0.0001
b = IF y<SP2 THEN 0.0001 ELSE 1.0
c = IF y<SP3 THEN 0.0001 ELSE 1.0
d = IF y<SP4 THEN 0.0001 ELSE 1.0
FW1 = y*a/(a+b+c+d)
FW2 = y*b/(a+b+c+d)
FW3 = y*c/(a+b+c+d)
FW4 = y*d/(a+b+c+d)
ts = t + k
END

DISCRETE SYSTEM con2
"Controller using sludge blanket height as signal
INPUT FW HB
OUTPUT FW1 FW2 FW3 FW4
TIME t
TSAMP ts
y = HB
x = FW
a = IF y<SP1 THEN 1.0 ELSE 0.0001
b = IF y<SP2 THEN 0.0001 ELSE 1.0
c = IF y<SP3 THEN 0.0001 ELSE 1.0
d = IF y<SP4 THEN 0.0001 ELSE 1.0
FW1 = x*a/(a+b+c+d)
FW2 = x*b/(a+b+c+d)
FW3 = x*c/(a+b+c+d)
FW4 = x*d/(a+b+c+d)
ts = t + k
END

CONNECTING SYSTEM cst
"Connects other systems
    "Connect four reactors in series"
FI[aeb2] = FE[aeb1]
FI[aeb3] = FE[aeb2]
FI[aeb4] = FE[aeb3]
XI[aeb2] = XE[aeb1]
XI[aeb3] = XE[aeb2]
XI[aeb4] = XE[aeb3]
    "Settler"
FR[aeb1] = FU[ses]
XR[aeb1] = XU[ses]
FI[ses]  = FE[aeb4]
XI[ses]  = XE[aeb4]
    "Connect flow rate signal to controller"
        "For con2, change con1 to con2 and
        "add HB[con2] = HB[ses]
FW[con1] = FW[fwi]
    "Controlled step feed"
        "For con2, change con1 to con2
FW[aeb1] = FW1[con1]
FW[aeb2] = FW2[con1]
FW[aeb3] = FW3[con1]
FW[aeb4] = FW4[con1]
END

CONTINUOUS SYSTEM fwi
"Sinusoidal influent flow rate to wastewater
"treatment plant with superimposed storm flow
OUTPUT FW
TIME t
FW = FA + FC*SIN(W*t + P) + FS
FS = IF t<ts THEN 0 ELSE IF t<te THEN FM ELSE 0
END

CONTINUOUS SYSTEM aeb1
"Model for 1st aeration basin
INPUT FW FR XR
OUTPUT FE
STATE XE
DER dXE
dXE = (FR*XR +FW*XW - FE*XE)/V
FE = FR + FW
END

CONTINUOUS SYSTEM aeb2
"Model for 2nd, 3rd, and 4th aeration basins
"Note: Although the models are identical,
"must use system names of aeb2, aeb3, and
"aeb4 when linking by a connecting system
INPUT FI XI FW
OUTPUT FE
STATE XE
DER dXE
dXE = (FI*XI + FW*XW - FE*XE)/V
FE = FI + FW
END

CONTINUOUS SYSTEM ses
"Secondary settler with variable sludge blanket
"depth
INPUT FI XI
OUTPUT FU XU HB
STATE MXT
DER   dMXT
dMXT = (FI*XI - FU*XU)/1000
MX1 = A*H1*XU/1000
MX2 = MXT - MX1
V2 = 1000*MX2/XL
H2 = V2/A
HB = H1 + H2
END
```

FIGURE 4. SIMNON PROGRAM FOR STEP FEED ACTIVATED SLUDGE MODEL

TABLE I. NUMERICAL VALUES FOR PARAMETERS AND INITIAL CONDITIONS

```
[fwi]
"Influent flow rate to plant
FA:100.
FC:50.
FM:100
ts:10
te:14
W:0.2618
P:-1.5708

[aeb1]
"Aeration basin 1
XE:2000.
V:100.

[aeb2]
"Aeration basin 2
XE:2000.
V:100.

[aeb3]
"Aeration basin 3
XE:2000.
V:100.

[aeb4]
"Aeration basin 4
XE:2000.
V:100.
```

```
[con1]
"Influent flow rate as signal
SP1:151.
SP2:151.
SP3:251.
SP4:251.
k:0.1

[con2]
"Sludge blanket height as signal
SP1:2
SP1:2
SP3:4
SP4:4

[ses]
"Secondary settler

MXT:1000.
A:80.
H1:0.3
XL:4000.
XU:8000.

[cst]
"Connecting system
```

Simulations are conducted and the results plotted by entering a series of commands directly at the keyboard or by writing a MACRO statement and entering only the name of the MACRO at the keyboard. Two example MACRO's are presented in Fig. 5 with acsa6 and acsa7 containing controllers 1 and 2. respectively. These MACROS also demonstrate how numerical values of the parameters and initial conditions can be obtained from separate files using the GET command. The MACROS also contain statements needed to establish the type of plot(s) to be used for presenting simulation results.

Simulation Results

Simulation results for the uncontrolled process and for control based on influent flow rate are presented in Figs. 6 and 7, respectively. In Fig. 6 it will be noted that the storm flow results in substantial decreases in the mixed liquor suspended solids concentrations (XE) in the aeration basins with a consequent increase in the sludge blanket height (HB) in the settler. Too large an increase in HB would result in process failure with large concentrations of solids spilling over the wiers of the settler. In the controlled process, the controller set points (SP1..SP4) are such that when the influent flow exceeds 151 cu m/h, the maximum sinusoidal flow rate, the gate to basin one is closed and the gate to basin two is opened. Consequently basin one, instead of the settler, serves tostore solids as evidenced by the rease in XE for this basin and decrease in HB for the settler.

A plot of HB for both simulations is presented in Fig. 8 for contrasting the controlled and uncontrolled cases as well as to illustrate the plotting of results by SIMNON without the use of a MACRO.

TABLE II. DEFINITIONS OF SYMBOLS AND UNITS

SYMBOLS AND UNITS

A = Surface area of settler, sq m
a..d = Valve settings for individual aeration basins, equals 1.0 if valve open and 0.0001 if valve closed.
FA = Average influent wastewater flow rate, cu m/h
FC = Cyclic component of influent wastewater flow rate, variation above and below avg, cu m/h
FE = Effluent flow rate from aeration basin, cu m/h
FI = Flow rate to aeration basin from previous basin, cu m/h
FL = Effluent flow rate from upper mass of sludge in settler, cu m/h
FM,FS = Height of pulse flow rate due to storm, cu m/h
FR = Recycle sludge flow rate, cu m/h
FU = Effluent flow rate from lower mass of sludge in settler, cu m/h
FW = Influent wastewater flow rate to plant, cu m/h
FW1..FW4 = Controlled wastewater flow rate to individual aeration basins, cu m/h
H2 = Depth of upper mass of sludge in settler, m
H1 = Depth of lower mass of sludge in settler, m
HB = Total depth of sludge in settler, m
k = Sampling increment for digital controller, h
MX2 = Upper mass of sludge in settler, kg
MX1 = Lower mass of sludge in settler, kg
MXT = Total mass of sludge in settler, kg
SP1..SP4 = Set points for control of wastewater flow to individual aeration basins, m/h or m depending upon whether Controller 1 or Controller 2 is used
P = Phase shift, radians, -1.5708 shifts backward 90 degrees so that the lowest flow occurs at midnight (0 h)
t = Time, h
ts* = Time at which storm starts, h, or sampling time for a digital controller, h
te = Time at which storm ends, hours
V = Aeration basin volume, cu m
V2 = Volume of upper mass of sludge in settler, cu m
V1 = Volume of lower mass of sludge in settler, cu m
W = Frequency, radians/h, 0.2618 yields one cycle per day
XE* = Effluent solids concentation from aeration basin, gm/cu m
XI = Influent solids concentration to aeration basin, gm/cu m
XL = Solids concentration in upper mass of sludge, gm/cu m
XR = Recycle sludge solids concentration, gm/cu m (also equals XU)
XU = Solids concentration in lower mass of sludge, gm/cu m

Notes: *In SIMNON, the same symbol can have different meanings in different systems. For example, ts equals the time at which a storm starts in system fwi or the sampling time for a digital controller (systems con1 or con2).

**The same symbol may be used in the different systems, for example, XE can mean the effluent solids concentration from any of the four aeration basins. The connecting system (cst) is used to instruct SIMNON to let the effluent concentration from one basin become the influent concentration to the following basin, i.e., XI[aeb2] = XE[aeb1].

```
MACRO acsa7
"Simulation and plotting for the step feed
"activated sludge process

syst fwi aeb1 aeb2 aeb3 aeb4 con1 ses cst
get acsp7
store FW[fwi] XE[aeb1] XE[aeb2] XE[aeb3] XE[aeb4] HB[ses]
simu 0 24/b1
split 3 2
axes h 8 16 v 0 250
show FW[fwi]/b1
Text 'Wastewater Flow Rate, cu m/h'
area 2 1
axes h 8 16 v 0 6000
show XE[aeb1]/b1
Text 'XE[aeb1] gm/cu m'
area 3 1
axes h 8 16 v 0 6000
show XE[aeb2]/b1
Text 'XE[aeb2] gm/cu m'
area 1 2
axes h 8 16 v 0 6000
show XE[aeb3]/b1
Text 'XE[aeb3] gm/cu m'
area 2 2
axes h 8 16 v 0 6000
show XE[aeb4]/b1
Text 'XE[aeb4] gm/cu m'
area 3 2
axes h 8 16 v 0 4
show HB[ses]/b1
Text 'Sludge Blanket Height, Meters'
END
```

```
MACRO acsa6
"Simulation and plotting for the step feed
"activated sludge process

syst fwi aeb1 aeb2 aeb3 aeb4 con2 ses cst
get acsp6
store FW[fwi] XE[aeb1] XE[aeb2] XE[aeb3] XE[aeb4] HB[ses]
simu 0 24/b1
split 3 1
axes h 0 24 v 0 250
show FW[fwi]/b1
Text 'Wastewater Flow Rate, cu m/h'
area 2 1
axes h 0 24 v 0 8000
show XE[aeb1] XE[aeb2] XE[aeb3] XE[aeb4]/b1
Text 'Solids Concentrations, gm/cu m'
area 3 1
axes h 0 24 v 0 4
show HB[ses]/b1
Text 'Sludge Blanket Height, Meters'
Mark A 12 0.75
Mark "Time, Hours
END
```

FIGURE 5. MACRO'S FOR SIMULATION AND PLOTTING

The results of implementing control based on measurement of the sludge blanket level (HB) are presented in Fig. 9. In this case the controller set points (SP1..SP2) are such that when HB exceeds 2 meters, the gate to basin one is closed and the gate to basin two opened. Control is thus experted not only during storm flow but also during a portion of the normal sinusoidal flow period. The result is a gradual decrease in HB until it averages about 2 meters with slight fluctuations above and below this level. A closer approach to a constant HB of 2 meters could be obtained by using throttling gates and PID controllers. A similar approach is that used by Norman, et al (1985) for the 69th Street plant in Houston, Texas. In this plant a separate pipe line with a flow control loop has been included in the plant design to permit adjustment of the influent wastewater flow rate to the fourth aeration basin. This control loop is used to protect against storm flows by control of the sludge blanket level.

Practical Implementation

The dynamic model presented is a simplified model designed primarily to qualitatively illustrate the basic principles of control by step feed for the prevention of process failure by hydraulic overload. It is unlikely that it would be suitable for quantitative predictions for specific plants without modification. However, it should be useful as a framework for use by practicing engineers in developing models and control systems for specific plants. It is obvious that numerical values for the parameters in the model, such as aerator volumes and settler dimensions, need to be those for the plant under considered. More basic changes in the model which may also be required as well as references to models and control systems developed by others for full scale application are discussed below.

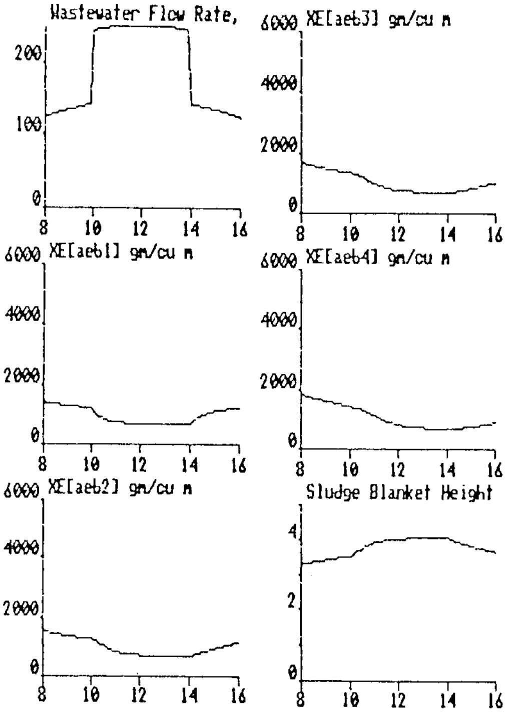


FIGURE 6. SIMULATION OF THE UNCONTROLLED PROCESS

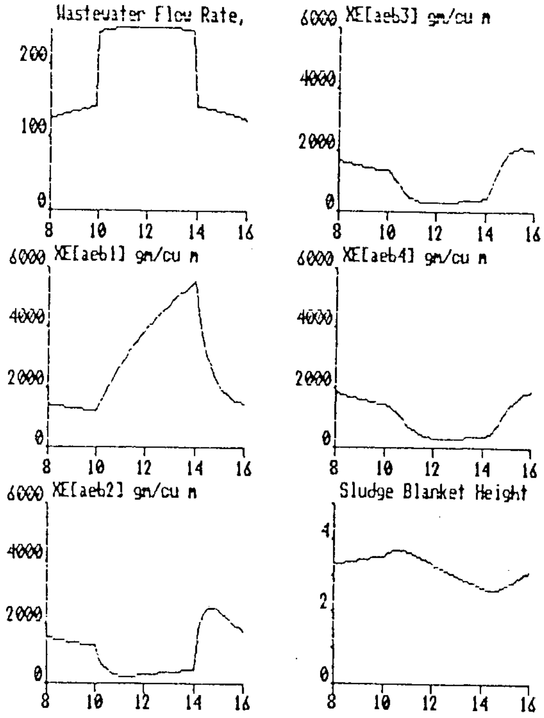
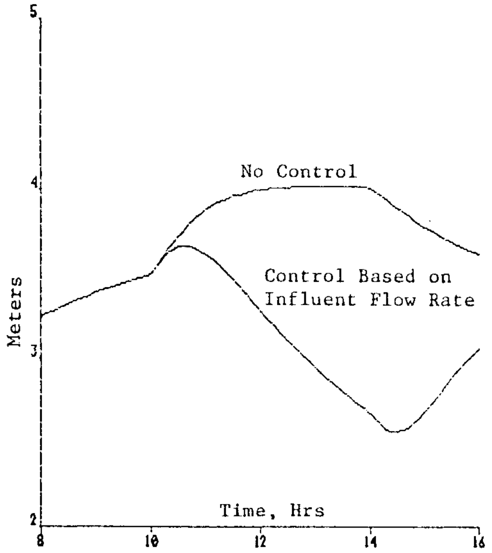


FIGURE 7. SIMULATION OF CONTROL BASED ON INFLUENT FLOW RATE



```
>syst fwi aebl aeb2 aeb3 aeb4 conl ses cst
>get acsp7
>axes h 8 16 v 2 5
>plot HB
>simu 0 24
>par SP1:151
>par SP2:151
>simu 0 24
>gin
>mark a 4.479 13.76
>mark "SLUDGE BLANKET HEIGHT, METERS - CONTROLLED
 AND UNCONTROLLED
>hcopy
>stop
```

FIGURE 8. SLUDGE BLANKET HEIGHT FOR CONTROLLED AND UNCONTROLLED PROCESS

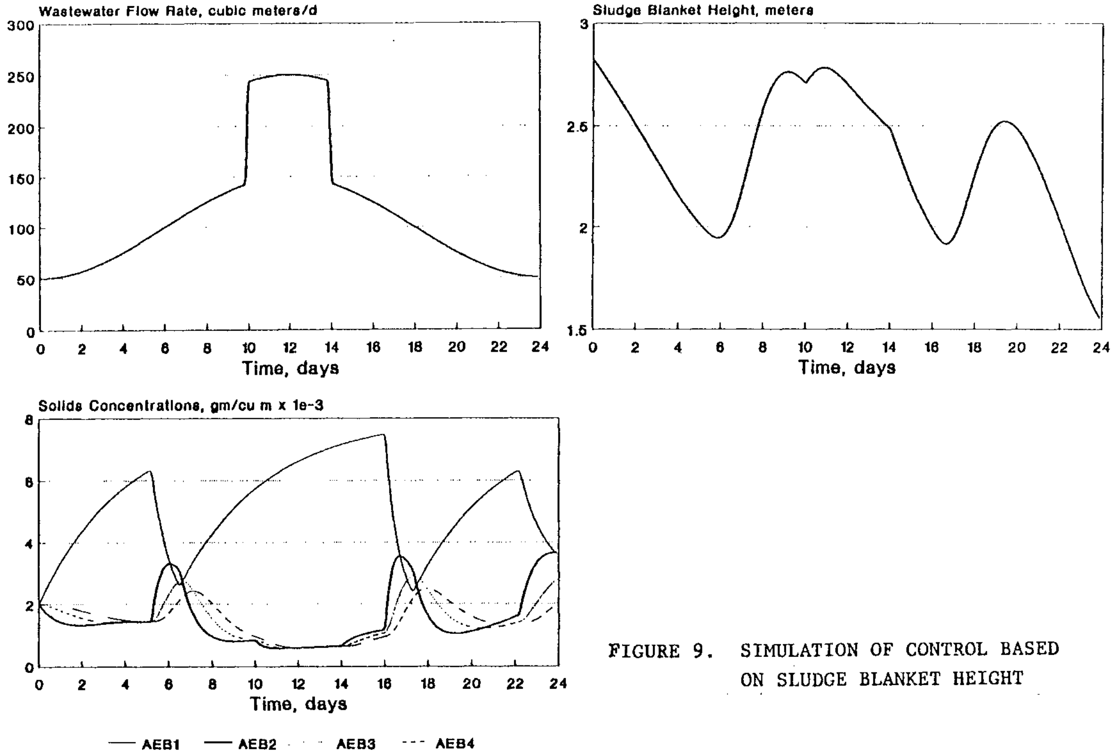


FIGURE 9. SIMULATION OF CONTROL BASED ON SLUDGE BLANKET HEIGHT

The most important modifications which may be needed are those connected with the assumptions made in developing the dynamic model for the settler. For example, the solids concentration in the recycle sludge is not constant but instead varies with both sludge depth and recycle sludge flow rate. More theoretical models which might be used, and which have been tested at full scale, include those of Garrett, et al (1984, 1987) for the Southwest and 69th Street plants in Houston, Texas, and that of Severin and Poduska (1985) for the Eastman Kodak plant at Kingsport, Tennessee. Stehfest (1984, 1985) has presented both theoretical and empirical models which have been tested at the Donaueschingen plant in West Germany. Lumley, et al (1988) have developed an empirical dynamic model for predicting the sludge mass in the settler at the Rya plant in Goteborg, Sweden while von Sperling and Lumbers (1989), working with the settler for an oxidation ditch at the Thames Water Authority plant in Leatherhead, England, have developed an empirical model for prediction of sludge blanket height.

Another modification which may be necessary is based on the dynamics of fluid flow through the plant. It has been assumed that the aerator volumes are constant and that there is no time delay in flow rates when flow passes from one vessel to another. However, this is only approximately true and an example of how the model can be modified to reflect the influence of these factors has been presented by Olsson and Stephenson (1985) for the Kirkeskoven plant in Denmark. The model presented also assumes that the mixing patterns in the aerator can be approximated by the use of four complete mixing aerators in series. Actual mixing patterns should be determined by tracer tests as discussed by Goto (1984) and Stehfest (1985), among others.

Although continued research is needed on the development of dynamic mathematical models for both improved understanding of dynamic behavior and application of this knowledge to practice, it should be noted that such models are not necessary to gain some of the benefits of step feed control in practice. This statement is more than adequately proven by examining Torpey's (1948) classic research on the use of step feed in which control was implemented based only on manual measurements of the sludge density index‡ and fluctuations in the volume to which a sample of the sludge would settle in 30 minutes.

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‡ SDI is an older measure of sludge settling characteristics. It is related to the sludge volume index (SVI) by the formula: SVI = 100/SDI.

CONCLUSIONS

The following conclusions may be drawn from the results of the research presented in this paper.

1. Dynamic modeling and computer simulation are useful tools for development of a "body of theory" for wastewater treatment plant operations.

2. Interactions between processes and their control loops as well as internal process interactions must be considered in developing integrated models and control systems for treatment plants.

3. Combinations of mechanistic, time-series, and linguistic models should be considered for use in control of treatment plants.

4. Changes in the wastewater feed point(s) for the step feed activated sludge process can be used to prevent process failure by storm flows or sludge bulking.

The author hesitated to list the use of step feed for prevention of process failure as a conclusion since this has already been well proven at full scale by Torpey (1948, 1972), among others. However, he does believe that the value of step feed for process control must be repeatedly stressed since many researchers and practioners are still unaware of the operational benefits of the step feed activated sludge process.

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REFERENCES

Akaike, H. and T. Nakagawa (1972). Statistical Analysis and Control of Dynamic System. Saienshusha, Tokyo (In Japanese).

Andrews, J.F., R. Briggs and S.H. Jenkins, Eds. (1974). Instrumentation, Control and Automation for Wastewater Treatment. Progress in Water Technology, 6.

Barnett, M. (1989). Anaerobic Digestion Process Operation Using a Knowledge Based System. Ph.D. Dissertation, Rice University, Houston, Texas.

Beck, M.B. (In Press). System identification and control. Dynamic Modelling and Expert Systems in Wastewater Engineering, (Patry, C.G. and D. Chapman, Eds.), Lewis Publishers, Chelsea, MI.

Box, G.E.P. and G.M. Jenkins. (1970). Time Series Analysis - Forecasting and Control. Holden Day, San Francisco.

Bryan, J.O. (1972). Continuous Time Simulation of the Conventional Activated Sludge Process. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.

Buhr, H.O. (1984). Making full use of step feed capability. Journal Water Pollution Control Federation, 56, 325-330.

Busby, J.B. (1973). *Dynamic Modeling and Control Strategies for the Activated Sludge Process*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.

Drake, R.A.R., Ed. (1985). *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*. *Advances in Water Pollution Control*, Pergamon Press, Oxford.

Epp, H., M. Kdalin and D. Miller. (1988). PC software for artificial intelligence applications, *Science*, *240*, 824-830.

Garrett, M.T., J. Ma, W. Yang, G. Hyare, T. Norman and Z. Ahmad. (1984). Improving the performance of Houston's Southwest wastewater treatment plant. *Water Science and Technology*, *16*, 317-329.

Garrett, M.T., Z. Ahmad, G. Hyare, and T. Tsai. (1987). The use of an on-line dynamic model to provide continuous prediction of activated sludge process variables. *Presented at the Texas Water Pollution Control Federation Conference*, Corpus Christi, Texas.

Goto, M. (1984). *On-line Estimation of Oxygen Uptake Rate for the Activated Sludge Process*, Ph.D. Dissertation, Rice University, Houston, Texas

Graef, S.P and J.F. Andrews. (1974). Stability and control of anaerobic digestion. *Journal Water Pollution Control Federation*, *46*, 666-683.

Hill, R.D. (1985). *Dynamics and Control of Solids-Liquid Separation in the Activated Sludge Process*, Ph.D. Dissertation, Rice University, Houston, Texas.

Hiraoka, M. K. Tsumura, T. Kanaya and I. Fujita. (1985). Statistical Analysis of Activated Sludge Process Dynamics in a Combined Wastewater Treatment Plant. *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, (Drake, R.A.R., Ed.), *Advances in Water Pollution Control*, Pergamon Press, Oxford, 661-664.

Hiraoka, M. and K. Tsumura. (1989). System identification and control of the activated sludge process by use of a statistical model. *Water Pollution Research and Control*, *21*, 1161-1172.

Jenkins, S.H., Ed. (1978). *Instrumentation and Control for Water and Wastewater Treatment and Transport Systems*. *Progress in Water Technology*, *9*, *Nrs*. *5/6*.

Jenkins, S.H., Ed. (1981). *Practical Experiences of Control and Automation in Wastewater Treatment and Water Resources Management*. *Progress in Water Technology*, *13*, *Nrs*. *5/6/7/8/9/10/11/12*.

Kanaya, T., I. Fujita, H. Hayashi, M. Hiraoka and K. Tsumura (1985). Automatic measurement and analysis of process data in a combined wastewater treatment plant. *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, (Drake, R.A.R., Ed.), *Advances in Water Pollution* Controll, Pergamon Press, Oxford, 77-84.

Lee, C.R. and J.F. Andrews. (1972). Dynamics and control of a multi-stage biological process. *Proceedings IV International Fermentation Symposium*: *Fermentation Technology Today*, (Gyozo, T., Ed.), 55-63.

Lumley, D.J., P. Balmer and J. Adamsson. (1988). Investigations of secondary settling at a large treatment plant. Water Science and Technology, 20, 133-142.

Norman, T., R.J. Borchardt, M.T. Garrett, Z Ahmand and G. Hyare. (1985). Start-up and interim control of Houston's 69th street wastewater complex. *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, (Drake, R.A.R., Ed.), *Advances in Water Pollution Control*, Pergamon Press, Oxford, 359-365.

Olsson, G., U. Holmberg and A. Wikstrom. (1985). A Model Library for Dynamic Simulation of Activated Sludge Systems. Instrumentation and Control of Water and Wastewater Treatment and Transport Systems, (Drake, R.A.R., Ed.), Advances in Water Pollution Control, 721-728, Pergamon Press, Oxford.

Olsson, G. and D. Chapman (1985). Modelling the dynamics of clarifier behavior in activated sludge systems. *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, (Drake, R.A.R., Ed.), *Advances in Water Pollution Control*, Pergamon Press, Oxford, 405-412.

Olsson, G. and J. Stephenson (1985). The propagation of hydraulic disturbances and flow rate reconstruction in activated sludge plants. *Environmental Technology Letters*, *6*, 536-545.

Patry, C.G. and D. Chapman, Eds. (In Press). *Dynamic Modelling and Expert Systems in Wastewater Engineering*, Lewis Publishers, Chelsea, MI.

Sperling, M. V. and Lumbers, J.P. (1989). Control objectives and the modelling of MLSS in oxidation ditches. *Water Science and Technology*, *21*, 1173-1183.

Severin, F. and R.A. Poduska. (1985) Prediction of clarifier sludge blanket failure. *Journal Water Pollution Control Federation*, *57*, 285-290.

Stehfest, H. (1984). An operational dynamic model of the final clarifier. *Transactions of the Institute of Measurement and Control (G.B)*. *6*, *No.3*, 160-165.

Stehfest, H. (1985). Optimal periodic control of a step-feed activated sludge plant. *Environmental Technology Letters*, *6*, 556-565.

Stenstrom, M.K. (1976). *A Dynamic Model and Computer Compatible Control Strategy for Wastewater Treatment* Plants, Clemson University, Clemson, South Carolina.

Torpey, W.N. (1948). Practical Aspects of Step Aeration. *Sewage Works Journal*, *20*, 781-788.

Torpey, W.N. (1972). Personal communication.

Vitasovic, Z. (1986). *An Integrated Control System for the Activated Sludge Process*, Ph.D. dissertation, Rice University, Houston, Texas.

Waterman, D.A. (1986). *A Guide to Expert Systems*. Addison-Wesley Publishing Co., Reading, Massachusetts.