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SYSTEM DYNAMICS MODELING OF BIOLOGICAL REACTORS FOR WASTE WATER TREATMENT

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ABSTRACT

This article presents a system dynamics model of an activated sludge plant that is used to treat waste water biologically under aerobic conditions. Three different physical flows (flow of liquid, biomass, and substrate) are considered in the model. The model is simulated with the help of IGRASP (software package). The transient and steady state behavior of the growth of biomass, sludge production, the treatment efficiency, and their sensitivity to parameter variations are studied in detail. Policies for recirculation of activated biomass in the treatment plant are evaluated. At the end, the article assesses the merits of system dynamics modeling as a tool for conceptualizing relationships, integrating knowledge about separate parts, and evaluating control policies in environmental systems.

INTRODUCTION

The process of waste water handling and its disposal has been a major concern for sustainable development in relation to human settlements and their allied industrial activities. Activated sludge plants (ASP) are one type of typical effluent treatment plants, which employ principles of biological reactors to convert soluble organic compounds into carbon dioxide, water, and biomass. Since its inception circa 1914 by Adern and Lockett [1, 2], this technology has undergone a train of systematic improvements. Today, the extended aeration version of the

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activated sludge process is the most widely employed treatment technique for industrial and domestic waste water. In the present article, a system dynamics model of such a process has been developed and the most viable recirculation policy for maximum efficiency has been designed.

A number of research works have been devoted to the study of individual elements of the treatment process [e.g., 3-10]. Sykes examined the relationships among chemical oxygen demand (COD) of influent and effluent and the specific growth rate of an activated sludge microbial culture [3]. Krishnan and Gaudy examined pilot scale activated sludge systems, with and without recycling, in order to determine the effects of step increases in substrate concentration on process performance [4]. Boyle discussed the effects of low temperature on the performance of activated sludge processes [5]. Sherrad and Benefield presented a method for determining the quantities and forms of carbon, nitrogen, and phosphorus in the effluent of an activated sludge process as a function of sludge age [6]. Kalinske compared activated sludge systems using air and pure-oxygen [7]. It was concluded that if dissolved oxygen levels were maintained above 2 mg/l, the air- and the pure-oxygen-activated sludge systems were comparable with regard to their sludge settling and dewatering characteristics, effluent quality, and waste sludge production. Kormanik examined high-speed high-trajectory, high-speed low-trajectory, and low-speed surface aerators to determine the effect of basin geometry on oxygen transfer [8]. Wu presented data for laboratory scale, completely mixed activated sludge systems, indicating the effects of ammonia concentration on process performance [9]. Krul concluded that denitrification occurs in aerobic populations with DO values below 1.5 mg/l in both pure and mixed cultures [10]. These studies have developed mathematical relationships among the individual factors, estimated individual parameter values, and tried to predict the performance of the system under various environmental conditions. Nonetheless, these studies are mostly fragmented, so that one often finds himself at a loss in conceptualizing system behavior at an aggregate level.

Besides the above research works, which are mainly concerned with individual components of the biological reaction process, a number of comprehensive models are also available for the entire process and the plant [11-15]. Middleton and Lawrence discussed a model for the cost optimization of a completely mixed activated sludge system, which incorporated both liquid treatment and sludge disposal costs [11]. Christoulas and Tebbutt presented a steady-state model for completely mixed activated sludge process, which included provisions for both soluble and suspended matter in the influent waste water [12]. Tang et al. presented a comprehensive model of activated sludge system, in which Chapman's model for clarifier settling has been employed [13]. The Task Group of The International Association for Water Pollution Research and Control (IAWPRC) have presented a general activated sludge process model in matrix form [14]. Dold and Marais have evaluated this Task Group model and introduced certain conceptual changes in hydrolysis of entrapped biodegradable particulate matter [15].

System dynamics models are continuous-time simulation models which explicitly consider information feedbacks that govern control actions in systems. Such models help put together, at the aggregate level, the relationships and values that are known at the individual (or component) level. This power of synthesizing the component-level knowledge into estimates of the behavior at the aggregate level has been very useful in analyzing and recommending policy decisions in management and social systems [16]. Since the work on World Dynamics by Forrester [17], system dynamics has been used in a number of environmental studies, prominent among them being those by Meadows and Meadows on models of natural resource usage [18], Vijayakumar and Mohapatra on environmental impacts of coalfields [19, 20], Naill et al. on the effects of energy use on global warming [21], Mashayekhi on solid waste disposal problems in cities [22], and Clemson et al. on the usefulness of Taguchi method in conducting a sensitivity analysis on a system dynamics model of a conventional activated sludge plant [23].

In the current article, a system dynamics model has been developed for waste water treatment by the extended aeration version of the activated sludge process. The relationships among the substrate, the biomass, the sludge, and its recirculation are modeled. The model is tested for variations in the input rate, influent substrate concentration, and the volume of aeration tank. At the end, the most viable recirculation policy is designed.

Figure 1 is a schematic diagram of the extended aeration version of the activated sludge process. The principle underlying the activated sludge process is that the biomass, through its enzymatic actions, consumes the substrate and multiplies so as to form a flocculent, insoluble mass (sludge) which separates from the system stream and settles down the clarifier. A part of the sludge, so formed, is recirculated to maintain the biomass population at a desired level.

Since a sewage treatment system is continuously operated for a number of years, it experiences diurnal (short range) and seasonal (medium range) fluctuations, and rising pollution load (long range) in the quality and quantity of influent. Thus, it is necessary to adjust the treatment system according to the prevailing influent quality and quantity, so as to achieve the desired effluent

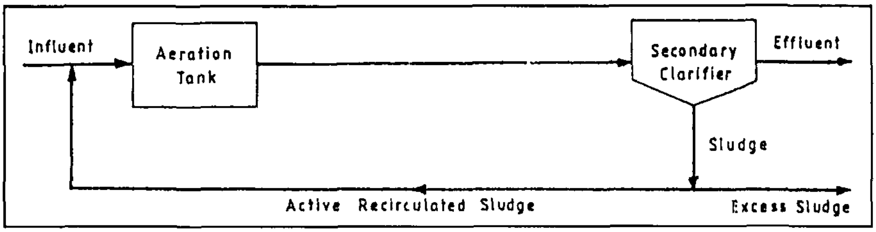

Figure 1. Physical layout of an activated sludge plant (ASP).

quality. Therefore, the design of the sludge recirculation policy, the subject of this article, assumes great importance.

SYSTEM DYNAMICS MODELING OF ACTIVATED SLUDGE PLANT (ASP)

A Brief Note on System Dynamics Modeling

One of the first steps in system dynamics modeling is to find the *physical flows* that occur in a real system. A physical flow is like the flow of water in pipes with tanks intermittently appearing along the flow. The water in the tank is an accumulation of water over time that rises if the net flow into the tank (i.e., the inflow minus the outflow) is positive, and falls if the net flow is negative. Thus the inflow into and the outflow from the tank determine (control) the amount of water in the tank at any moment of time. In system dynamics parlance, such an accumulation is called a *level* or *state* variable, and the inflow and the outflow as *rate* or *control* variables.

Rates indicate laws of nature in natural systems, controls in man-made physical systems, and policies and decisions in social and management systems. The rates depend on the desired values of the level variables (the system goals) and their actual values. Thus the rates depend on the actual values of the levels. Such dependence of the rates is shown by *flows of information* from the level variables to the rate variables.

A *flow diagram* is normally drawn to show the physical flows and the information flows. A firm line is used for a physical flow and a dotted line for an information flow. A level is conventionally denoted by a rectangle and a rate by a valve. Often, the dependence of a rate upon the levels is defined by means of complex relationships. For clarity, such a complex relationship is broken down into many simple interrelated relations defined through intermediate *auxiliary* variables. Conventionally, such variables are denoted by circles. Such variables appear only in information flows.

In system dynamics modeling, one often represents the cause-effect relationships among the variables with the help of *causal-loop diagrams.* In such diagrams, an arrow is drawn from a causal variable to an affected variable. A plus sign at the head of the arrow indicates that as the value of the causal variable (appearing at the tail of the arrow) increases, the value of the affected variable (appearing at the head of the arrow) increases. A minus sign indicates that as the value of the causal variable increases, the value of the affected variable decreases. Such a diagram is invaluable in communicating the intricate cause-effect relationships that are considered in a system dynamics model.

To obtain the dynamic behavior of a system, one transforms the information available in the causal-loop and flow diagram into difference equations (which are actually discrete equivalents of the ordinary differential equations meant for

Euler method of solution). Many dedicated software packages (such as IGRASP [24]) are available for carrying out the continuous simulation and generating dynamic behavior.

One may refer to [16] for more information on system dynamics modeling and to [24] for an example of a system dynamics simulation package.

The Physical Flows in an Activated Sludge Plant

We can distinguish three main physical flows in the ASP:

1. Flow of Liquid (Figure 2),
2. Flow of Biomass (Figure 4), and
3. Flow of Substrates or Pollutants (Figure 6).

Usually, in system dynamics model building procedures, the flow diagrams and the subsequent causal loop diagrams help in segregating and then aggregating each conceptual component of the system. The equations are written in the IGRASP-compatible language [24]. IGRASP has the capability of building and simulating system dynamics models.

Flow of Liquid

Figure 2 is the flow diagram for the flow of liquid in the ASP. It considers the volume of sewage in the aeration tank (VAT) and in the clarifier (UVC) as the level variables, each measured in M^3. The rate at which the inflow of sewage takes place into the aeration tank (IRAT), the outflow from the aeration tank (ORAT), the sludge volume withdrawal rate (SVWR), the sludge volume recirculation rate (SVRR), and the overflow rate from the clarifier (ORC), measured in M^3/hr, are considered as rate variables. Thus, the volume of liquid in the aeration tank at time (t + dt) equals the volume at time (t) plus the net inflow taking place during a very small time increment (dt). Assuming the initial value of the volume to be 3200 M^3 and the inflow rate to be 200 M^3/hr, the IGRASP-compatible equations can be written as follows:

```
L  VAT=VAT+DT*(IRAT+SVRR-ORAT)
N  VAT=3200
R  IRAT=200
```

VAT : Volume of aeration tank (M^3)
IRAT : Inflow rate to aeration tank (M^3/hr)
SVRR : Sludge volume recirculation rate (M^3/hr)
ORAT : Overflow rate from aeration tank (M^3/hr)
DT : Solution time interval (hr)

The inflow to the tank is the sum of the sewage inflow rate (IRAT) and the sludge recirculation rate (SVRR). The tank is set to be in full condition so that the

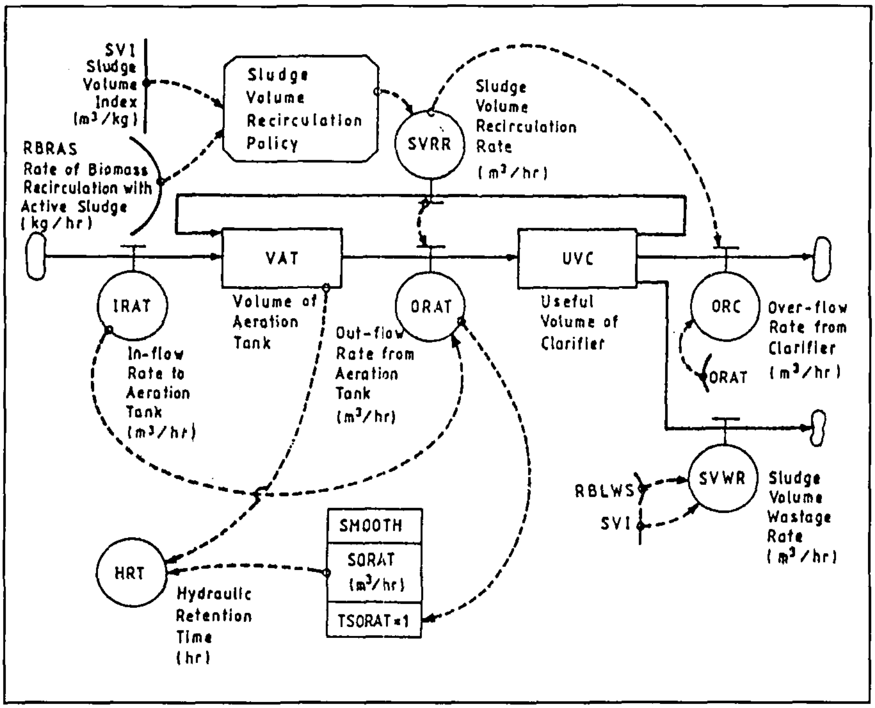

Figure 2. Flow diagram for sewage quantity in the ASP system.

outflow from the tank is always equal to the net inflow. Similarly, the net outflow from the clarifier is taken equal to the inflow (ORAT). The sludge recirculated is taken equal to the product of the biomass recirculated (discussed later) and the sludge volume index (SVI, assumed constant at 0.2 M^3/kg for the base run). The sludge wasted is taken as equal to the product of the biomass withdrawn and the SVI.

```
R  ORAT=IRAT+SVRR
R  SVRR=RBRAS*SVI
C  SVI=0.2
A  HRT=VAT/SORAT
L  SORAT=SMOOTH(ORAT,SORAT)
N  SORAT=200
L  UVC=UVC+DT*(ORAT–ORC–SVWR–SVRR)
N  UVC=800
R  ORC=ORAT–SVRR–SVWR
R  SVWR=RBLWS* SVI
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SVWR : Sludge volume wastage rate (M^3/hr)
HRT : Hydraulic retention time (hr)
SVI : Sludge volume index (M^3/kg)
ORC : Overflow rate from clarifier (M^3/hr)

Figure 3 is the causal-loop diagram for the flow of liquid. It shows that as the inflow to the aeration tank increases, the liquid (sewage) accumulation in the tank increases. It causes an increase in the outflow from the tank which, in turn, decreases the liquid accumulation (level) in the tank. The treated outflow from the tank increases the sludge quantity trapped (settled) in the clarifier and subsequently increases the clarified effluent quantity, waste sludge quantity and recirculated active sludge quantity.

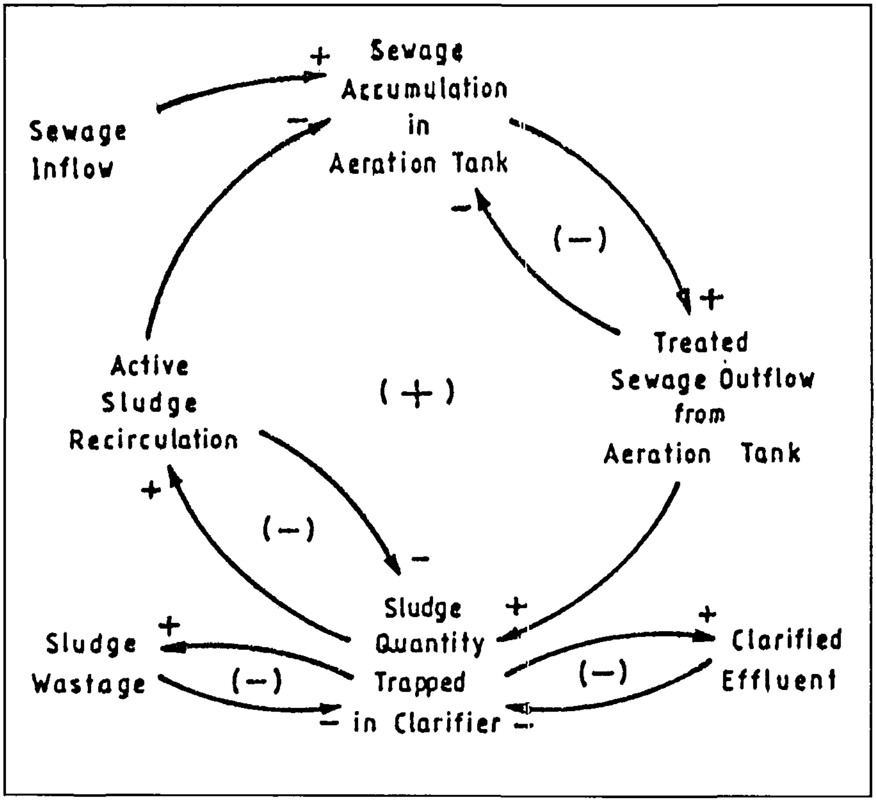

Figure 3. Causal loop diagram for sewage quantity status in ASP.

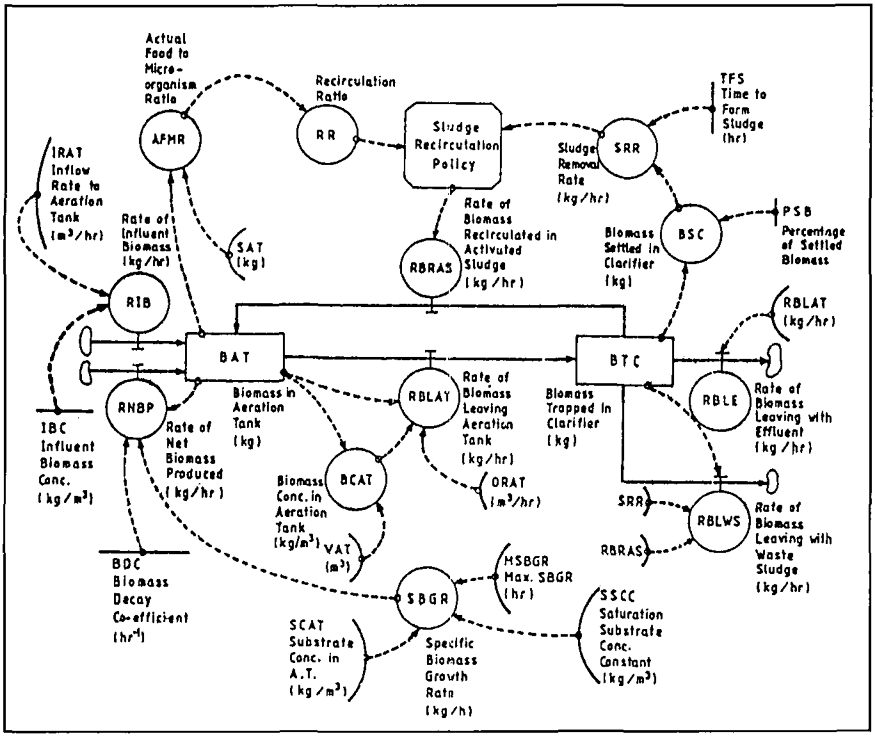

Figure 4. Flow diagram for biomass with ASP system.

Flow of Biomass

Figure 4 shows the flow of biomass in the system, wherein it considers total biomass quantity in the aeration tank (BAT) and the biomass trapped in the clarifier (BTC) as levels, both measured in M^3. The rate of influent biomass (RIB) is a product of IRAT and the influent biomass concentration (IBC). The rate of net biomass produced in aeration tank (RNBP) is dependent upon BAT, specific biomass growth rate (SBGR), biomass decay coefficient (BDC) and the hydraulic retention time (HRT). HRT denotes the average time for which the sewage flow stays in the aeration tank.

L BAT=BAT*DT(RIB+RNBP+RBRAS–RBLAT)
N BAT=10
R RIB=IBC*IRAT
C IBC=0.02
R RNBP=BAT*(SBGR–BDC)*HRT
A SBGR=MSBGR*(SCAT/(SCAT+SSCC))

```
C  SSCC=1.2
C  BDC=0.003
```

BAT : Biomass in aeration tank (Kg)
RIB : Rate of influent biomass (Kg/hr)
RNBP : Rate of net biomass produced (Kg/hr)
RBRAS : Rate of biomass recirculated with activated sludge (Kg/hr)
RBLAT : Rate of biomass leaving the aeration tank (Kg/hr)
BDC : Biomass decay coefficient (Kg/Kg/hr)
SBGR : Specific biomass growth rate (Kg/Kg/hr)
SCAT : Substrate concentration in aeration tank (Kg/M^3)
SSCC : Specific substrate consumption coefficient (Kg/M^3)

The SBGR (expressed in Kgs of biomass produced per Kgs of biomass per hour) is modeled here following the well-known Monod's equation [25]. It is considered as a function of the substrate concentration in the aeration tank (SCAT) (discussed later) and the two other biomass culture-specific coefficients—the maximum value of SBGR and the saturation substrate concentration constant (SSCC). The biomass concentration in the tank (BCAT), considered as an auxiliary variable, is a ratio of BAT and VAT. Following Westberg [26], BDC is assumed to depend upon the substrate concentration. Since there is continuous stirring in the tank, the biomass concentration remains uniform throughout the tank. The rate of biomass leaving the aeration tank (RBLAT) is a product of ORAT and BCAT.

Figure 5 is the causal-loop for the flow of biomass. As the waste water (sewage) inflow increases, the biomass inflow increases, thus resulting in the increase of total biomass in the aeration tank. This increase in the level of biomass increases the biomass generation rate within the tank, resulting in a positive feedback loop. The increase of biomass leaving rate through the outflow from the tank causes an increase of biomass in the clarifier and in the increase of biomass leaving rate through the clarified effluent. The increase of biomass trapped in the clarifier to form sludge increases the biomass recirculated as active sludge and also the biomass leaving the system through the waste sludge. However, both the outflows reduce the biomass trapped in the clarifier to form sludge.

Sludge Recirculation Policy

Biomass settled in clarifier (BSC), considered as an auxiliary variable, is the product of BTC and the percentage of settled biomass (PSB) (which is considered as a constant). This factor is introduced here to compute the efficiency of the clarifier. Under the normal operating condition of the system, PSB is assumed as 90 percent; this implies that 90 percent of the biomass is retained in the clarifier as sludge. Sludge retention rate (SRR) is the ratio of BSC and the time of formation of sludge (TFS). The rate of biomass recirculated in the activated sludge (RBRAS)

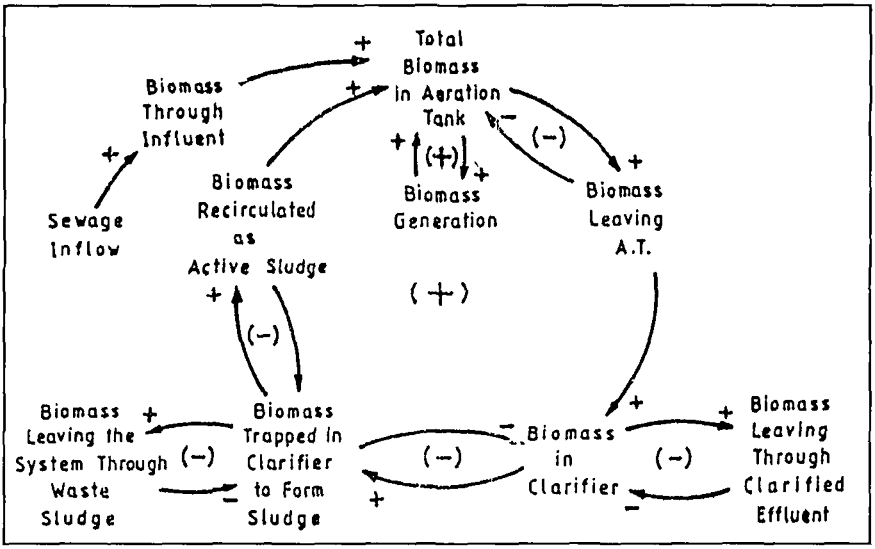

Figure 5. Causal loop diagram for biomass status in ASP.

is the product of SRR and the recirculation ratio (RR). The biomass recirculation ratio is assumed to be constant at 0.8 in the base run.

R RBRAS=SRR*RR
C RR=0.8
R SRR=BSC/TFS
C TFS=1
A BSC=BTC*PSB
C PSB=0.9

RBRAS : Rate of biomass recirculated in the activated sludge (Kg/hr)
SRR : Sludge retention rate (Kg/hr)
RR : Recirculation ratio (dimensionless)
BSC : Biomass settled in clarifier (Kg)
TFS : Time for formation of sludge (hr)
BTC : Biomass trapped in clarifier (Kg)
PSB : Percentage of settled biomass (dimensionless)

Flow of Substrate

Figure 6 depicts the flow of the substrate in the system. The substrate in the tank (SAT) is considered as a level. The rate of substrate inflow is the product of substrate concentration (ISC) and IRAT. Due to biological actions, the

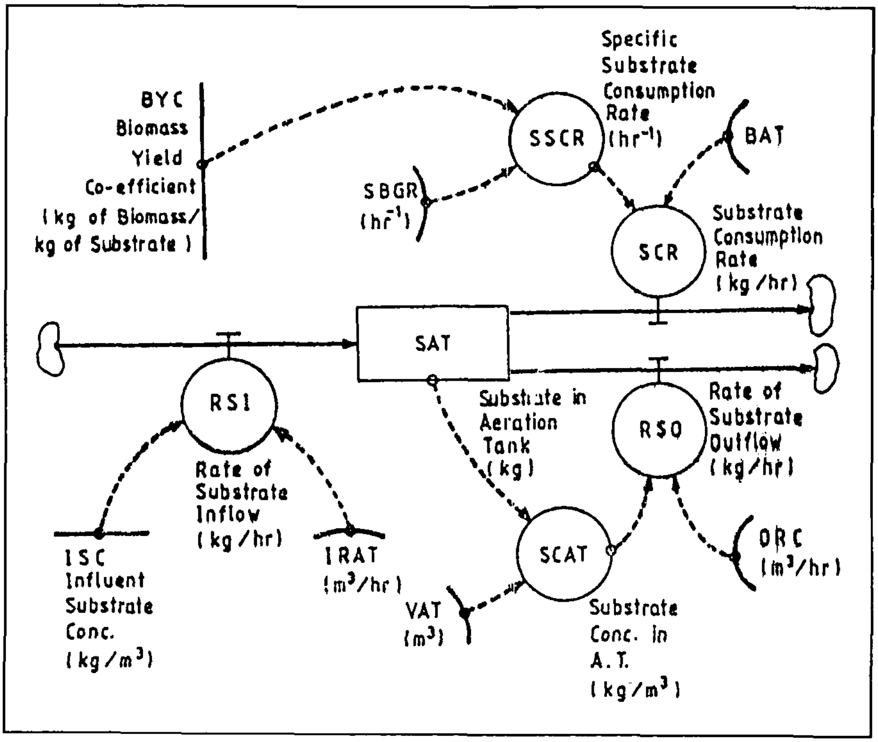

Figure 6. Flow diagram for substrate in the ASP system.

consumption of substrate in the tank (SCR) is a product of the biomass (BAT) and the specific (or unit) rate of substrate consumption (SSCR). SSCR, in turn, depends on the specific biomass growth rate (SBGR) and the biomass yield coefficient (BYC), following the Monod's law. The rate of substrate outflow (RSO) is a product of SCAT and the overflow rate from the clarifier (ORC).

```
L  SAT=SAT+DT*(RSI–SCR–RSO)
N  SAT=800
R  RSI=ISC*IRAT
C  ISC=0.25
R  RSO=SCAT*ORC
A  SCAT=SAT/VAT
R  SCR=BAT*SSCR
A  SSCR=SBGR/BYC
C  BYC=0.5
A  EFFI=(RBMCI–RBMLE) / RBMCI
```

A RBMCI=RSI+RIB

A RBMLE=RSO+RBLE

SAT : Substrate in aeration tank (Kg)
RSI : Rate substrate coming in the influent (Kg/hr)
ISC : Initial substrate concentration (Kg/M^3)
BYC : Biomass yield coefficient (Kg/Kg)
EFFI : Efficiency of the system (dimensionless)
RBMCI : Rate of biodegradable matter coming in influent (Kg/hr)
RBMLE : Rate of biodegradable matter leaving through effluent (Kg/hr)
RSO : Rate of substrate outflow (Kg/hr)
RBLE : Rate of biomass leaving through effluent (Kg/hr)

Figure 7 is the causal-loop diagram for the flow of substrate. It shows that as the inflow of sewage increases, the substrate coming with the influent increases and so the substrate accumulation in the aeration tank increases. This results in an increase of substrate concentration in the tank. Any increase of substrate concentration enhances the specific biomass growth rate and the substrate outflow through the effluent. As the specific biomass growth rate increases, the specific substrate consumption rate increases. This increases the substrate consumption rate and decreases the substrate accumulation level in the aeration tank.

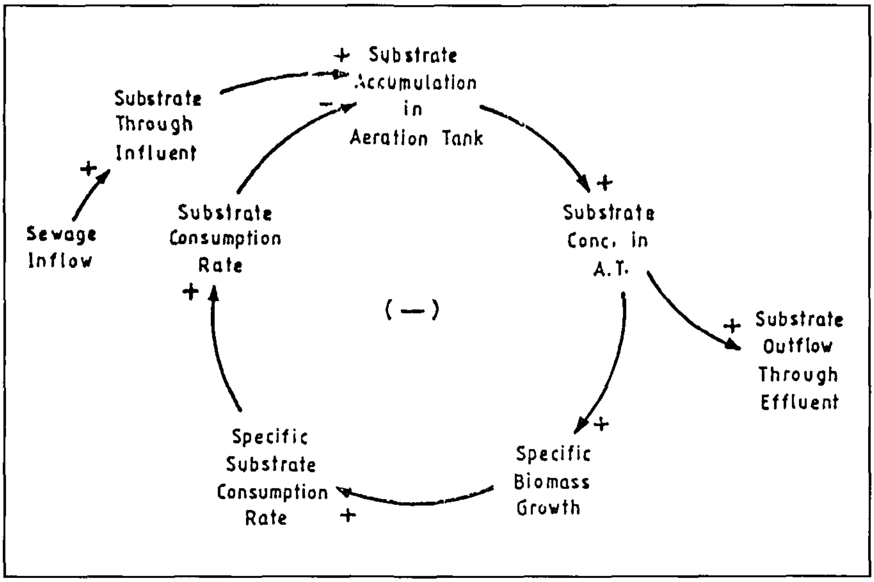

Figure 7. Causal loop diagram for substrate status in ASP.

The following assumptions are made for the base simulation run:

1. The biomass culture is unique mixture, viable and typically acclimatized with domestic sewage in aerobic environment.
2. The pollution level is measured in terms of total carbon substrates and is expressed as Kg/M^3 of COD.
3. The extended aeration method of ASP is considered for modeling, with an average hydraulic retention time as sixteen hours.
4. Initial average influent rate (IRAT) is 200 M^3/hr.
5. The volume of the aeration tank (VAT) is 3200 M^3 and is full with sewage in the initial stage.
6. The initial biomass concentration (IBC) is 0.01 Kg/M^3 as COD and the initial influent substrate concentration (IBC) is 0.25 Kg/M^3 as COD.
7. The typical saturation substrate constant (SSCC) is 0.13 Kg/M^3 as COD.
8. The typical maximum specific biomass growth rate (MSBGR) is 0.06 Kg/Kg/hr.
9. The typical biomass decay coefficient (BDC) is 0.003 per hr.
10. The dissolved oxygen is assumed to be maintained continuously at a level adequate for proper biomass growth.
11. The recirculation ratio for activated sludge is kept at a constant rate of 0.8.

The values of SSCC, MSBGR, and BDC, given in serial numbers 7 through 9 above, are taken from [27].

MODEL VALIDATION AND BASE RUN RESULTS

The model was simulated using IGRASP. Figure 8 depicts the base run results for 120 hrs (5 days). Here the inflow rate (IRAT) is assumed to be constant at 200 M^3/hr. The biomass concentration increases very slowly for the first fifteen hours, confirming the trend of the Lag-phase. It thereafter increases exponentially for the next twenty-three hours, displaying the characteristics of the well-known Log-phase. The system becomes more or less stabilized after forty hours. Since the recirculation ratio of the activated sludge was kept constant, at 0.8, irrespective of the actual food to microorganism ratio, the biomass concentration (BCAT) increases continuously and slowly, leading thereby to a gradual fall in the overall efficiency. The negative trend of the substrate concentration in the aeration tank is commensurate with the rising trend of the biomass concentration. However, the substrate concentration in the aeration tank more or less stabilizes at 0.05 Kg/M^3 of COD after forty-eight hours.

A more realistic case, however, considers the diurnal variation in the influent rate. Figure 9 shows the simulated results when the influent (IRAT) is assumed to undergo typical diurnal variations. The diurnal variation of the sewage inflow to a municipal waste water treatment plant in the United States, as reported by Metcalf and Eddy [28], is adopted here for testing the model. The trends and

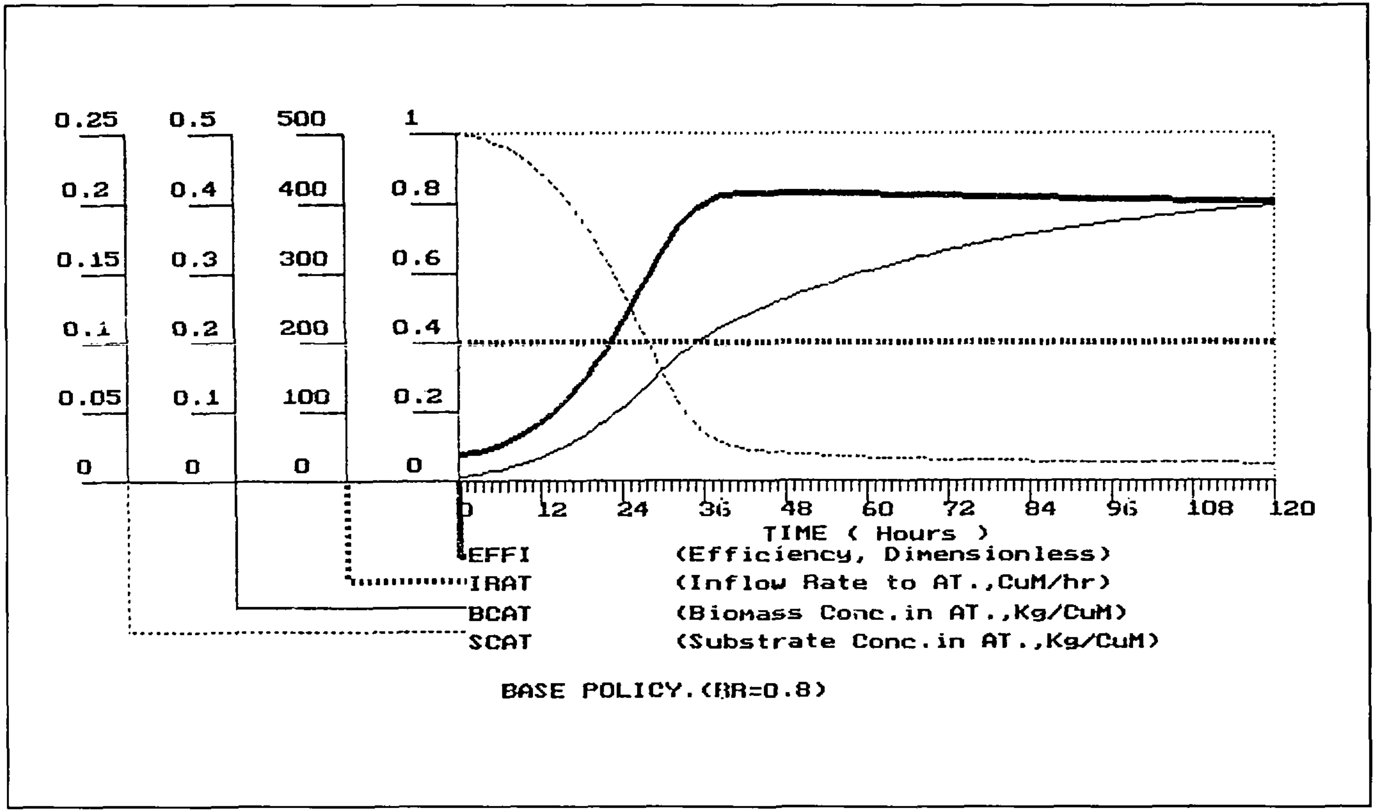

Figure 8. Average inflow rate.

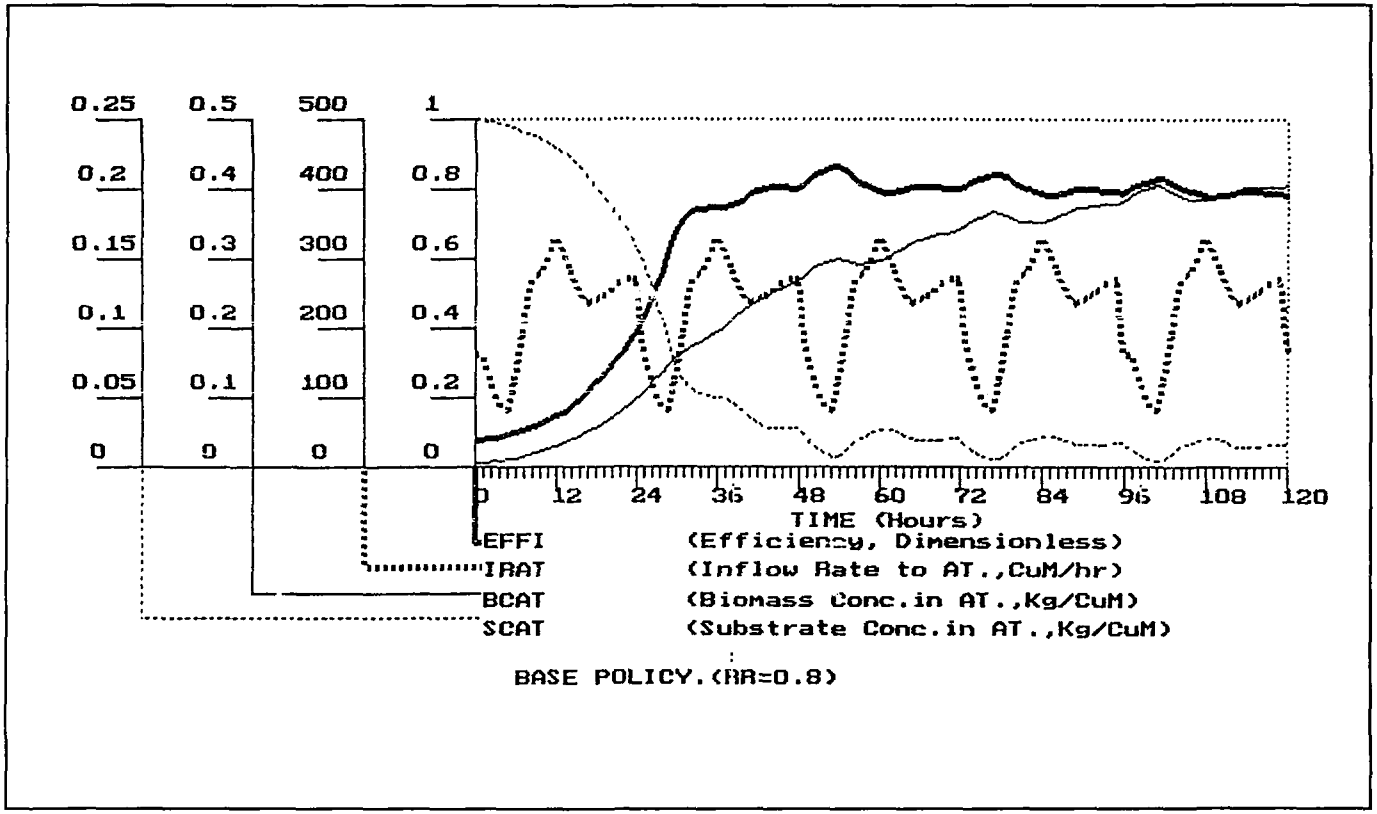

Figure 9. Diurnal variations in influent.

fluctuations of biomass concentration (BCAT), substrate concentration (SCAT), and the time to reach a zone of stable behavior (about 60 hours) match with the values that are generally experienced in practice. The viable biomass concentration (BCAT) in the tank more or less matches with other reported results [29]. The effluent substrate concentration (SCAT) stabilizes within the reported range of 0.015 Kg/M^3 to 0.035 Kg/M^3.

System dynamics model validation is a multistage process and several qualitative tests are normally forwarded for validating a system dynamics model [16]. The system dynamics model for the activated sludge plant was considered an adequate representation of the reality for the following reasons:

1. The structure (i.e., the flow and the configuration) of the system dynamics model matches with that of a real activated sludge plant.
2. Model parameters (such as MSBGR, SSCC, SSCR, etc.) have real life meaning and are measurable.
3. All the model equations are dimensionally matched.
4. The model results were plausible and matched with results observed in practice and reported in research papers.

DESIGNING ALTERNATIVE OPERATING POLICIES

The most important operating decision for an activated sludge plant concerns the recirculation of the sludge. In the base run it was assumed that a constant fraction of the sludge is always recirculated. However, it is obvious from the base model results, discussed above, that the removal efficiency displays a slow negative trend, after attaining a maximum. This happens because the policy of constant sludge recirculation leads to biomass concentration (that reflects the sludge-age or the solids retention time) that often is much higher than that sustainable by the available substrate level in the aeration tank. This is the reason the actual food-to-microorganism ratio (AFMR) is selected as the basis of designing the recirculation policy.

Testing Viable Recirculation Policy Trends

Figure 10 shows the assumed variations of the recirculation ratio versus the actual food-to-microorganism ratio. Four different recirculation strategies, designed heuristically, are considered here. We have deliberately considered strategies which are very different from each other. Policy 1 assumes the recirculation ratio to be zero, meaning that the sludge is not recirculated at all. Policy 2 assumes a linear rise of the recirculation ratio (RR) with the food-to-microorganism ratio (AFMR). No sludge is recirculated when the food in the tank is zero, and the total sludge formed in the clarifier is recirculated when the AFMR takes a value of 0.6 or more. (The value of 0.6 was chosen at first; later, simulation experiments were carried out to find out the value of AFMR which gives the

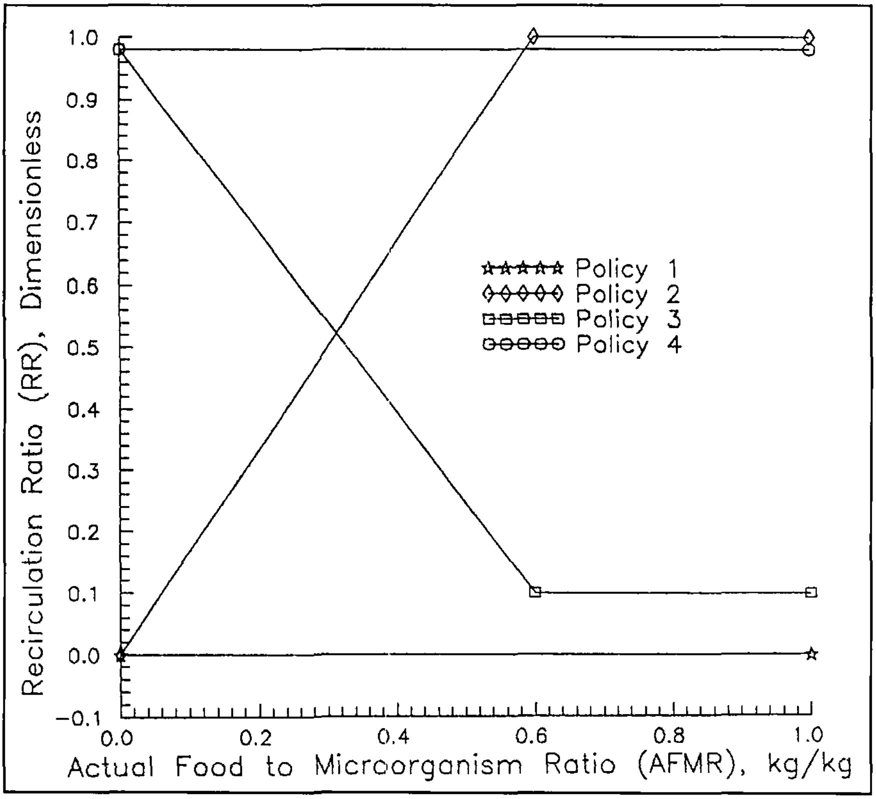

Figure 10. Heuristic design of alternative operating policies.

best result for the efficiency of the plant.) In Policy 3, RR is considered to vary inversely from 90 percent to 10 percent with AFMR from 0 to 0.6 respectively. Such a policy appears to be counterintuitive. However, it was considered because we wanted to study the performance of the plant with a wide variety of policies and to come up with the most viable policy. Policy 4 assumes that 98 percent of the sludge formed is recirculated back to the aeration tank at all times.

Figure 11 shows the co-plot of the efficiencies for these operational strategies. All the results pertain to the case of diurnal variation of the inflow rate. For Policy 1, in which the recirculation ratio is taken to be zero throughout, the efficiency, i.e., the overall pollutant removal rate, is less than 75 percent most of the time. Such a low value indicates that the recirculation of activated biomass is a necessity for improving the plant efficiency. For Policy 4, in which the recirculation ratio (RR) is constant at 98 percent, irrespective of the food-microorganism ratio in the aeration tank, the efficiency remains higher during the first sixty-five hours,

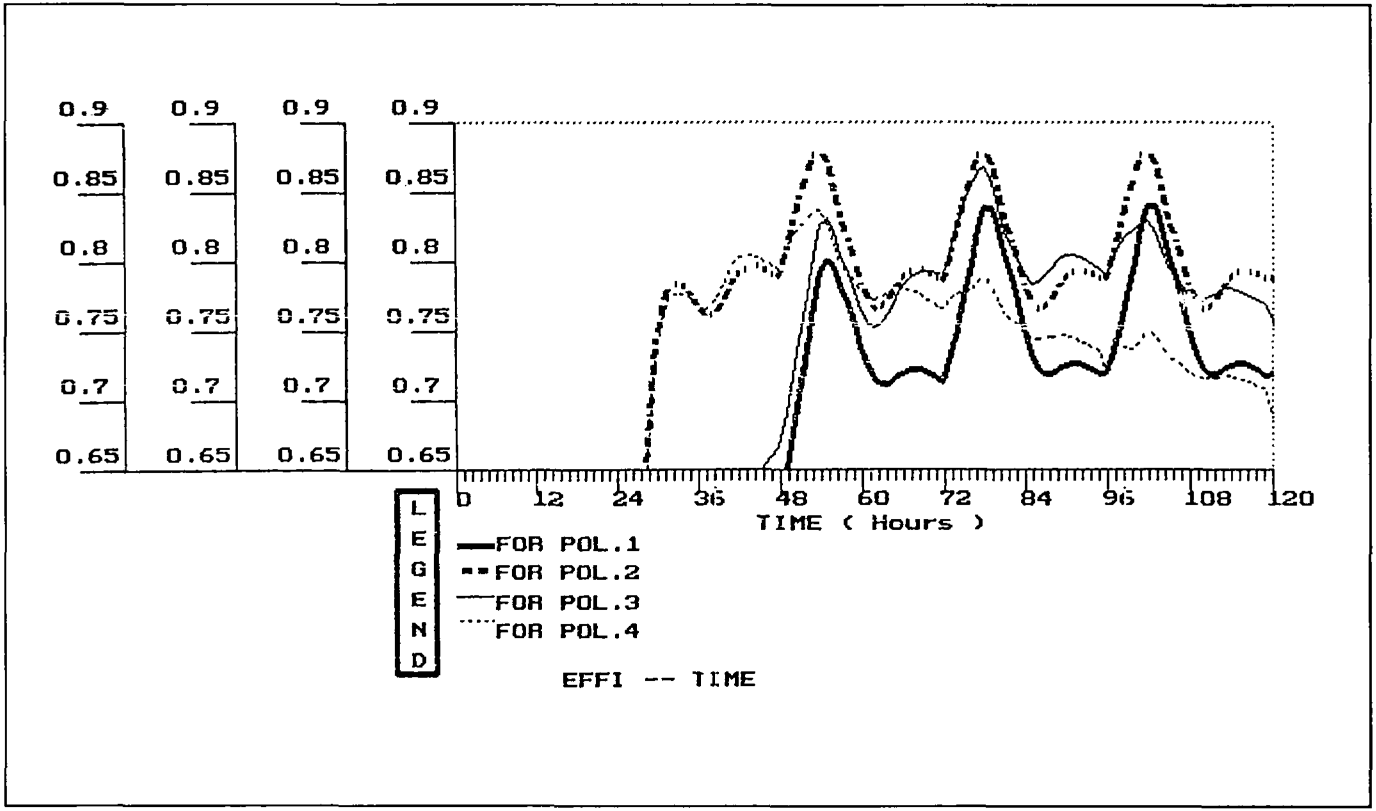

Figure 11. Co-plot for recirculation policy alternatives.

but deteriorates thereafter to values which are much lower compared to those obtained in other policies. This is due to the fact that biomass concentration in the aeration tank increases rapidly, and therefore appears in suspended condition and escapes with the effluent, thereby deteriorating its quality.

Policy 3 results in trends and fluctuations of efficiency which are interesting. Here, the efficiency makes a slow start, touching 65 percent at about forty-five hours, but thereafter rises very fast before achieving the steady state. This counterintuitive Policy 3 results in an efficiency which, as expected, is generally higher than those obtained for Policy 1 where no sludge recirculation takes place. In the first fifty hours, the efficiency obtained for Policy 3 is lower than that obtained for Policy 4 but thereafter the efficiency shows higher values compared to those for Policy 4. However, it is observed that the efficiency decreases slowly from about the seventy-fifth hour onward. This downward trend of the efficiency can be attributed to the fact that the basically illogical strategy of high amount of recirculation during the period of low food-to-microorganism ratio has led to more biomass which leaves along with the effluent, so reducing the quality and the efficiency of the plant.

The efficiency figures obtained for Policy 4 appear to be the best compared to all other policies discussed above. In this case, the efficiency rises to approach the steady state condition very early and continues to have the highest values compared to those for the other policies. Therefore, Policy 2, in which the sludge recirculation is considered to be a rising function of the food-to-microorganism ratio, seems to be well-founded. However, one needs to investigate further in order to capture the most viable range of policy actions.

Designing the Most Viable Policy Range

After selecting the viable policy trend, as above, three new policies, termed Policies 5, 6, and 7, are tried. These policies are shown in Figure 12. They have the same trend as that for Policy 2, but they have peak recirculation ratio (RR) values occurring at AFMR values of 0.3, 0.1, and 0.8 respectively. Figure 13 depicts the co-plot of efficiency for Policies 2, 5, 6, and 7. It is noticed in the figure that the maximum value of the efficiency occurs for Policy 5. But Policy 5 also displays a very low efficiency during the troughs of the oscillation. However, during that period Policy 6 shows the highest efficiency. Thus it may be inferred that the most viable recirculation strategy should have a trend that lies within those for Policy 5 and 6.

In an effort to further narrow the range to the most viable recirculation policy, three more policies, termed Policies 8, 9, and 10, are tried. They are shown in Figure 14. They have the same trend as that of Policy 5, but they have peak recirculation ratio (RR) values occurring at AFMR values of 0.2, 0.25, and 0.275, respectively.

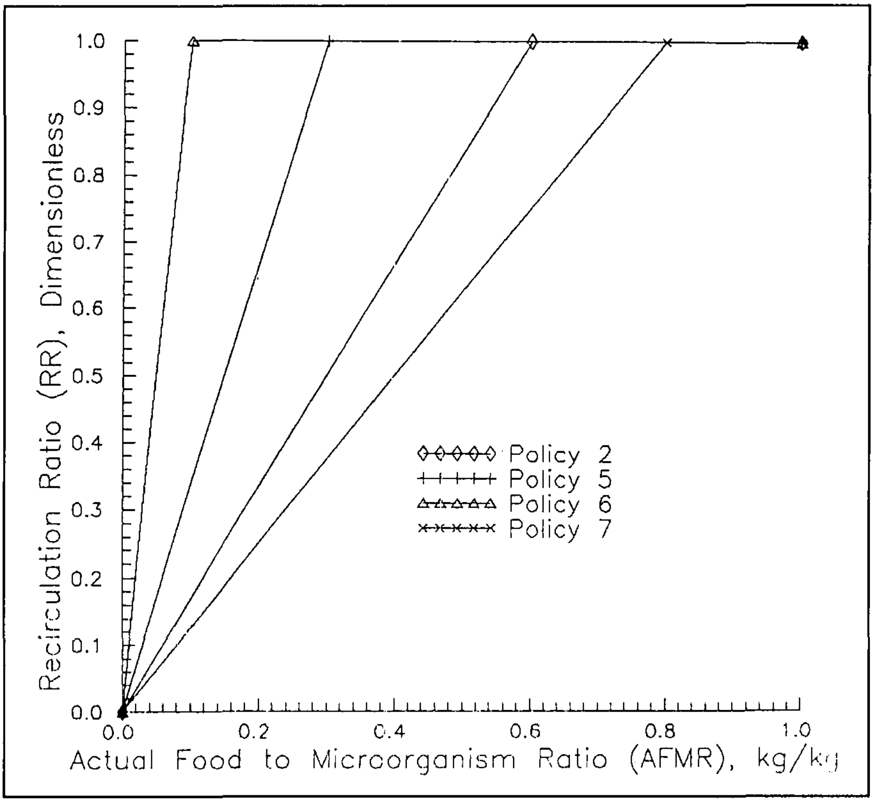

Figure 12. Heuristic design of alternative operating policies.

Figure 15 shows the co-plot of efficiency for Policies 5, 8, 9, and 10. It is seen from the figure that maximum value of efficiency occurs for Policy 8. Policy 8 thus proves to be the most viable one. For Policy 8 the recirculation ratio reaches the maximum when the food-to-microorganism ratio reaches 0.2. This suggests that the desired food-to-microorganism ratio lies in the range of 0.2 to 0.3, which has also been suggested by Arceivala [1].

Sensitivity Analysis of the Most Viable Recirculation Policy

The best recirculation policy having been found, it is desirable to carry out a sensitivity analysis for it. The sensitivity of this policy to changes in the influent substrate concentration and in the volume of the aeration tank are reported below.

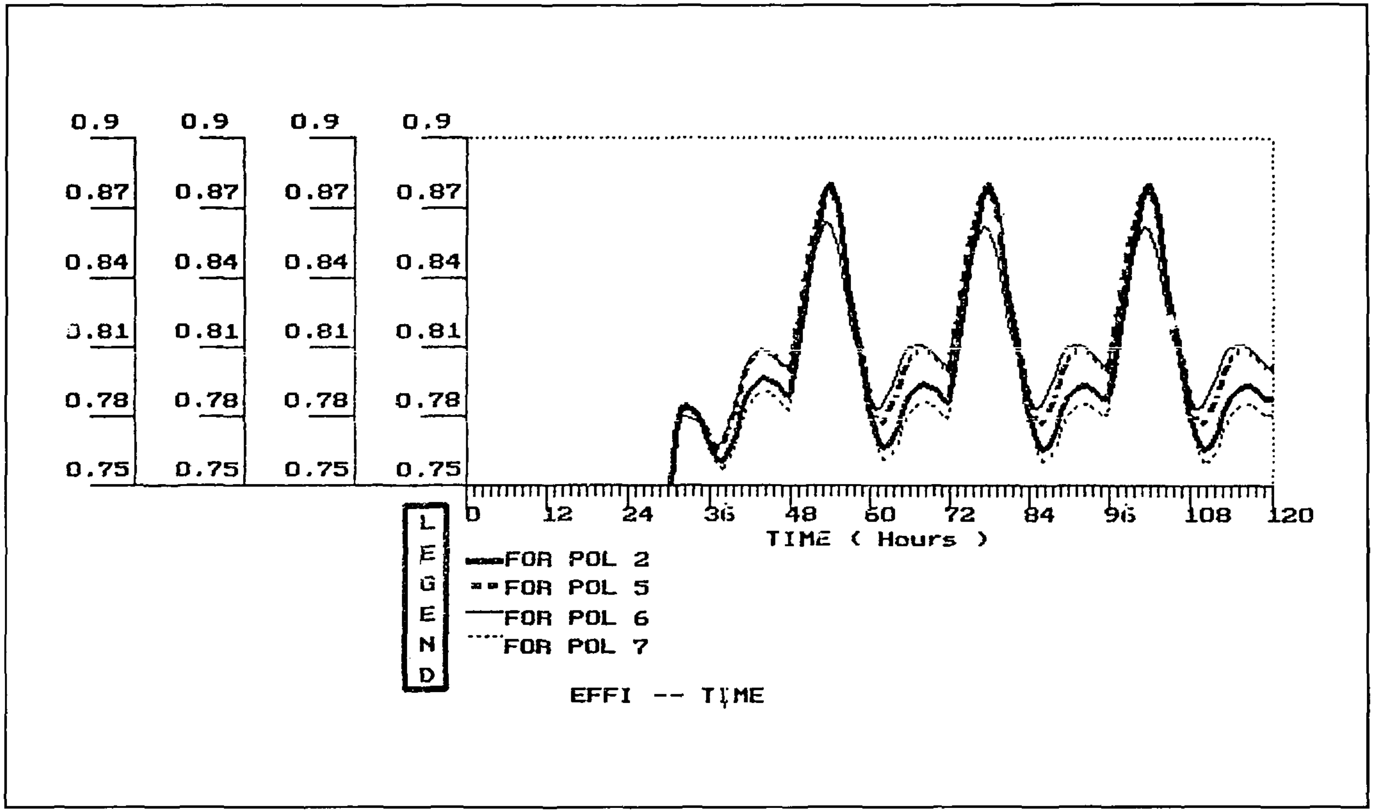

Figure 13. Co-plot for sensitivity testing on optimal trend policy.

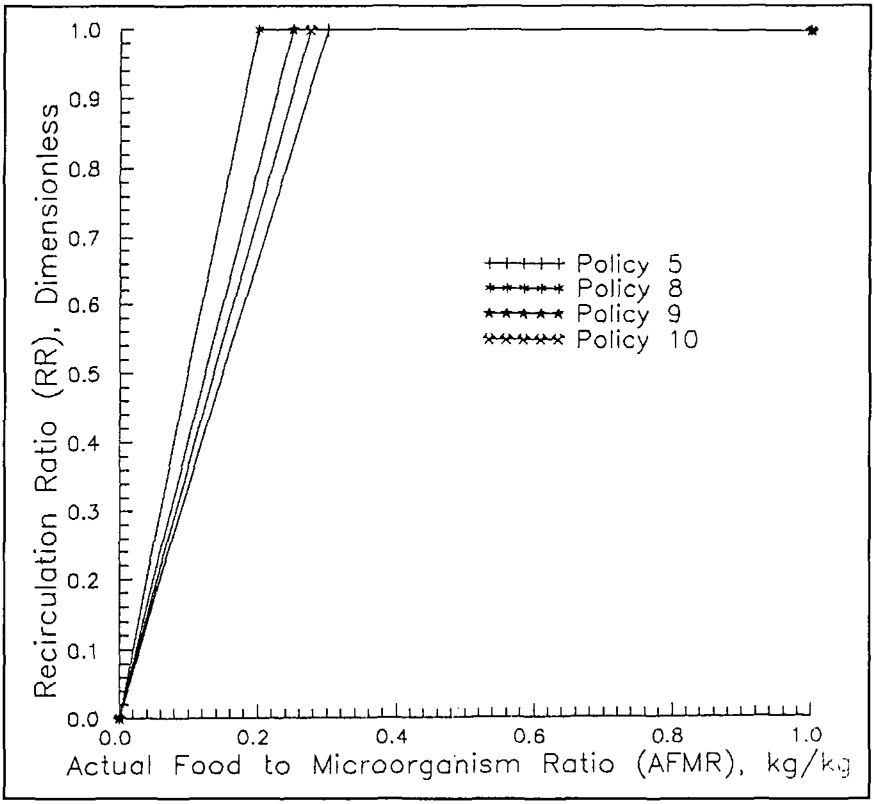

Figure 14. Design of most viable policy range.

Figure 16 shows the effect of variation on influent substrate concentration (ISC) on the substrate concentration in the tank. It shows that as the rate of substrate in the influent increases, the fluctuations in the substrate concentration in aeration tank (SCAT) increase. The fluctuation is the least for ISC = 0.2. For this case the peak of the fluctuation is within the permissible limit of 0.03 Kg/M^3. This justifies the adequacy of the recirculation policy for the hydraulic design configuration discussed above, because it can safely handle the influent pollution concentration level up to 0.2 Kg/M^3.

Figure 17 shows the effect of variations of volume of aeration tank (VAT) on substrate concentration in the aeration tank. It is seen that as volume decreases, the substrate concentration increases, and, therefore, the efficiency decreases in the peak periods. This is because, as the volume of the tank decreases, the hydraulic retention time decreases, and, hence, the net biomass growth and the substrate removal rate are reduced. Thus, for a known diurnal variation of inflow

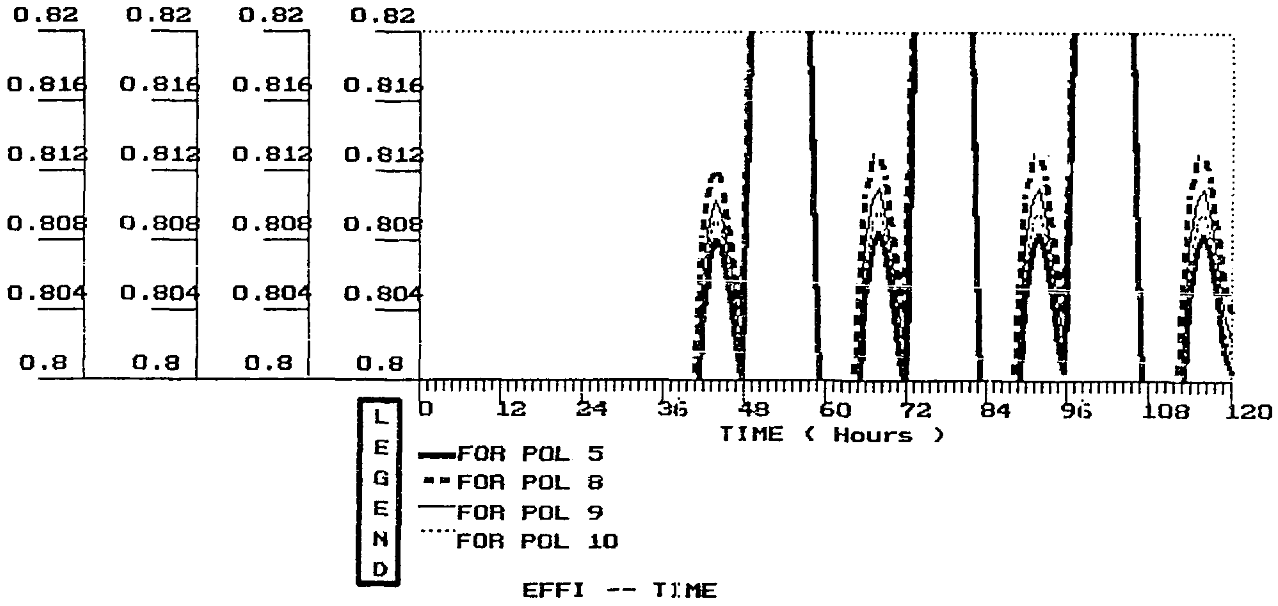

Figure 15. Co-plot for sensitivity testing of best policy.

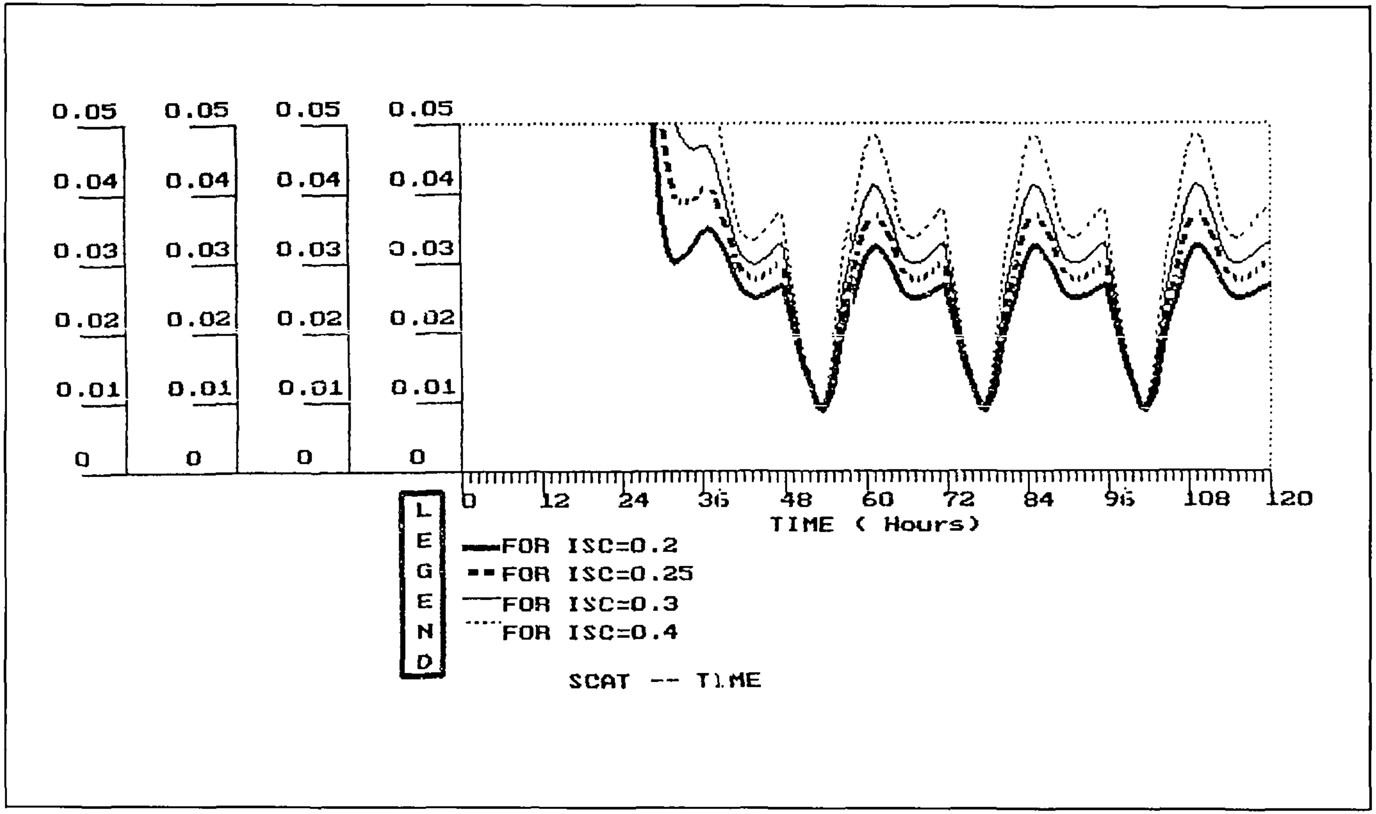

Figure 16. Co-plot of substrate concentration in AT for various ISC.

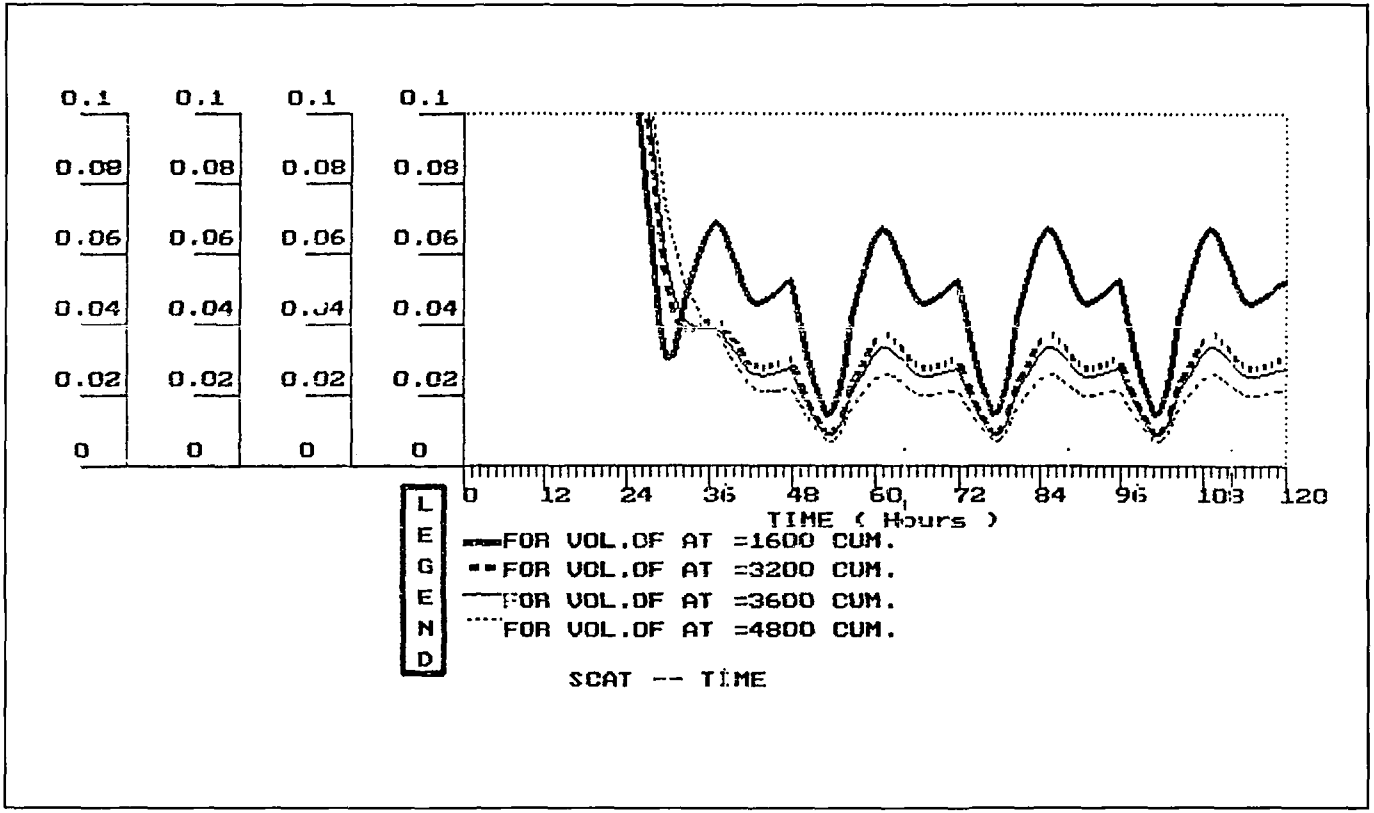

Figure 17. Co-plot for determining optimum volume of AT.

rate and known pollution level, the hydraulic design of the treatment plant component can be decided. For this case, a volume of aeration tank equal to 3600 M^3 (i.e., average hydraulic retention time of 18 hours) appears to be the most suitable size, since, for this case, the maximum substrate concentration level remains within the permissible limit of discharge (0.03 Kg/M^3) to the water bodies.

CONCLUSIONS

A number of research studies have been made on biomass growth, in particular reference to use in waste water treatment. These studies, however, are by and large directed toward identifying relationships at the component level. One therefore finds it difficult to conceptualize the problem in an integrated manner and to estimate the likely changes in the performance of the system due to variations of parameter and/or the control policies. System dynamics modeling of waste water treatment through activated sludge process has helped in the following ways:

1. It has helped in forecasting the treatment efficiencies in varying conditions.
2. It has helped in conceptualizing, at an aggregate level, the individual cause-and-effect relationships and their effect on the performance of the treatment system under varying input and plant design changes.
3. The model has helped in arriving at viable recirculation policies.

Certain other uses of the model are the following:

1. The model can help environmental managers predict the least allowable period during which they can allow additional institutional or industrial pollution loads to enter the municipal system with existing treatment facilities.
2. The model can help authorities of environmental statutory bodies make a realistic assessment of the performance of pollution treatment facilities.
3. The model can help even in the design stage, in setting the capacities of the treatment plant components.

Admittedly, the assumptions made in the model are too simplistic to be very realistic. For example, the model has not considered the presence of non- or slowly-biodegradable matter in the influent, the absence of other nutrients that affect the growth of the biomass, the presence of other organisms that display complex relationships with the biomass, and the effect of such environmental factors as temperature, alkalinity, dissolved oxygen content. We, however, feel that the model presented in this article is a beginning. Efforts are underway to extend the model to include such considerations.

REFERENCES

1. S. J. Arceivala, *Wastewater Treatment and Disposal: Engineering and Ecology in Pollution Control,* Marcel Dekker, Inc., New York, 1981.
2. C. P. L. Grady, Jr. and H. C. Lim, *Biological Wastewater Treatment: Theory and Applications,* Marcel Dekker, Inc., New York, 1980.
3. R. M. Sykes, Microbial Product Formation and Variable Yield, *Journal of Water Pollution Control Federation, 48,* pp. 2046-2054, 1976.
4. P. Krishnan and A. F Gaudy, Response of Activated Sludge to Quantitative Shock Loading, *Journal of Water Pollution Control Federation, 48,* pp. 906-919, 1976.
5. J. D. Boyle, Biological Treatment Process in Cold Climates, *Water and Sewage Works, 123,* p. R-28, 1976.
6. J. H. Sherrard and L. D. Benefield, Elemental Distribution Diagrams for Biological Wastewater Treatment, *Journal of Water Pollution Control Federation, 48,* pp. 562-578, 1976.
7. A. A. Kalinske, Comparison of Air and Oxygen Activated Sludge Systems, *Journal of Water Pollution Control Federation, 48,* pp. 2472-2485, 1976.
8. R. Kormanik, How Does Tank Geometry Affect the Oxygen Transfer Rate of Mechanical Surface Aerators? *Water and Sewage Works, 123*:1, pp. 64-76, 1976.
9. Y. C. Wu, Role of Nitrogen in Activated Sludge Process, *Journal of Environmental Engineering Division, American Society of Civil Engineers, 102,* pp. 887-894, 1976.
10. J. M. Krul, The Relationship between Dissimilatory Nitrate Reduction and Oxygen Uptake by Cells of an *Alcaligenens* Strain in Flocs and in Suspension and by Activated Sludge Flocs, *Water Research (G.B.), 10,* p. 337, 1976.
11. A. C. Middleton and A. W. Lawrence, Least Cost Design of Activated Sludge Systems, *Journal of Water Pollution Control Federation, 48,* pp. 889-905, 1976.
12. D. G. Christoulas and T. H. Y. Tebbutt, Mathematical Model of a Complete-Mix Activated-Sludge Plant, *Water Research (G.B.), 10,* pp. 797-812, 1976.
13. C. Tang, E. Downey-Brill, and J. T. Pfeffer, Comprehensive Model of Activated Sludge Waste Water Treatment System, *Journal of Environmental Engineering Division, American Society of Civil Engineers, 113*:5, pp. 952-969, 1987.
14. C. P. L. Grady, Jr., W. Gujer, M. Henze, G.v.R. Marais, and T. Matsus, A Model for Single Sludge Waste Water, *Journal of Water Science & Technology, IAWPRC, 18*:6, pp. 47-62, 1986.
15. P. L. Dold and G.v.R. Marais, Evaluation of General Activated Sludge Model Proposed by the IAWPRC Task Group, *Journal of Water Science & Technology, IAWPRC, 18*:6, pp. 63-90, 1986.
16. P. K. J. Mohapatra, P. Mandal, and M. C. Bora, *Introduction to System Dynamics Modeling,* Orient Longman Ltd., Hyderabad, India, 1994.
17. J. W. Forrester, *World Dynamics,* The Productivity Press, Cambridge, 1971.
18. D. L. Meadows and D. H. Meadows (eds.), *Toward Global Equilibrium: Collected Papers,* Wright-Allen Press, Inc., Massachusetts, 1973.
19. K. Vizayakumar and P. K. J. Mohapatra, Environmental Impact Analysis of a Coalfield, *Journal of Environmental Management, 34,* pp. 73-93, 1991.
20. K. Vizayakumar and P. K. J. Mohapatra, Modelling and Simulation of Environmental Impacts of a Coalfield: System Dynamics Approach, *Journal of Environmental Systems, 22*:1, pp. 59-73, 1993.

21. R. F. Naill, S. Belanger, A. Klinger, and E. Petersen, An Analysis of Cost Effectiveness of U.S. Energy Policies to Mitigate Global Warming, *System Dynamics Review, 8*:2, pp. 111-118, 1992.
22. A. N. Mashayekhi, Transition in New York State Solid Waste System: A Dynamic Analysis, *System Dynamics Review, 9*:1, pp. 23-48, 1993.
23. B. Clemson, Y. Tang, J. Pyne, and R. Unal, Efficient Methods of Sensitivity Analysis, *System Dynamics Review, 11*:1, pp. 31-49, 1995.
24. S. Banerjee, M. Juneja, and P. K. J. Mohapatra, IGRASP—A System Dynamics Software Package with Automatic Code Generation Facility, *Proceedings of the 1995 International System Dynamics Conference, Tokyo, Japan, 2,* pp. 356-365, 1995.
25. J. Monod, The Growth of Bacterial Cultures, *Annual Review of Microbiology, 1*:3, pp. 371-394, 1949.
26. N. Westberg, A Study of Activated Sludge Process as a Bacterial Growth Process, *Water Research, 1,* pp. 795-804, 1967.
27. M. D. Mynhier and C. P. L. Grady, Design Graphs for Activated Sludge Process, *Journal of Environmental Engineering Division, American Society of Civil Engineers, 101*:4, pp. 829-846, 1975.
28. Metcalf & Eddy, Inc. and G. Tchobanglous, *Waste Water Engineering: Treatment, Disposal, Reuse,* McGraw-Hill, Inc., New Delhi, 1990.
29. C. L. Weddle and D. Jenkins, The Viability and Activity of Activated Sludge, *Water Research, 5,* pp. 621-640, 1971.

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