# Chapter I

## Introduction

The process of wastewater handling and its disposal has been a major concern for sustainable development in relation to human settlements and their allied industrial activities. Biological processes employed for municipal wastewater treatment involve extremely complex microbial interactions that determine the effluent concentrations of individual pollutants.

Bio-degradation of natural and synthesized organic pollutants that takes place with the help of microorganisms has proved to be cost-effective and environmentally viable. Activated sludge treatment system is one type of sewage/effluent treatment plant, which employs the principles of biological processes to convert soluble organic compounds into carbon dioxide, water and microorganism (i.e. bacteria cell).

Since its inception during 1914 by Adern and Lockett (Arceivala, 1981), the process of Activated Sludge Treatment System has undergone a lot of systematic improvements. Today it is the most widely and popularly employed technique for wastewater Treatment.

Drawing from years of practical experience of the author as a Public Health Engineer in designing and operating a municipal waste water treatment plant, experiments on a laboratory scale model, and from information and knowledge from a rich source of literature, this thesis attempts to synthesize various theories of biological municipal wastewater treatment system (Activated Sludge Plant) in the framework of a system dynamics model. The model is then simulated to arrive at viable operating control policies in order to achieve acceptable effluent quality and minimize energy expense.

## 1.1 Principles Underlying the Activated Sludge Treatment System

Figure 1.1 is a schematic diagram of the extended aeration version of the activated sludge treatment system. In general, the influent stream of municipal wastewater, rich in soluble organic compounds (known as substrate or food for the bacteria), enters the reactor (known as Aeration Tank). As the name depicts, the aeration or the supply of air and oxygen is done by mechanical means so as to create an engineered environment for the growth and promotion of the bio-chemical activities of the bacteria in this tank. Here the bacteria culture consumes the substrate through the cell-wall diffusion mechanism (Grady and Lim, 1980; Gaudy and Gaudy, 1984) and grows in size and number on getting a conducive environment.

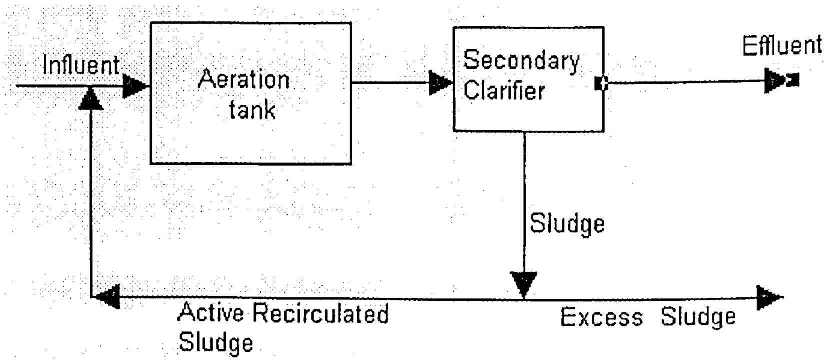

**Figure 1.1 Schematic Diagram of Activated Sludge Treatment System.**

Since the bacteria are not mobile in nature, the churning action of mechanical aerator in this continuously stirred tank reactor (CSTR) helps in bringing the substrate concentration close to bacteria or biomass (McKinney, 1958). Thereafter, the sewage stream loaded with biomass goes out of the aeration tank and reaches the clarifier. The clarifier allows the biomass to flocculate (or coalesce) and settle down due to gravity, as sludge. The sludge, so collected, contains live (or active) biomass. It is re-circulated in a controlled manner to the aeration tank, so as to maintain the biomass concentration or bacteria population at a desired level. Thus, the residence period for the biomass culture in this reactor system increases to the desired level. The excess sludge, which is not re-circulated, is withdrawn and put to sludge drying beds for future use as manures. The clarified supernatant stream goes out of the system as treated effluent. Thus the system operates continuously and removes the soluble organic pollutants efficiently and economically.

To sum up, the essence of the principle underlying the activated sludge process is that the biomass, through its enzymatic actions, consumes the substrate in the presence of oxygen environment and multiplies so as to form a flocculent and insoluble mass. This mass separates from the system stream and settles down in the clarifier.

Employing this broad principle, a number of process modifications have been developed and engineered. They are as under:

(i) Step Aeration arrangement,
(ii) Tappered Aeration arrangement,
(iii) Contact Stabilization arrangement,
(iv) Extended Aeration arrangement, and
(v) Nitrification De-nitrification arrangement,

The most popular and typical is the Extended Aeration process, where, as the name depicts, the aeration is extended above the normal/conventional period.

## 1.2 Scope of Model Development

Modeling is an inherent part of design and monitoring of a wastewater treatment system. During the last four decades, many researchers have worked on several aspects of the following components of this complex biological treatment system:

- System biology
- System kinetics
- Reactor engineering

Systems biology embraces chemical, genetic and ecological or adaptive processes of the natural microorganisms that are cultured in an engineered way. The enzymatic actions and metabolic abilities of the biomass have already been identified and described in the published literature (e.g. Grady and Lim, 1980; Gaudy and Gaudy, 1984).

Similarly, parameters related to system kinetics of a biomass-substrate system, such as specific growth rate, specific decay rate, and substrate utilization rate, have already been individually examined, mostly in laboratory scale experiments, and a few in prototype experiments (e.g., Grady and Lim, 1980; Arceivala, 1981).

Reactor engineering encompasses the scope of configuration, shape, and dimensioning of individual biological reactors, considering their hydraulic and mechanical aspects (Grady and Lim, 1980; Arceivala, 1981). The interrelations of all these three important considerations are essential for proper functional design and development of operational strategies of any wastewater treatment system.

In addition to models developed at the component level of an activated sludge treatment system, several attempts have been made in the past to develop comprehensive mathematical models based on pragmatic and fundamental models (Jones, 1997). The Comprehensive model (Tang, *et al.*,1988), the International Association of Water Pollution, Research and Control (IAWPRC) model (Henze, *et al.*, 1986), and the model of

Dold *et al.* (1980) are a few notable developments in this direction. This thesis extends the boundary of comprehensive mathematical models to include the system dynamics paradigm for designing control strategies for activated sludge plant.

## 1.3 Objectives

The objectives of this thesis are to

1. Develop a comprehensive dynamic model of activated sludge treatment system by integrating the prevailing fragmented knowledge of its components and design viable strategies for controlling effluent quality to acceptable limits.

2. Develop and experiment with a laboratory-scale model so as to obtain pollution removal efficiencies at varied influent conditions and to examine the significance of input factors.

3. Reflect on the cause-effect relationships among individual components of the dynamic model, so that a user can simulate the model incorporating the location- specific kinetic and stoichiometric parameters of the wastewater, and decide the operational strategies for controlling the output quality failures.

4. Identify the control variables and determine their significance with reference to explaining the variation of the response variables.

5. Experiment the following control strategies so as to control the exceedences over the permissible output quality:

   (a) Open-loop control

      1. Constant control [Recirculation ratio and Aerators-in-use held constant]
      2. Time varying control [Recirculation ratio and Aerators-in-use held

constant during a season and varied across seasons]

(b) Closed-loop control

1. Output-feedback Control [output: Effluent quality]
2. Output-integrated feedback control (output: Effluent quality).

## 1.4 Scope of the Work

The work presented here makes the following general assumptions:

1. The extended aeration version of the activated sludge process has been adopted for modeling.
2. Modular surface aerators are adopted for this treatment system.
3. Only carbonaceous, biodegradable, soluble pollutional load has been considered as the substrate in the treatment system.
4. Other nutrients, such as nitrogen, phosphorus and other micronutrients, are assumed to be available in more than the deficiency level in a soluble form in the substrate.
5. Inhibition to biomass growth due to any type of toxicity has been kept beyond the scope of this investigation.
6. The biomass culture is a viable, floc-forming mixture and is typically acclimatized with domestic sewage in aerobic environment.
7. The pollution load (substrate) is measured in its equivalence of oxygen requirement, i.e. Chemical Oxygen Demand (COD), and expressed as kilogram of COD per cubic meter of the liquid (kg of COD/m$^3$).
8. The biomass or the suspended solids is measured in terms of its weight and expressed as kilogram (kg) of biomass.
9. The hydraulic regime of the aeration tank, as usual, has been adopted to be a single continuously stirred tank reactor (completely mixed system).

## 1.5. System Dynamics - the Principal Methodology for the Study

In this investigation, the system dynamics approach is used to develop a dynamic model for the activated sludge treatment system. The following points are given to justify the choice of this modeling approach.

1. System dynamics models explicitly consider flow of physical entities. This is analogous to flow of liquid. The activated sludge treatment system physically matches with the concept of such flows, representing the sewage flow and the re-circulation of activated sludge with that of physical feedback.

2. System dynamics models work on the principle of continuous time simulation, as apposed to discrete-event simulation. In the activated sludge treatment system, the flow of liquid, growth of bacteria or biomass, and re-circulation of sludge take place in a continuous manner.

3. Feedback is a central concept in system dynamics models. Therefore, the macro-feedbacks involving sludge re-circulation, and micro-feedbacks involving growth or decay of bacteria, as a function of amount of nutrient and oxygen, are easily modeled and visualized in a system dynamics framework.

4. System dynamics is well-known for the ease with which one can construct and combine micro-structures to generate macro-behavior. Bacterial action and oxygen infusion involve micro-structures which can be included in a system dynamics model to show how they influence quality of the flow or degree of treatment of the sewage.

5. System dynamics is a potent methodology to synthesize knowledge in fragmental, elemental subsystems to generate behavior of the whole system. The literature of activated sludge treatment system is replete with in-depth studies related to individual components (micro-structures) of the activated sludge treatment system. System

components (micro-structures) of the activated sludge treatment system. System dynamics can combine knowledge in these fragmental component systems to generate systemic behavior.

6. Analyzing existing policies and determining new policies are two significant contributions of the system dynamics approach. System dynamics can play a very useful role in designing the operational strategies for activated sludge treatment system, a function that has not received its due share of importance in the research approaches of activated sludge treatment system.

## 1.6 Chapter-wise Summary

This thesis is organized into nine chapters. A brief chapter-wise summary follows.

### Chapter - I

This chapter introduces the thesis, discusses the principles underlying an activated sludge treatment system, and presents the scope of model development, defines the objectives of the thesis, gives a defense of the choice of system dynamics as the principal methodology for the study.

### Chapter – II

It presents a literature review conducted by the author. The review is organized according to (a) principal features of activated sludge plant, (b) modeling practices in the activated sludge process, and (c) system dynamics applications to environmental issues.

During the literature review, it is noticed that but for Anderson *et al.* (2000) who developed a simulation mode of a comprehensive model of activated sludge Anderson, none has presented any control strategy for the output exceedences. Anderson, *et al.* have considered the aerobic-anoxic activated sludge systems with control variables as recirculation ratios between aerobic suspension and anoxic suspension and between activated sludge and aerobic suspension.

## Chapter-III

This chapter describes the development of a laboratory-scale model of the extended aeration version of activated sludge treatment system. The model consisting of a 37-liter capacity aeration tank with requisite surface aeration and secondary clarification arrangements, was commissioned and continuously operated round-the-clock for more than six months on the designed synthetic feed with acclimatized sludge seed under aerobic environment.

After the steady state conditions were achieved, experimental results were noted for four different strengths of influent concentrations under three different influent flow rates. Besides, the dissolved oxygen content, ammonia-nitrogen content, and nitrate-nitrogen content were periodically monitored, so as to ensure that they were above the deficiency level for avoiding any stressed condition.

An analysis of variance (ANOVA) has been conducted on the experimental results for examining the significance of the input variables (inflow rate and influent substrate concentrations) on the variations in effluent quality. The influent flow rate is seen to have more dominating significance than the influent substrate concentration.

## Chapter-IV

This chapter describes the development of a system dynamics model, [Flow of Liquid, Flow of Biomass, and Flow of Substrate or Pollutant] for activated sludge treatment system. Causal loop diagrams and flow diagrams are drawn to develop the model and understand its behavior. The model is developed and simulated with the help of POWERSIM software package (1996).

Model verification is done by considering the real life equivalents of model structure model variables, and model parameters and by checking the dimensional consistency each model equation. The model is validated by conducting a sensitivity analysis and a thorough and careful analysis of model behavior.

The model behavior is found to be generally insensitive to changes in a number variable values. However, it is sensitive to two major input variables: 'Inflow rate aeration tank' and 'Influent substrate concentration'. Besides the above, simulatio experiments are conducted for the laboratory conditions and the results obtained thereo are found comparable to the experimental results.

To represent a real-life situation more fully, the model is enriched by adopting a typica diurnal variation in the inflow rate and by including random variations in the influen substrate concentration.

## Chapter-V

This chapter discusses the intuitive design of a recirculation policy. Four differen recirculation policies are tected. The policy that allows the recirculation ratio to rise with a rise in food-to-microorganism ratio results in the most acceptable effluent quality values.

Additional experiments are conducted to determine the optimal food-to-microorganism ratio for the best mean efficient quality. For the policy, adjudged the best, the peak recirculation ratio values are adopted at the designed food-to-microorganism ratio values of 0.3, 0.1, and 0.8. The minimum value of food-to-microorganism ratio is found to lie within a range of 0.25 - 0.3, a value that matches with that reported in the literature.

## Chapter-VI

This chapter discusses an extended system dynamics model that incorporates the dissolved oxygen stressed condition. A surface aerator system is considered in this model. The temperature-dependent oxygen-assimilative capacity and aerator-specific oxygen-transforming ability are considered. Aerator-specific 'Alpha factor' and wastewater-specific 'Beta factor', and a multiplier indicating oxygen requirement for biomass growth are introduced into the biomass sector.

Simulation experiments are conducted for four different values of aerators-in-use. The response variable is the 'Average Effluent Quality'. It is concluded that beyond an aerator capacity of 100 hp, the improvement in average effluent quality is not commensurate with the addition in capacity, for the defined set of influent characteristics.

## Chapter-VII

In this chapter, design of simulation experiments is conducted under $2^2$ and $3^2$ factorial designs in order to identify the significance of the effects of various policies on the effluent quality. 'Average Effluent Quality' is selected as the response variable. 'Aerator Capacity' and 'Sludge Recirculation Ratio' are chosen as the factors. An experiment for each factor combination is conducted for four replicates. Replicates are generated by introducing variations in seed values in normally distributed random noises. Noises are introduced in four variables to reflect real-life stochasticity.

It is concluded from the $2^2$-factorial analysis that both the factors and their interaction significantly affect the effluent quality. A regression model, constructed for the purpose, describes the variations in effluent quality. The residuals are computed and checked to follow the normal distribution. It is inferred from the $3^2$-factorial analysis that the interaction effect on response variable was present. It is inferred that the optimal conditions for achieving desired level of effluent quality are obtained for recirculation ratio equal to 0.65 and aerators-in-use equal to 100 hp.

## Chapter VIII

This chapter presents results and discussion pertaining to simulation experiments carried out for operational strategies for (1) controlling the exceedences of the effluent quality beyond the permissible output quality and (2) minimizing the aerator energy consumption. The exceedence of the effluent quality is judged by the mean and the standard deviation of the effluent quality in the steady-state period.

### I. Open-loop Control

(a) **Constant Control**: Here the two control variables (aerators-in-use and sludge recirculation ratio) are held constant during the entire simulation run of the extended model. The following values are assumed for the two control variables:

Aerators-in-Use : 50 hp, 75 hp, and 100 hp.
Sludge recirculation ratio : 0.1, 0.5, 0.65, and 0.8.

Further, these factor combinations are also taken for the winter and the summer seasons for which different diurnal temperature variations are assumed.

A summary of the results of the simulation experiments along with the mean and the standard deviation of effluent quality during the period 100-200 hours (neglecting the initial transient period between 0-100 hours) is presented in this chapter. Considering the values of all the figures of merit, it is observed that the sludge recirculation ratio of 0.65 with 100 hp aerators-in-use gives the best results for both the seasons.

### (b) Time-Varying Control

Having known the best sludge recirculation ratio as 0.65, a time-varying control strategy for aerators-in-use is now used to restrict the effluent quality within acceptable limits. These strategies take cognizance of diurnal temperature variations and inflow rate variations. The results are indicative of very acceptable effluent quality values associated with reduced aerator energy consumption.

## II. Feedback Control

### (a) Output feedback Control

Considering that the average effluent quality is 0.03 kg/m$^3$ and the standard deviation is 0.005 kg/m$^3$, a feedback strategy is adopted here. The strategy allows increasing aerators-in-use whenever effluent quality deteriorates and decreasing it whenever the quality improves, The aerators-in-use vary in a modular fashion, in a step of 25hp and remain within the range of 25-100 hp. The effluents are sampled every fourth hour to measure its quality and actuate the control. The strategy of feedback control gives quite acceptable results in terms of mean and standard deviation of the effluent quality and the energy expended in aerators.

### (b) Output-Integrated Feedback Control

The deviations of average effluent quality from its target value are accumulated over time in order to implement this category of feedback control. On-line and off-line computations are made to implement this strategy. Plotting of cumulative sum of deviations at regular intervals and using a V-mask to detect out-of-control points are done manually (off-line). The results, however, do not indicate very encouraging results or for as effluent quality or aerator energy are considered.

This chapter ends with a comparison of results for various strategies. The comparison indicates that the strategy of closed-loop control with output feedback gives the best result for both the season.

## Chapter IX

This chapter summarizes the results, discusses their practical utility and indicates scope for future research.

## 1.7 Novel Features of the Thesis

In the attempt to study the activated sludge treatment system, this thesis

1. Combines the results of laboratory experiments, results of studies made by numerous researchers, and simple logic used by practitioners in the field.
2. Uses the system dynamics framework to develop a comprehensive model for testing and designing viable strategies for sludge recirculation and aeration for the control of effluent quality.
3. Makes use of some of the fundamental concepts of modern control theory to generate control strategies for activated sludge treatment system.
4. Draws upon the rich ideas of statistical quality control to maintain effluent quality within acceptable limits.
5. Utilizes the rudimentary techniques of design and analysis of experiments to identify the significant of control strategies that explain the variation of effluent quality.
6. Lastly, this thesis combines the managerial concepts of strategy and policy.

Koontz and Weihrich (1990) defined strategy as 'the general programs of action and deployment of resources to attain comprehensive objectives'. They also define policies as 'plans ... which guide or channel thinking in decision making'. Thus a strategy provides a broad framework within which many policies can be envisioned.

This thesis focuses on broad control strategic framework to economically attain effluent quality norm. It also makes an inquiry into important policy considerations within each such control strategic framework.