Introduction to Wastewater Treatment Processes

Second Edition

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Preface

This book is an introductory presentation meant for both students and practicing engineers interested in the field of wastewater treatment. Most of the earlier books discuss the subject industry by industry, providing solutions to specific treatment problems. More recently, a scientific approach to the basic principles of unit operations and processes has been utilized. I have used this approach to evaluate all types of wastewater problems and to properly select the mode of treatment and the design of the equipment required.

In most cases, the design of specific wastewater treatment processes, e.g., the activated sludge process, is discussed following (1) a summary of the theory involved in the specific process, e.g., chemical kinetics, pertinent material and energy balances, discussion of physical and chemical principles; (2) definition of the important design parameters involved in the process and the determination of such parameters using laboratory-scale or pilot-plant equipment; and (3) development of a systematic design procedure for the treatment plant. Numerical applications are presented which illustrate the treatment of laboratory data, and subsequent design calculations are given for the wastewater processing plant. The approach followed, particularly in the mathematical modeling of biological treatment processes, is based largely on the work of Eckenfelder and associates. This second edition represents a major revision with respect to the first. Greater emphasis upon the principles of chemical kinetics, reactor design, and the mechanism of biological treatment processes has been the major goal in this revision.

Clarity of presentation has been of fundamental concern. The text should be easily understood by undergraduate students and practicing engineers. The book stems from a revision of lecture notes which I used for an introductory course on wastewater treatment. Not only engineering students of diverse backgrounds but also practicing engineers from various fields have utilized these notes at the different times this course was offered.

I wish to express my appreciation to Mrs. Helene Michel for typing the manuscript. I owe sincere thanks to Mr. Alex Légaré for the artwork and to Mr. Martin Lecours for his assistance in proofreading the manuscript and in the correction of the page proofs.

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Chapter 1

Introduction

1. INTRODUCTION

It was only during the decade of the 1960s that terms such as "water and air pollution," "protection of the environment," and "ecology" became household words. Prior to that time, these terms either would pass unrecognized by the average citizen or, at most, would convey hazy ideas to his mind. Since then mankind has been bombarded by the media (newspapers, radio, television) with the dreadful idea that humanity is effectively working towards its self-destruction through the systematic process of pollution of the environment for the sake of achieving material progress. In some cases, people have been aroused nearly to a state of mass hysteria. Although pollution is a serious problem, and it is of course desirable that the citizenry be concerned about it, it is questionable that "mass hysteria" is in any way justifiable. The instinct of preservation of the species is a very basic driving force of humanity, and man is equipped to correct the deterioration of his environment before it is too late. In fact, pollution control is not an exceedingly difficult technical problem as compared to more complex ones that have been successfully solved in this decade, such as the manned exploration of the moon. Essentially, the basic technical knowledge required to cope with pollution is already available to man, and as long as he is willing to pay a relatively reasonable price tag, the nightmare of self-destruction via pollution will never become a reality. Indeed, much higher price tags are being paid by humanity for development and maintenance of the war-making machinery.

This book is primarily concerned with the engineering design of process plants for treatment of wastewaters of either domestic or industrial origin. It is only in the last few years that the design approach for these plants has changed from empiricism to sound engineering basis. Also, fundamental research in new wastewater treatment processes, such as reverse osmosis and electrodialysis, has only recently been greatly emphasized.

2. THE ROLE OF THE ENGINEER IN WATER POLLUTION ABATEMENT

2.1. The Necessity of a Multidisciplinary Approach to the Water Pollution Abatement Problem

Although it has been stated previously that water pollution control is not an exceedingly difficult technical problem, the field is broad and of sufficient complexity to justify several different disciplines being brought together for achieving optimal results at a minimum cost. A systems approach to water pollution abatement involves the participation of many disciplines: (1) engineering and exact sciences [sanitary engineering (civil engineering), chemical engineering, other fields of engineering such as mechanical and electrical, chemistry, physics]; (2) life sciences [biology (aquatic biology), microbiology, bacteriology]; (3) earth sciences (geology, hydrology, oceanography); and (4) social and economic sciences (sociology, law, political sciences, public relations, economics, administration).

2.2. A Survey of the Contribution of Engineers to Water Pollution Abatement

The sanitary engineer, with mainly a civil engineering background, has historically carried the brunt of responsibility for engineering activities in water pollution control. This situation goes back to the days when the bulk of wastewaters were of domestic origin. Composition of domestic wastewaters does not vary greatly; therefore, prescribed methods of treatment are relatively standard with a limited number of unit processes and operations involved in the treatment sequence. Traditional methods of treatment involved large concrete basins, where either sedimentation or aeration were performed, operation of trickling filters, chlorination, screening, and occasionally a few other operations. The fundamental concern of the engineer was centered around problems of structure and hydraulics, and quite naturally, the civil engineering background was an indispensable prerequisite for the sanitary engineer.

This situation has changed, at first gradually, and more recently at an accelerated rate with the advent of industrialization. As a result of a new large variety of industrial processes, highly diversified wastewaters requiring more complex treatment processes have appeared on the scene. Wastewater treatment today involves so many different pieces of equipment, so many unit processes and unit operations, that it became evident that the chemical engineer had to be called to play a major role in water pollution abatement. The concept of unit operations, developed largely by chemical engineers in the past 50 years, constitutes the key to the scientific approach to design problems encountered in the field of wastewater treatment.

In fact, even the municipal wastewaters of today are no longer the "domestic wastewaters" of yesterday. Practically all municipalities in industrialized areas must handle a combination of domestic and industrial wastewaters. Economic and technical problems involved in such treatment make it very often desirable to perform separate treatment (*segregation*) of industrial wastewaters prior to their discharge into municipal sewers.

Even the nature of truly domestic wastewaters has changed with the advent of a whole series of new products now available to the average household, such as synthetic detergents and others. Thus to treat domestic wastewaters in an optimum way requires modifications of the traditional approach.

In summary, for treatment of both domestic and industrial wastewaters, new technology, new processes, and new approaches, as well as modifications of old approaches, are the order of the day. The image today is no longer that of the "large concrete basins," but one of a series of closely integrated unit operations. These operations, both physical and chemical in nature, must be tailored for each individual wastewater. The chemical engineer's skill in integrating these unit operations into effective processes makes him admirably qualified to design wastewater treatment facilities.

2.3. A Case History of Industrial Wastewater Treatment

An interesting case history, emphasizing the role of the chemical engineer in the design of a wastewater treatment plant for a sulfite pulp and paper mill, is discussed by Byrd [2]. This pulp and paper plant was to discharge its wastewaters into a river of prime recreational value with a well-balanced fish population. For this reason, considerable care was taken in the planning and detailed design of the wastewater treatment facilities. A study of assimilative capacity of the river was undertaken and mathematical models were developed.

Design of the treatment plant involved a study to determine which wastewater effluents should be segregated for treatment and which ones should be combined. For the treatment processes a selection of alternatives is discussed [2]. Some of the unit operations and processes involved in the treatment plant, or considered at first but after further study replaced by other alternatives, were the following: sedimentation, dissolved air flotation, equalization, neutralization, filtration (rotary filters), centrifugation, reverse osmosis, flash drying, fluidized bed oxidation, multiple hearth incineration, wet oxidation, adsorption in activated carbon, activated sludge process, aerated lagoons, flocculation with polyelectrolytes, chlorination, landfill, and spray irrigation.

Integration of all these unit operations and processes into an optimally designed treatment facility constituted a very challenging problem. The treatment plant involved a capital cost of over $10 million and an operating cost in excess of $1 million per year.

2.4. The Chemical Engineering Curriculum as a Preparation for the Field of Wastewater Treatment*

Chemical engineers have considerable background that is applicable to water pollution problems. Their knowledge of mass transfer, chemical kinetics, and systems analysis is specially valuable in wastewater treatment and control. Thus training in chemical engineering represents good preparation for entering this type of activity. In the past, the majority of engineers working in this field have been sanitary engineers with a civil engineering background.

The multidisciplinary nature of the field should be recognized. Chemical engineering graduates envisioning major activity in the field of wastewater treatment are advised to complement their background by studying microbiology, owing to the great importance of biological wastewater treatment processes, and also hydraulics [since topics such as open channel and stratified flow, mathematical modeling of bodies of water (rivers, estuaries, lakes, inlets, etc.) are not emphasized in fluid mechanics courses normally offered to chemical engineering students].

2.5. "Inplant" and "End-of-Pipe" Wastewater Treatment†

2.5.1. Introduction

Frequently one may be tempted to think of industrial wastewater treatment in terms of an "end-of-pipe" approach. This would involve designing a plant without much regard to water pollution abatement and then considering separately the design of wastewater treatment facilities. Such an approach should not be pursued since it is, in general, highly uneconomical.

The right approach for an industrial wastewater pollution abatement program is one which uncovers all opportunities for inplant wastewater treatment. This may seem a more complicated approach than handling wastewaters at the final outfall. However, this inplant approach, which is described in Sections 2.5.2 and 2.5.3, is usually the one recommended as determined by an economic balance.

2.5.2. What Is Involved in Inplant Wastewater Control

Essentially, inplant wastewater control involves the three following steps:

Step 1. Perform a detailed survey of all effluents in the plant. All pollution sources must be accounted for and cataloged. This involves, for each polluting

* See Ref. [5].
† See Ref. [6].

stream, the determination of (a) flow rate and (b) strength of the polluting streams.

(a) *Flow rate.* For continuous streams, determine flow rates (e.g., gal/min). For intermittent discharges, estimate total daily (or hourly) outflow.

(b) *Strength of the polluting streams.* The "strength" of the polluting streams (concentration of polluting substances present in the streams) is expressed in a variety of ways, which are discussed in later chapters. For organic compounds that are subject to biochemical oxidation, the biochemical oxygen demand (BOD) (which is defined in Chapter 2, Section 2.3) is commonly employed. In the case history summarized in Section 2.5.3 of this chapter, BOD is used to measure concentration of organics.

Step 2. Review data obtained in Step 1 to find all possible inplant abatement targets. Some of these targets are (1) increased recycling in cooling water systems; (2) elimination of contact cooling for off vapors, e.g., replacement of barometric condensers by shell-and-tube exchangers or air-cooling systems; and (3) recovery of polluting chemicals. Profit may often be realized by recovering such chemicals, which are otherwise discharged into the plant sewers. A by-products plant may be designed to recover these chemicals. Further targets are (4) reuse of water from overhead accumulator drums, vacuum condensers, and pump glands (devise more consecutive or multiple water uses); (5) design a heat recovery unit to eliminate quenching streams; and (6) eliminate leaks and improve housekeeping practices. Automatic monitoring and additional personnel training might be profitable.

Step 3. Evaluate potential savings in terms of capital and operating costs for a proposed end-of-pipe treatment if each of the streams considered in Steps 1 and 2 are either eliminated or reduced (reduction in flow rates or in terms of strength of polluting streams). Then design the end-of-pipe treatment facilities to handle this reduced load. Compare capital and operating costs of such treatment facilities with that of an end-of-pipe facility designed to handle the original full load, i.e., the pollutant streams from a plant where inplant wastewater control is not practiced. The two case histories described in Ref. [6] are quite revealing in this respect.

For practicing inplant wastewater control, a deep knowledge of the process and ability to modify it, if necessary, are required. The chemical engineer is admirably well suited to handle this job.

2.5.3. Case Histories of Inplant Wastewater Control

Two interesting case histories are discussed by McGovern [6]. One of these, pertaining to a petrochemical plant, is summarized next.

A petrochemical plant already in operation conducted an effluent and inplant survey while evaluating a treatment plant to be designed and built. This plant would handle 20 million gal/day (MGD) of wastewater with a BOD load of 52,000 lb/day. The plan called for an activated sludge unit to remove over 90% of the BOD load. This included vacuum filtration and incineration of the sludge and chlorination of the total effluent.

Capital cost of the treatment facility was estimated at $10 million. Operating and maintenance costs were also estimated. All cost data were converted to an annual basis, using a 20-yr project life and 15% interest rate.

Then a study of the possibility of reducing both the flow and the strength of the wastewaters was undertaken. This study followed the steps outlined under

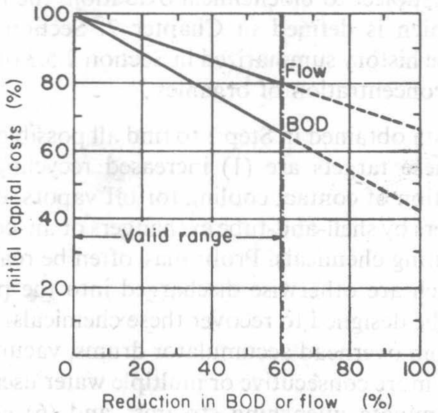

Fig. 1.1. Effect of waste load reductions on capital cost of treatment plant [6]. (Excerpted by special permission from Chemical Engineering, May 14, 1973. Copyright by McGraw-Hill, New York.)

TABLE 1.1
Savings from Inplant Wastewater Reductions[a]

Inplant savings	$/yr
Flow reduction (1424 gal/min)	$410,000
BOD reduction (2000 lb/day)	302,000
Water use reduction	
Treated water (0.24 MGD)	34,000
River water (1.37 MGD)	14,000
Product recovery	14,000
Total inplant saving	$774,000
Cost of inplant control	$/yr
Engineering	$ 15,000
Capital investment	150,000
Operating and maintenance	33,000
Total cost of inplant control	$198,000
Net savings: $774,000 − $198,000 = $576,000/yr	

[a] Excerpted by special permission from *Chemical Engineering*, May 14, 1973. Copyright by McGraw-Hill, Inc., New York 10020.

Section 2.5.2 with a number of changes being proposed for the process flowsheet. The reduction accomplished in flow rate and strength resulted in substantial savings in the total cost of the proposed treatment plant. Figure 1.1, prepared for this case history, illustrates the effect of reduction in BOD or flow rate upon the capital cost of the treatment facilities. This graph is valid to approximately 60% reduction in flow or BOD. Any further reduction probably requires a significantly different treatment system.

Savings from inplant wastewater control are tabulated in Table 1.1. Wastewater flow was cut to 85% of its value prior to inplant control and BOD load was cut to 50%. Moreover, the cost of these inplant controls was more than offset by economies in the treatment plant. As shown in Table 1.1 the program realized a net saving of $576,000/yr.

2.6. A New Concept in Process Design: The Flowsheet of the Future

The considerations in Section 2.5 are leading engineers to a new concept in process design. The flowsheet of the future will no longer show a line with an arrowhead stating "to waste." Essentially everything will be recycled, by-products will be recovered, and water will be reused. Fundamentally, the only streams in and out of the plant will be raw materials and products. The only permissible wastages will be clean ones: nitrogen, oxygen, carbon dioxide, water, and some (but not too much!) heat. In this connection, it is appropriate to recall the guidelines of the United States Federal Water Pollution Control Act of 1972: (1) best practical control technology, by July 1, 1977; (2) best available technology, by July 1, 1983; and (3) zero discharge by July 1, 1985.

3. DEGREES OF WASTEWATER TREATMENT AND WATER QUALITY STANDARDS

The degree of treatment required for a wastewater depends mainly on discharge requirements for the effluent. Table 1.2 presents a conventional classification for wastewater treatment processes. Primary treatment is employed for removing suspended solids and floating materials and also for conditioning the wastewater for either discharge to a receiving body of water or to a secondary treatment facility through neutralization and/or equalization. Secondary treatment comprises conventional biological treatment processes. Tertiary treatment is intended primarily for elimination of pollutants not removed by conventional biological treatment.

These treatment processes are studied in following chapters. The approach utilized is based on the concepts of unit processes and operations. The final objective is development of design principles of general applicability to any wastewater treatment problem, leading to a proper selection of process and the design of required equipment. Consequently, description of wastewater treatment sequences for specific industries, e.g., petroleum refineries, steel mills, metal-plating plants, pulp and paper industries, breweries, and tanneries, is not included in this book. For information on specific wastewater treatment processes, the reader should consult Eckenfelder [3] and Nemerow [7].

Water quality standards are usually based on one of two criteria: stream standards or effluent standards. *Stream standards* refer to the quality of receiving water downstream from the origin of sewage discharge, whereas *effluent standards* pertain to the quality of the discharged wastewater streams themselves.

TABLE 1.2
Types of Wastewater Treatment

Primary treatment
Screening
Sedimentation
Flotation
Oil separation
Equalization
Neutralization
Secondary treatment
Activated sludge process
Extended aeration (or total oxidation) process
Contact stabilization
Other modifications of the conventional activated sludge process: step aeration, complete mix activated sludge process, tapered aeration, high-rate activated sludge process, and pure oxygen aeration
Aerated lagoons
Wastewater stabilization ponds
Trickling filters
Rotating biological contactors
Anaerobic treatment: anaerobic contact process and anaerobic (submerged) filters
Tertiary treatment (or "advanced treatment")
Microscreening
Filtration (sand, anthracite, and diatomaceous beds)
Precipitation and coagulation
Adsorption (activated carbon)
Ion exchange
Reverse osmosis
Electrodialysis
Chlorination and ozonation
Nutrient removal processes
Sonozone process

A disadvantage of effluent standards is that it provides no control over total amount of contaminants discharged in the receiving water. A large industry, for example, although providing the same degree of wastewater treatment as a small one, might cause considerably greater pollution of the receiving water. Effluent standards are easier to monitor than stream standards, which require detailed stream analysis. Advocates of effluent standards argue that a large industry, because of its economic value to the community, should be allowed a larger share of the assimilative capacity of the receiving water.

Quality standards selected depend on intended use of the water. Some of these standards include: concentration of organic matter (see Chapter 2: BOD, COD, TOD, TOC), concentration of dissolved oxygen (DO, mg/liter), pH, color, turbidity, hardness (mg/liter), total dissolved solids (TDS, mg/liter), suspended solids (SS, mg/liter), concentration of toxic (or otherwise objectionable) materials (mg/liter), odor, and temperature. Extensive tabulation of water quality standards for various uses and for several states in the United States is presented by Nemerow [7].

4. SOURCES OF WASTEWATERS

Four main sources of wastewaters are domestic sewage, industrial wastewaters, agricultural runoff, and storm water and urban runoff. Although the primary consideration in this book is the study of treatment of domestic and industrial wastewaters, contamination due to agricultural and urban runoffs is becoming increasingly important. Agricultural runoffs carrying fertilizers (e.g., phosphates) and pesticides constitute a major cause of eutrophication of lakes, a phenomena which is discussed in Section 7 of this chapter. Storm runoffs in highly urbanized areas may cause significant pollution effects. Usually wastewaters, treated or untreated, are discharged into a natural body of water (ocean, river, lake, etc.), which is referred to as the receiving water.

5. ECONOMICS OF WASTEWATER TREATMENT AND ECONOMIC BALANCE FOR WATER REUSE

In the United States the average cost per thousand gallons of water is approximately \$0.20, which corresponds to \$0.05/ton. It is a relatively cheap commodity, and as a result the economics of wastewater treatment is very critical. In principle, by utilizing sophisticated treatment processes, one can obtain potable water from sewage. Economic considerations, however, prevent the practical application of many available treatment methods. In countries where water is at a premium (e.g., Israel, Saudi Arabia) some sophisticated water treatment facilities, which are not economically justified in North America, are now in operation. In evaluating a specific wastewater treatment process, it is important to estimate a cost/benefit ratio between the cost for accomplishing this upgrading of quality and the benefit derived from the treatment to obtain water of a specified quality.

Reuse of water by recycling has been mentioned in connection with inplant wastewater control (Section 2.5). Selection of an optimum recycle ratio for a specific application involves an economic balance in which three factors must be considered [3]: (1) the cost of raw water utilized in the plant; (2) the cost of wastewater treatment to suitable process quality requirements (in Example 1.1, this is the cost of wastewater treatment preceding recycling to the plant for reuse); and (3) the cost of wastewater treatment prior to discharge into a receiving water, e.g., in a river.

This economic balance is illustrated by Example 1.1.

Example 1.1.* A plant uses 10,000 gal/h of process water with a maximum contaminant concentration of 1 lb per 1,000 gal. The raw water supply has a contaminant concentration of 0.5 lb/1,000 gal. Optimize a water reuse system for this plant based on raw water cost of $0.20/1,000 gal. Utilize data in Fig. 1.2 to estimate costs for the two water treatment processes involved in the plant. The contaminant is nonvolatile.

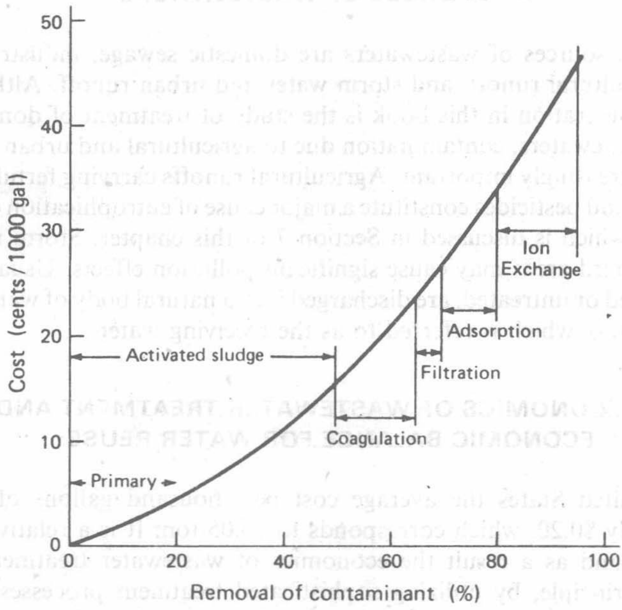

Fig. 1.2. Relationship between total cost and type of treatment [3].

The following conditions apply: (1) evaporation and product loss (stream E in Fig. 1.3): 1,000 gal/h of water; (2) contaminant addition (stream Y in Fig. 1.3): 100 lb/h of contaminant; and (3) maximum discharge allowed to receiving water: 20 lb/h of contaminant.

Solution A block flow diagram for the process is presented in Fig. 1.3. Values either assumed or calculated are underlined in the figure. Values not underlined are basic data for the problem. Volumetric flow rates of streams 9, 10, and 11 are negligible.

* See Ref. [3].