EDWARD D. SCHROEDER

Water and Wastewater Treatment

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WATER AND WASTEWATER TREATMENT

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PREFACE

This book is intended for advanced undergraduate and graduate-level courses on water and wastewater treatment. A previous course or experience with the subject is helpful in that the processes and systems discussed will be familiar. In addition, some knowledge of the nomenclature of water and wastewater treatment is assumed. Students using this book for their first course in the area can usually solve any problems associated with a lack of background by taking field trips and consulting standard undergraduate textbooks.

The material is presented in a slightly modified unit operations–unit processes approach. A general description of reacting systems and methods of modeling treatment processes is given in Chap. 2. Following chapters utilize the format developed in Chap. 2. Each chapter deals with a treatment objective rather than a type of process. Thus Chap. 3 discusses physical-chemical removal of dissolved materials and includes sections on adsorption, ion exchange, precipitation, chemical oxidation, and membrane processes. Chapter 4 discusses gas transfer, including both aeration and stripping, and other chapters include similar topic groupings. Including all the methods used to meet a treatment objective in a single chapter allows the reader to associate the process used with the objective and to compare available treatment methods. This combines many of the strengths of the unit operations approach and traditional methods of presentation.

Because the book is intended for use in advanced level courses, the emphasis has been on conceptual and theoretical development rather than on design procedures. Limitations of theoretical expressions, development of experimentally derived coefficients, and relationships between theory and practice are discussed on a case-by-case basis. The objective of this approach is to help the reader understand how processes work and the theoretical and practical constraints involved in process design. Insight into how and why processes function as they do, limitations or constraints on process operation, and limitations of design equations is as useful to the practicing design engineer as to the student. Thus it is hoped that this book will be an aid to practicing engineers as well as students.

Emphasis on theory should not be taken as a slight against empiricism. Theoretical models help the reader gain understanding of the mechanisms involved in a process. In many cases, satisfactory theoretical models are not available and wholly empirical models must be used in process design. More commonly, a theoretical model is modified by including factors or coefficients based upon experience. The empirical nature of these relationships is noted where they are presented. An interesting corollary to the place of empirical relationships in design is that quite often new processes are developed with empirical design relationships long before theoretical descriptions are derived. When the theory is developed, it simply supports the empirical relationships.

Chapters 1 and 2 should be read first, and Chap. 6 should be read before Chaps. 7 to 10. Otherwise there is no specific order in which the book should be read. The order used is based on a graduate sequence of courses presented at the University of California, Davis. Others may find a completely different order suitable, however. Similarly, the relative emphasis on certain topics reflects our particular program interests and goals. Many instructors may wish to supplement the text areas in which they have a particular interest.

This book is a composite of the ideas of many individuals with whom I have been fortunate to work over the past 12 years. Virtually daily conversations with George Tchobanoglous have contributed enormously to my understanding of the relationship between process theory and process design. A. A. Friedman carefully read the entire manuscript; his suggestions covered the range of improved clarity to theoretical development and were virtually all incorporated into the text. J. H. Sherrard reviewed the manuscript and made many helpful suggestions, particularly on subject coverage. Discussions over the past 12 years with R. L. Irvine, G. J. Kehrberger, A. P. Jackman, and D. P. Y. Chang have been very helpful in developing the text and the course on which it is based. Graduate students I have been fortunate enough to work with have also contributed a great deal to my understanding of process kinetics and stoichiometry. Their work is noted in a number of the chapters on biological wastewater treatment. The original manuscript was written while I was a visiting staff

member at University College of Swansea, Wales. Conversations with B. Atkinson and J. A. Howell during this period were very helpful, and I am grateful for their interest and support. Joyce Brown edited and typed the final manuscript. Her concern for detail has kept this book from being a grammatical embarrassment.

This book is dedicated to two close friends who have also served as my teachers, A. W. Busch and R. B. Krone.

EDWARD D. SCHROEDER

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1
INTRODUCTION

Water quality management is a societal necessity rather than an optional undertaking. Where industries such as steel or gasoline production may be considered necessary to the formation or maintenance of a scale or form of society, water quality management is necessary if society is to operate at all. As the structure of society becomes more complex, water quality requirements, wastes produced, management processes, and environmental impact of the wastes become greater in subtlety, complexity, and magnitude. Water quality management and the subareas of water and wastewater treatment reflect this increasing complexity in a number of ways.[1] Modern society is centered around the industrial city. The flow of wastewaters from these centers is generally large, and the area or volume into which the wastewaters are discharged is generally small in a relative sense (at the other end of the scale is the nomadic community, small in population, water usage, and wastewater production, with large areas or volumes into which the wastes can be discharged). In addition, industrial processes often produce wastewaters that are toxic to many forms of living organisms. Examples are abundant and include acids and bases that normally change the environment rather than directly attacking organisms, poisons such as cyanide from metal-plating operations, toxic substances such as phenol from the petrochemical industry, and high-temperature cooling waters that can both alter the environment or cause thermal shock. Thus the increasing sophistication of society has resulted in the production of larger quantities of wastewater that generally are far more concentrated and potentially harmful to the receiving environment.

Even if toxic materials were not a problem in modern wastewaters, the increasing volume would place great pressure on the engineering community to develop improved methods of wastewater treatment. Most cities have been using the same receiving waters for many years even though they have grown considerably in population and, hence, discharge quantity. Arguments can be made that any discharge is damaging, but in any case, the effects are closer to being an exponential rather than a linear function. Only minor, if any, measurable effects are noted up to a particular waste loading above which receiving-water quality declines at a relatively high rate. As a result, many cities have found that the level of wastewater treatment necessary to protect receiving-water quality has increased much faster than the population, and, of course, the cost of treatment is roughly exponentially related to the extent of treatment also.

Water treatment for domestic and industrial use is directly related to the quality of the source. In many cases, the source is also a receiver of industrial and domestic wastewaters, and therefore water treatment and wastewater treatment are closely tied together. In recent years, there has been an increasing concern with asbestos, pesticides, and chlorinated hydrocarbons found in small quantities in water supplies. Many of these compounds are known or suspected carcinogens. Because threshold concentrations and mechanisms of infection are not known or understood, regulatory agencies are understandably conservative in setting requirements.

Both treatment level and cost are engineering problems. The general problem statement is to provide maximum treatment at minimum cost. However, certain constraints must also be considered. A minimum quality must be related to the use and local environment of sources or receiving waters. For example, a generally accepted societal value is that natural fisheries should not be damaged even if they are of limited direct commercial value. This means that many communities or industries must provide treatment systems that will remove the toxic materials, growth stimulants (e.g., nitrogen and phosphate), and residual organics which are not easily removed by conventional wastewater treatment processes. The need for these *advanced wastewater treatment* processes may often be limited to short periods of the year, and therefore the problem of cost control becomes increasingly difficult.

Engineering responsibility for water and wastewater treatment begins with the determination of the level of treatment necessary or desirable and extends to system design and operation. In most cases, the level of treatment required is set by a regulatory agency that, in the United States at least, is largely influenced by engineers. These agencies receive advice and other needed information from other disciplines and governmental bodies. For example, fisheries management, mines, water resources development, and agriculture specialists often are involved in regulatory-agency decision formulation, and in some cases, their inclusion is legally required. Most regulatory agencies have also been adding biologists, geologists, land-use planners, and attorneys to their staffs. Engineers remain the predominant group, and agency statements and decisions usually have an engineering flavor, however. While this fact is advantageous with respect to making communication between the agency and the designer simple, it places a responsibility on the engineering community to find methods of incorporating nonquantitative information into regulatory and design decisions.

1-1 STANDARDS AND REQUIREMENTS

Water quality standards have both qualitative and quantitative aspects. The qualitative aspects include the concepts of what is a standard and what type of standards should be set. For example, the question of what level of water quality should be maintained, or in the case of many rivers and lakes returned to, is basically a conceptual problem. Until recently standards were locally determined in the United States. People directly affected thus were the predominant decision makers with respect to water quality. Unfortunately, the involvement of taxes, industrial jobs, and desired community growth in the standard formulation process usually resulted in a decision to fish upstream. Since 1960 there has been an increasing movement of the authority to formulate and maintain water quality standards into state and federal regulatory agencies. This change has been primarily due to the development of a greater understanding by the public of the importance of environment quality on the overall quality of life and recognition of this increased understanding by Congress and the state legislatures. Unfortunately the engineering community has had little positive input into the process.

Standards are defined here as values of water quality parameters (e.g., dissolved-oxygen concentration, temperature, turbidity) which must be met in a stream or lake to maintain a specified environment. Thus there will be a specified minimum dissolved-oxygen value in a given stream for the maintenance of trout fishery. *Requirements* differ from standards, at least as defined here, in that they are set by regulatory agencies and take into account other constraints. For example, a given river may have year-round dissolved-oxygen values greater than 8 mg/l, well above the value needed to support game fish. Dischargers would be required to maintain this level rather than meet the actual water quality standard for game fish. Justification for this approach is based primarily on the complexity of the ecosystem. All the organisms in a stream interact, and it is difficult to determine how a decrease in dissolved oxygen from 8 mg/l to, say, 5 mg/l would affect the total system over a long period of time. In addition, the decrease in oxygen would normally mean the addition of substantial numbers of microorganisms to the stream, a generally undesirable change and one that would both modify the natural (i.e., predischarge) situation considerably and decrease the stability of the ecosystem.

Requirements can also be used to equalize treatment costs for industrial discharges. Arguments against discharge requirements have often been made on the basis of making a manufacturing site uncompetitive. When requirements are made uniform over a large area without regard to local receiving-water quality, the problem of competitive advantage is greatly decreased. The U.S. Environmental Protection Agency (EPA) has proceeded on this philosophy by setting guidelines for the treatment of wastewaters from various industries. Authority for this approach was given in the 1970 Environmental Protection Act,[1] which requires that all wastewaters be treated to a technologically feasible level. Feasibility is construed to include economic considerations, but the EPA has considerable latitude in the matter.

Another difference between standards and requirements is that standards are based upon the existing or desired environment and, therefore, are usually tied to these conditions. Examples are dissolved oxygen, turbidity, or pH standards in a stream. Requirements are related to the standard but may well be placed upon the wastewater rather than the stream. California's dissolved oxygen requirements are normally stated for the stream (e.g., the discharge shall not depress the dissolved-oxygen concentration in the stream more than n tenths mg/l or below m mg/l) while biochemical oxygen demand (BOD) requirements are placed on the discharge stream (e.g., the discharge shall not have a BOD concentration greater than p mg/l or a total daily mass greater than q grams). Requirements for other parameters are set in the same manner. Of *special* engineering significance is that this approach virtually eliminates the concept of assimilative capacity of a stream or lake.

1-2 WATER TREATMENT PROCESSES AND SYSTEMS

Water treatment involves the removal from water of constituents detrimental to a specific use. Domestic water supplies must be nearly sterile and turbidity-free and should have a low total-dissolved-solids (TDS) concentration. Specific chemical species such as the hardness ions, calcium and magnesium, or toxic materials such as lead and the pesticide dieldrin must be removed in some cases.

Requirements for industrial uses of water vary widely. Cooling is a major industrial water use and has relatively loose requirements. Corrosion, scale formation, and bacterial growth in pipes and cooling towers are the primary concerns. Boiler feedwater is necessary in many industries. Because of the high temperatures and pressures in boilers, scale formation is a major problem. Boiler feedwater must be low in turbidity, dissolved oxygen, and hardness. Silica is a particular problem in boilers. Water is often directly in contact with or incorporated into an industrial product. Quality is obviously an important factor in such cases, and the requirements are specific to the particular use. A summary of such uses and an excellent list of references is given in "Water Quality Criteria."[2]

The intended use of a water directly affects the choice of sources and treatment method. Groundwaters are normally higher in TDS than surface waters and are often relatively hard. Surface waters usually require turbidity removal. The quality of water from either source varies widely. For example, groundwaters in the Willamette Valley of Oregon often have TDS concentrations less that 100 mg/l, while Los Angeles utilizes surface sources such as the Colorado River with TDS concentrations well over 500 mg/l. Portland, Ore., utilizes a surface-water source that is nearly turbidity-free. This would be a rare situation in the Eastern United States where most streams carry a considerable turbidity load.

Processes commonly used to treat water are listed in Table 1-1. Groundwaters are often distributed without treatment or with disinfection only. Surface

Table 1-1 WATER TREATMENT PROCESSES IN COMMON USE

Purpose	Process	Comments
Turbidity removal	Coagulation Flocculation Sedimentation Filtration: Depth Precoat	Often used for domestic water treatment
Dissolved-solids removal	Precipitation ion exchange	Often used to remove hardness
	Distillation Reverse osmosis	Reduction in TDS
Dissolved-organic removal	Activated-carbon adsorption	Used for removal of color, tastes, and odors and low concentrations of toxic organics
	Chemical oxidation	Chlorine, ozone, permanganate or peroxide used to oxidize organics
Cooling	Cooling towers	
Disinfection	Chlorination	Most common method in United States
	Ozonation	Effective, leaves no residual products, more expensive than chlorination

waters usually require coagulation, flocculation, sedimentation, filtration and disinfection prior to distribution. The first four steps only remove turbidity, and therefore water quality characteristics related to dissolved materials are unchanged.

Dissolved inorganic materials are often removed by precipitation. The most common examples of the use of precipitation are for hardness removal (Ca^{2+}, Mg^{2+}) and iron and manganese removal. In the latter case, the ions are first oxidized to the insoluble trivalent form. Ion exchange is also used quite often for the removal of undesirable dissolved constituents of water. Home water softeners are usually simple ion-exchange units that exchange Na^+ for Ca^{2+} and Mg^{2+}.

Organic materials can be removed by adsorption on activated carbon. This material has a very large surface-to-mass ratio (1000 m^2/g is typical) and provides a great number of adsorption sites for nonpolar molecules. Organic contaminants of concern include those responsible for taste, odor, and color in water as well as low concentrations of pesticides and petrochemical wastes. In some cases, oxidation of the organics provides satisfactory organic removals or can be used to improve adsorption-process effectiveness.

The most important application of disinfection is the production of safe drinking water. Industrially, disinfection also serves to prevent or control slime growth in pipes, cooling towers, and mechanical systems. A number of disinfectants are technically possible to use, but chlorine and ozone are preferred for operation and cost reasons.

1-3 WASTEWATER TREATMENT PROCESSES AND SYSTEMS

Treatment processes and systems for wastewater renovation can be classified in a number of ways. The most common method is to characterize them by function, e.g., precipitation, biooxidation, or adsorption. In the case of wastewater treatment, the majority of treatment plants built are for municipalities and, until very recently, have been generally restricted to a narrow group of operations and processes. The terms *primary*, *secondary*, and *tertiary* treatment have become synonomous with sedimentation, biological treatment with sedimentation, and removal of residual or nonbiodegradable materials by any means, respectively. In the treatment of domestic wastes, primary treatment usually removes about 35 percent of the BOD and 60 percent of the suspended solids.† Secondary treatment can be expected to remove an additional 50 percent of the incoming BOD (77 percent of primary effluent BOD) and reduce the suspended-solids concentration by an additional 33 percent. These estimates are based on "typical" domestic sewages and are often quite misleading. For example, a correctly designed and operated treatment system should consistently produce an effluent

† Measured as residual dry weight by filtration.