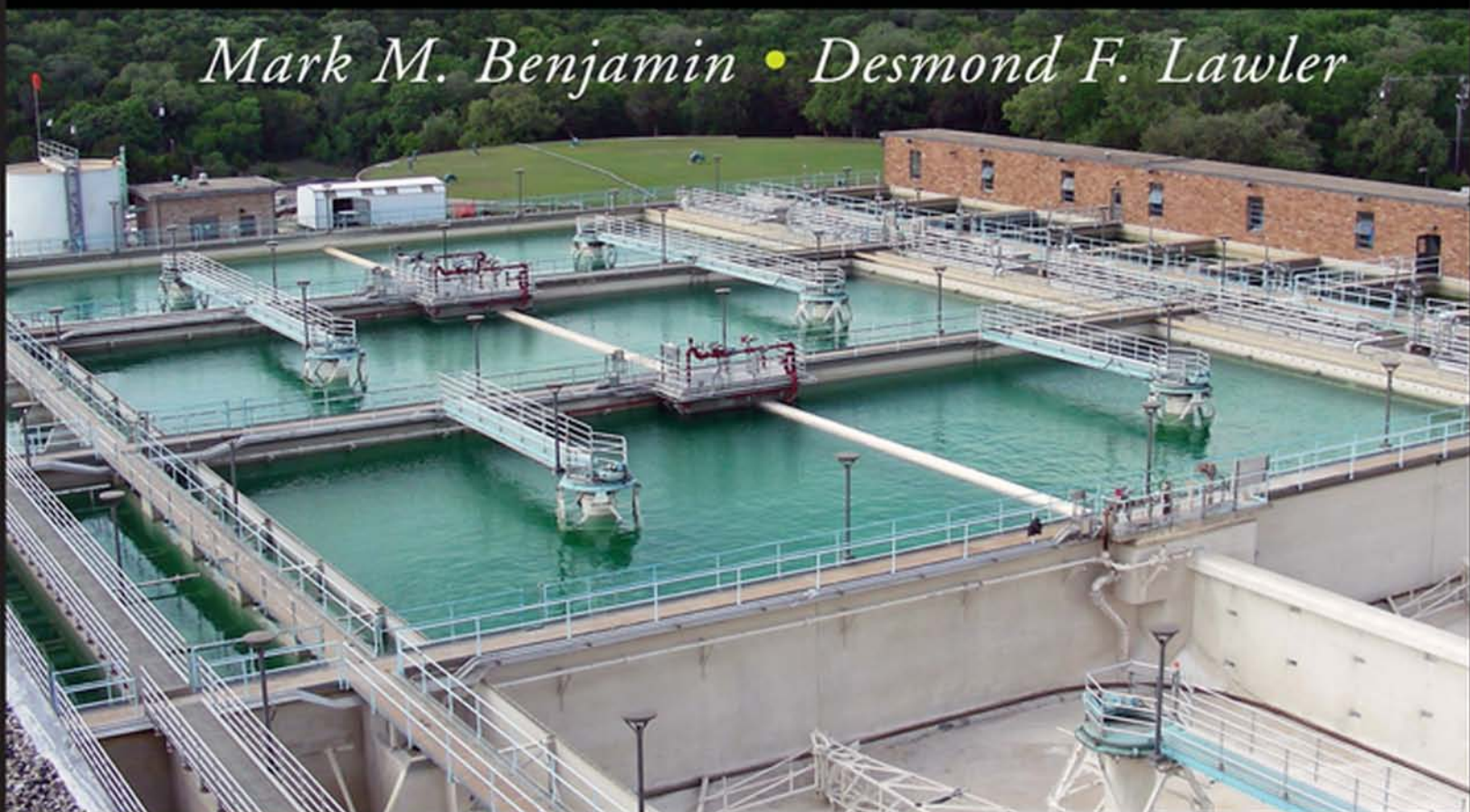

Water Quality Engineering

Physical/Chemical Treatment Processes

Mark M. Benjamin • Desmond F. Lawler



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WATER QUALITY ENGINEERING

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**MARK M. BENJAMIN
DESMOND F. LAWLER**

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PREFACE

PURPOSE

This book has been written primarily as a textbook for a graduate course in physical/chemical treatment processes for water and wastewater. However, it should also be useful to working environmental engineers in providing a thorough and cohesive understanding of processes that would not be easily achieved by reading journal articles. While some introductory material is given for each subject, this book has been written with the assumption that the reader has had previous exposure, by class work or experience, with standard water and wastewater treatment processes. To illustrate specific applications, examples are woven throughout this book and problems are given at the end of each chapter. This book is divided into four parts, as explained below.

ORGANIZATION

Part I: Chapters 1–4. This part of this book describes the fundamental tools for investigating and studying water and wastewater treatment processes. It sets the stage for the subsequent chapters by presenting the background that is common to the analysis and understanding of many treatment processes. At the end of this section, the reader should have an advanced understanding of how mass balances are used in continuous flow systems in which reactions occur, and thereby will be able to understand and predict the changes in water quality that occur in such reactors. Details of the construction of mass balances are presented in Chapter 1; descriptions of flow characteristics are given in Chapter 2; the study of reaction kinetics is introduced in Chapter 3; and the material in the first three chapters is synthesized in Chapter 4. These chapters are written in a

completely generic manner (i.e., with little attention to the application of the material to specific processes of interest in water and wastewater treatment) to emphasize that the material is usable in a wide variety of situations.

Part II: Chapters 5–10. This part of the book describes processes for removing soluble contaminants from water (or, in a few cases, inserting chemicals of interest into water). The processes are used in various applications, from treatment of municipal and industrial wastes to the production of drinking water or high-purity industrial process water. All the major processes that are used broadly to remove soluble contaminants are covered in this section or in the membrane chapter that ends this book. In each case, the emphasis is on fundamental understanding of the process dynamics through an analysis of batch (no flow) systems, followed by the interplay between the reaction kinetics and the flow characteristics of systems in which these processes are often carried out. The effects of process variables (i.e., hydraulic, equilibrium, and kinetic) on process design and process performance are emphasized.

The order of these chapters is such that they build on each other, and on the earlier chapters. Gas transfer is covered in Chapters 5 and 6, because it is usually independent of other processes (even if they happen simultaneously) and it builds directly on the earlier fundamental chapters. Gas transfer is one of the few common processes for which design is always closely related to theory, and so the analysis can be quite fundamental and still provide a picture of how gas transfer is achieved in real-engineered systems. Adsorption (Chapters 7 and 8) has many similarities to gas transfer and is often considered as a possible alternative process to gas stripping for the removal of specific contaminants, so it is presented next. For both gas transfer and adsorption, two chapters are provided, with the first describing the

underlying fundamental science and the second presenting the application in water treatment engineering.

Precipitation (Chapter 9) relies (in part) on adsorption and creates particles that must be removed in subsequent processes (that are covered in the third part of this book). Chemical oxidation (and, to a lesser extent, reduction) (Chapter 10) is widely used for the destruction of organic compounds and the transformation of objectionable inorganics to less toxic species; the use of so-called advanced oxidation processes is expanding rapidly in the field and will continue to do so in future years. Disinfection (the inactivation of microorganisms) relies directly on oxidation processes and is included in the chapter on oxidation and reduction.

Part III: Chapters 11–14. This part of the book focuses on processes for removing particulate materials from water. Many contaminants of water are particles to begin with, are made into particles by precipitation, or are associated with particles by adsorption; hence, particle removal processes are used to remove contaminants that came into the treatment system as soluble materials as well as to remove those that entered as particles. Chapter 11 describes the fundamentals that are common to all the particle removal processes, such as properties of particles and interactions of particle surfaces with chemicals in solution that determine much of particle behavior and particle–particle interactions. Particle removal processes are intrinsically physical/chemical processes—the chemistry of all these processes is essentially identical and is therefore covered in this chapter. This chapter also draws heavily on the chapters on adsorption and precipitation, as the chemistry of particle removal processes relies on these phenomena. Subsequently, the chapters on flocculation (Chapter 12), gravity separations (Chapter 13), and granular media filtration (Chapter 14) emphasize the physical aspects of these processes. These processes (or some subset of them) are often performed in series, and the order of the chapters reflects the order of their appearance in a treatment train.

Part IV: Chapter 15. An extensive chapter on membrane processes ends this book; membrane processes are used to remove both soluble and particulate materials. Rather than divide this material into separate chapters so that they could be incorporated into Parts II and III, we thought that this subject should stand alone and be treated in a unified way. The distinction between “what is a particle” and “what is a soluble entity” is blurry, and the continuum of membrane processes does not force one to make an arbitrary dividing line between them.

APPROACH

The approach throughout this book is to elucidate the fundamentals of physical/chemical treatment processes for water

and wastewater, that is, to provide the basis for understanding that underlies the application of these processes in various treatment systems. Our belief is that fundamental understanding requires both a conceptual or qualitative picture of each process and a mathematical description of the process. Throughout this book, we have related the conceptual and mathematical descriptions. The level of mathematical treatment is, in a few cases, sophisticated but always accessible to beginning graduate students and to professionals with a Master’s degree. Different people have different ways of learning with respect to the conceptual/mathematical continuum—some learn the concepts through the mathematics, others learn to appreciate the mathematical description only because they see the concepts first. It has been our goal to write this book in such a way that both these types of learners can reach a deep level of understanding of these processes. Detailed examples are provided throughout this book to illustrate the linkage between the mathematical and conceptual approaches to this understanding.

We also believe that the best practical knowledge is a good understanding of theory. When a process is not working properly, or when conditions have changed since the time of design, a good understanding of the fundamental theory is often the only guide for changing the operation to solve the problem. When faced with a new problem that is not envisioned today (and very few of the current hot topics in environmental engineering were envisioned 15–25 years ago when many professionals were graduate students), a good understanding of theory is the place to start developing a solution.

Throughout this book, we have used a consistent approach. After the generic description of mass balances in continuous flow systems in Part I, the processes described in every subsequent chapter are explained and analyzed by writing the relevant mass balance for the process, reactor geometry, and flow pattern under consideration. Our goal is to equip readers with this tool, so that as a question arises about how some process will work, they can generate and solve an appropriate mass balance that helps to answer that question. While the details of the mass balances and associated solutions vary for different unit processes, the approach is consistent. After describing the common ways in which each process is configured, the role of different variables in achieving the process objectives is discussed. Each chapter also gives the reader an overview of the ways in which the process is used in water and wastewater treatment.

In writing this book, one of us would write a first draft of a chapter or section and then the other would comment or edit; the process went back and forth until both of us were satisfied. That is, the tasks of writing and editing were mutually shared throughout the production of this book. In light of this process, the author order for this book was chosen as alphabetical.

HOW TO USE THIS BOOK?

This book is too long to complete in a one-semester (or one-quarter) course. Professors need to choose how to use this book in one or two courses, and how it will fit into a broader curriculum for environmental engineering students interested in treatment processes. The material in Part I is covered in greater depth than is done in most curricula, but still can be covered in depth within approximately four to five weeks. Part I can be combined with either Part II or with Parts III and IV to form a full semester course. Much of the material that is in Part II is closely related to what is

taught in many Water Chemistry courses, and so it is best if students studying Part II have already taken such a course, or are taking it simultaneously. Although the order of the chapters is purposeful, Part III (and to a lesser extent, Part IV) can be studied independently of Part II without too much difficulty.

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PART I

REACTORS AND REACTIONS IN WATER QUALITY ENGINEERING

