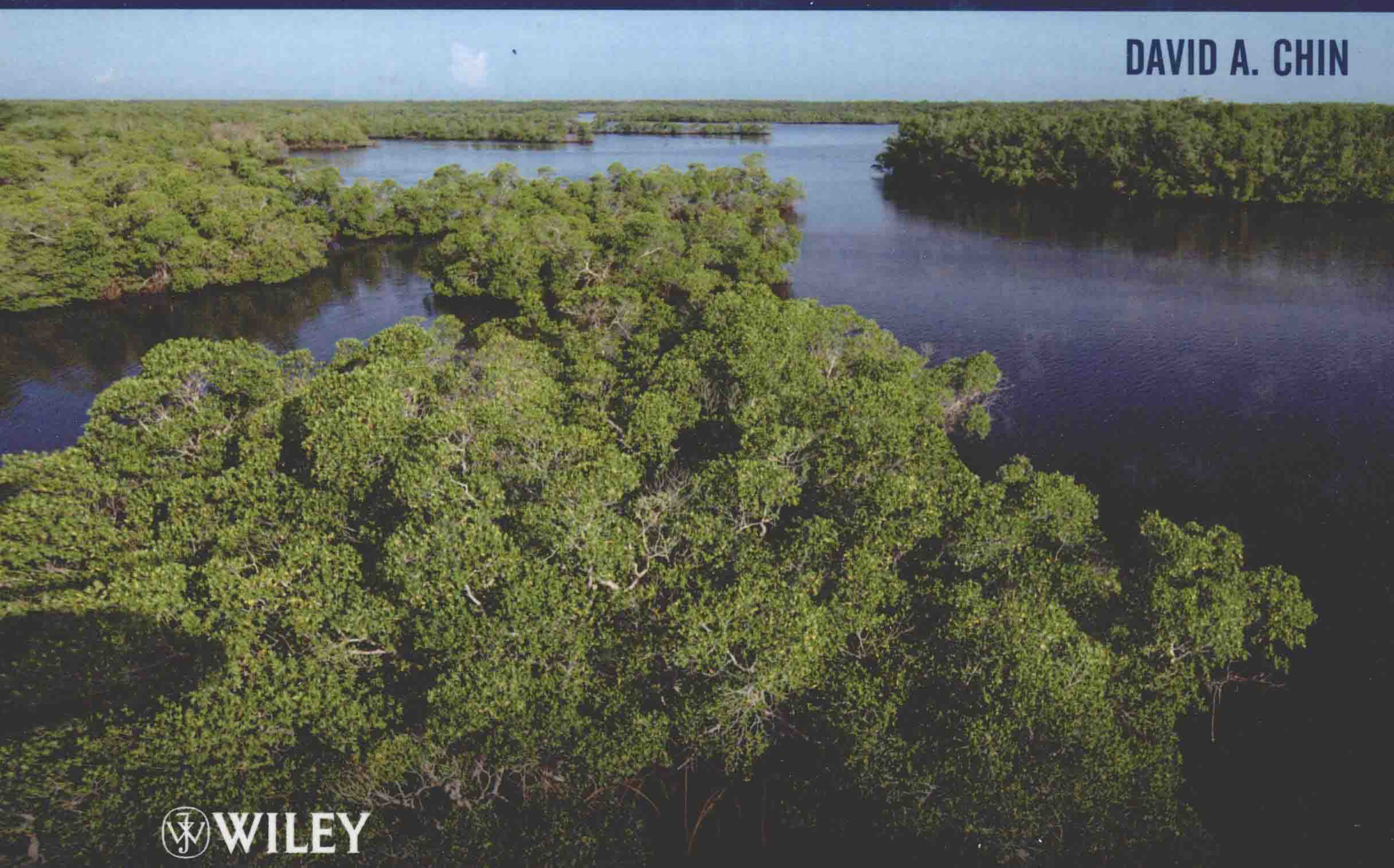
Second Edition

WATER-QUALITY ENGINEERING IN NATURAL SYSTEMS

Fate and Transport Processes in the Water Environment



DAVID A. CHIN

WILEY

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Fate and Transport Processes in the Water Environment

Second Edition

DAVID A. CHIN

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WATER-QUALITY ENGINEERING IN NATURAL SYSTEMS

To Andrew and Stephanie.

Trust in the Lord with all your heart and lean not on your own understanding; in all your ways acknowledge him, and he will make your paths straight.

Proverbs 3: 5–6

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PREFACE

This book is primarily intended for use as a core textbook by undergraduate and graduate students in environmental engineering, and as a technical reference for practicing environmental engineers. It focuses on the topic of water-quality engineering, which is the broadest specialty area in the field of environmental engineering and includes the principal subspecialties of water treatment, wastewater treatment, and water-quality control in natural systems. This textbook encompasses the latter subspecialty. In practical applications, water-quality engineering in natural systems is primarily concerned with protecting humans, aquatic life, and other users of water bodies from exposure to harmful levels of pollutants. In this context, water-quality engineers and managers must understand the types and characteristics of pollutants discharged into a water body, the manner in which they affect water quality, and the fate and transport of these pollutants within the water body. All of these topics are covered in detail in this textbook.

The need for competent water-quality engineers is clearly apparent when one realizes that, in the United States, over 50% of natural surface water bodies do not meet their designated water uses and statutory water-quality goals. In addition, many shallow aquifers are contaminated by anthropogenic contaminants, such as nitrates and organic chemicals, primarily pesticides and solvents. It is clear that water-quality engineering in natural systems is and will be an important practice area for the foreseeable future.

The practice of water-quality engineering is significantly influenced by laws and regulations, and it is essential that practitioners be aware of all applicable statutory requirements relating to water quality. The phenomenological bases of water-quality engineering in natural systems are: the relationships between contaminant concentrations in the aqueous phase and other phases (solid and vapor), the biochemical reactions of the contaminant in the environment, and the flows that transport the contaminant in the environment. These fundamental phenomenological processes are typically brought together in a single fate and transport equation whose solution is closely tied to the advection–diffusion equation. Although the generic fate and transport equation can be applied in most natural waters, the physical, chemical, and biological differences between various types of water bodies dictate that these water bodies be considered separately to more closely focus on the processes that are important to a particular water body. For example, nutrient enrichment (eutrophication) is a primary concern in lakes and reservoirs, while toxic substances released from spills or leaking storage facilities is a primary concern in groundwaters. The major categories of natural waters are: rivers and streams, lakes and reservoirs, wetlands, groundwater, and oceans and estuaries. Aside from assessing the fate and transport of contaminants purposely discharged into natural waters, remediation of contaminated waters also requires an understanding of fate and transport processes in the water environment.

An important aspect of water-quality engineering in natural systems is the analysis of water quality and related data that is commonly used to assess the state of a water body. Generally speaking, water-quality data are samples of stochastic variables, and therefore these data must be analyzed using appropriate probabilistic and statistical methods in order to properly evaluate the state of a water body relative to benchmark conditions, such as water-quality standards or permit requirements. The appropriate analytical techniques must generally be tailored to specific circumstances, such as limited amounts of data and the types of questions that are posed, such as the likelihood of exceeding a standard or the identification of any trends in the data. In water environments that cannot be adequately described by simple analytical models, numerical water-quality models are sometimes used to simulate the fate and transport of contaminants. In using these models, a basic understanding of acceptable methods of calibration, validation, and estimation of predictive uncertainty are essential for the proper use of these models and the interpretation of model results.

The book begins with an introduction to the principles of water-quality control and is followed in Chapter 2 by an exposition of the various measures of water-quality standards, including the physical, chemical, and biological measures. Chapter 3 covers the mathematical formulation of fate and transport processes in aquatic systems, including the advection–diffusion equation (ADE) derived from first principles, and the fundamental mathematical solutions and properties of this equation. The ADE is applicable to all natural waters with the principal differences being the relative importance and nature of the fate and transport processes represented in the ADE. Chapter 4 covers fate and transport processes in rivers and streams, including the dispersion of contaminants originating from instantaneous spills and continuous discharges, the fate of volatile organic compounds in streams, the depletion of dissolved oxygen in streams resulting from the discharge and accumulation of biodegradable organics, and the determination of allowable loadings of various contaminants in impaired streams. Chapter 5 covers water-quality related processes in groundwater, including the natural quality of groundwater, quantification of sources of groundwater contamination, advection, dispersion, sorption onto aquifer materials, biochemical decay, and the fate and transport of nonaqueous phase liquids in groundwater. Detailed coverage is provided on the application of fate and transport principles to the remediation of contaminated groundwater. Chapter 6 covers water-quality based watershed management where the primary focus is on estimating the contaminant loading on receiving waters from activities within the watershed. Detailed attention is given to sources of pollution and fate and transport processes associated with urban and agricultural watersheds. Chapter 7 describes water-quality processes in lakes and reservoirs, with particular emphasis on quantitative relationships describing flow and dispersion, sedimentation, eutrophication, nutrient recycling, and thermal stratification. Techniques to control eutrophication, dissolved oxygen levels, toxic contaminants, acidity, and aquatic plants are all covered. Chapter 8 describes the occurrence, function, and hydrology of wetlands, the delineation of jurisdictional wetlands, and the design, construction, and operation of artificial (constructed) wetlands. Particular attention is given to factors controlling contaminant removal efficiencies in constructed wetlands. Chapter 9 covers water-quality processes in oceans and estuaries, with particular attention to the design and operation of domestic wastewater outfalls and water-quality control in estuaries as they relate to the physical, chemical, and biological conditions in an estuary. Analysis of environmental data is covered in Chapter 10, which includes a concise review of the relevant basics of probability and statistics, and an exposition of statistical methods commonly used in analyzing water-quality data. The fundamentals of numerical modeling are covered in Chapter 11, with particular emphasis on calibration, validation, and estimation of predictive uncertainty when using numerical models.

The material covered in this book is most appropriate for seniors and first-year graduate students in environmental and civil engineering programs. Practicing environmental engineers and others with backgrounds in environmental science will also find the contents of this book comprehensible and useful.

The practice of water-quality engineering in natural systems as described in this book reflects the reality that the fate and transport of anthropogenic contaminants introduced into natural waters must be understood and manipulated to minimize the impacts of contaminant discharges into these waters. By controlling contaminant discharges into the water environment, the effects of human activities on natural waters can be controlled and/or predicted. The design of effective remediation measures in contaminated waters is based on these same principles, with additional technological considerations relating to the efficacy of various remediation systems. The essential background for all these practices is contained in this book.

David A. Chin
University of Miami

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1

INTRODUCTION

1.1 THE PROBLEM

Natural waters can be grouped into surface waters, groundwaters, and coastal waters, with each having their unique characteristics and dynamics, and yet all are connected. Surface waters and groundwaters are sources of drinking water for humans, and, along with coastal waters, are habitats for aquatic life. However, these waters are also depositories of discharges of human and industrial wastewaters. As a consequence, the relationship between waste discharges into natural waters and the resulting quality of these receiving waters is at the core of water-quality management.

Hydrology, chemistry, biology, and ecology are the scientific foundations of water-quality management. Hydrology is concerned with the occurrence and movement of water, chemistry is concerned with the properties of matter and their reactions, biology is concerned with the structure and function of living organisms, and ecology is concerned with interactions between living things and their nonliving (abiotic) environment or habitat. The discipline of *ecohydrology* covers the intersection of ecology and hydrology; however, ecohydrology is sometimes more narrowly understood to mean the interaction of plants and water. Civil and environmental engineering are the professional disciplines that are commonly associated with designing systems for water-quality control, with particular concerns regarding the interrelationship between surface water, groundwater, chemical pollutants and nonchemical stressors, water quantity, and land management.

Changing land uses, the addition of new pollutant sources, the establishment of new hydrologic connections, and modification of natural connectivity in landscapes can have significant ecosystem impacts. For example, the modification of free-flowing rivers for energy or water supply and the drainage of wetlands can have a variety of deleterious effects on aquatic ecosystems, including losses in species diversity, floodplain fertility, and biofiltration capability. Specific environmental issues that are of global concern include regional declines in the numbers of migratory birds and wildlife caused by wetland drainage, bioaccumulation of methylmercury in fish and wildlife in newly created reservoirs, and deterioration of estuarine and coastal ecosystems that receive the discharge of highly regulated silicon-depleted and nutrient-rich rivers.

Water above land surface (in liquid form) is called *surface water*, and water below land surface is called *groundwater*. Although surface water and groundwater are directly connected, these waters are typically considered as separate water bodies and are usually managed under different rules and regulations. A key feature of any surface water body is its *watershed*, which is delineated by topographic high points surrounding the water body, and all surface runoff within the watershed has the potential to flow into the surface water body. Consequently, surface water bodies are the potential recipients of all contamination contained in surface runoff from all locations within the watershed. In the case of rivers, the watershed area contributing to any river section increases as one moves downstream. Since

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