WATER-QUALITY ENGINEERING in Natural Systems

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WILEY-INTERSCIENCE

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To my wife, Linda Sue, for her love and support

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PREFACE

Water-quality engineering is a specialty area in environmental engineering that includes the subspecialties of water treatment, wastewater treatment, and water-quality control in natural systems. This textbook is intended to encompass the latter subspecialty, and the content of this book constitutes baseline knowledge expected of water-quality engineers and managers. The need for competent water-quality engineers and managers is 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 will be an important practice area for the foreseeable future.

The practice of water-quality engineering is significantly influenced by laws and regulations, and practitioners must be fully aware of all applicable statutory requirements. The phenomenological foundations of water-quality control in natural systems are the relationships between contaminant concentrations in the aqueous phase and other phases (solid, vapor), the biochemical reactions of the contaminant in the environment, and the flows that transport the contaminant in the environment. The fundamental phenomenological relationships are typically brought together in a single fate and transport equation whose solution is closely tied to the advection–dispersion 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 focus more closely on the processes that are important to that particular water body. For example, nutrient enrichment (eutrophication) is a primary concern in lakes and reservoirs, whereas toxic substances released from spills or leaking storage facilities is a primary concern in ground waters. The major categories of natural waters are rivers and streams, lakes and reservoirs, wetlands, ground water, 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 the relationship between contaminant-generating activities in the surrounding watershed and the contaminant input to the receiving water body. In this regard, terrestrial fate and transport processes and their relationship to various best management practices must be understood and quantified.

The book begins with an introduction to the principles of water-quality control and the laws and regulations relating to water-quality control in the United States. Particular attention is given to use-attainability analyses and the estimation of total maximum daily loads, both of which are essential components of water-quality control in natural systems. Chapter 2 covers the essential components of water-quality standards, including the physical, chemical, and biological measures of water quality. Chapter 3 covers the mathematical formulation of fate and transport processes in aquatic systems, including the derivation of the advection–dispersion equation from first principles and the mathematical solution and properties of this fundamental equation. The advection–dispersion equation is applicable to all natural waters. Chapter 4 covers fate and transport processes in rivers and streams, including lateral and longitudinal mixing from both instantaneous spills and continuous discharges, the fate of volatile organic compounds in streams, and the depletion of dissolved oxygen in streams resulting from the discharge and accumulation of biodegradable organics. Guidelines for the restoration and management of polluted rivers are also provided. Chapter 5 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 6 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 the contaminant-removal efficiencies in constructed wetlands. Chapter 7 covers water-quality-related processes in ground water, including the natural quality of ground water; quantification of sources of ground-water contamination; advection, dispersion, and sorption onto aquifer materials; biochemical decay; and the fate and transport of nonaqueous phase liquids in ground water. Detailed coverage is provided on the application of fate and transport principles to the remediation of contaminated ground water. Chapter 8 covers water-quality processes in oceans and estuaries, with particular emphasis on 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 the estuary. Chapter 9 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. Atmospheric loading on natural waters due to airshed activities is also covered.

The material covered in this book is most appropriate for seniors and first-year graduate students in environmental and civil engineering programs. Others with backgrounds in environmental science might also find the contents of this book 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 impact of contaminant discharges into these waters. By controlling the quality, quality, timing, and distribution of contaminant discharges into the environment, the effects of human activities on natural waters can be controlled. 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 cleanup systems. The essential background for all these practices is provided.

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CHAPTER 1

INTRODUCTION

Water is essential for life on Earth, and any changes in the natural quality and distribution of water have ecological impacts that can sometimes be devastating. The sciences of hydrology and ecology are the scientific foundations of water-quality management. *Hydrology* is the science dealing with the occurrence and movement of water, *ecology* is the science dealing with interactions between living things and their nonliving (abiotic) environment or habitat, and the relationship between hydrology and ecology is sometimes called *hydrologic connectivity* (Pringle, 2003).

It is widely recognized that the establishment of new hydrologic connections in the landscape and modification of natural connectivity in highly modified human-dominated 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 (Gleick, 1993). Specific environmental issues that are of global concern include regional declines in 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 *ground water*. Although surface water and ground water are directly connected, these waters are typically considered as separate systems and 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. For this reason, the

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management of water quality in surface waters is best done at the watershed scale rather than at the scale of individual water bodies. This is the *watershed approach* to water-quality management. The main limitations to implementing the watershed approach are rooted in our inability to quantify most of the sub-watershed-scale contaminant-transport processes that are fundamental to implementing watershed models of water quality. Contaminant inputs into surface waters from the atmosphere are also considered in water-quality management plans (Patterson, 2000). In contrast to surface waters, the quality of ground water is influenced primarily by activities on and below the ground surface, and the potential sources of ground-water contamination are determined primarily by overlying land uses and subsurface geology. The concept of a watershed is not applicable to ground water.

Identification of some polluted water bodies are obvious to the casual observer, such as the stream shown in Figure 1.1, but some polluted water bodies are not so obvious, such as an apparently pristine lake that is so contaminated with acid rain that the existence of aquatic life is extremely limited.

To put the water-quality problem in perspective, a comprehensive study of the quality of waters in the United States (USGS, 1999) determined that:

- The highest levels of nitrogen occur in streams and ground waters in agricultural areas. Fifteen percent of samples exceeded the drinking-water standard for nitrate nitrogen, 10 mg/L as N.
- Pesticides, primarily herbicides, are found frequently in agricultural streams and ground water. Pesticides found most frequently include atrazine, metachlor, alochlor, and cyanazine.
- Urban streams have the highest frequencies of occurrence of DDT, chlordane, and dieldrin in fish and sediments. Complex mixtures of pesticides are commonly found in urban streams.

FIGURE 1.1 Polluted stream. (From Wetlands Connection Center, 2005. Photo by Suzanne Dilworth Bates.)