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PRINCIPLES OF WATER TREATMENT

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Principles of Water Treatment

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Contents

Preface

Without water, life cannot exist. Thus, securing an adequate supply of fresh, clean water is essential to the health of humankind and the functioning of modern society. Water is also known as the universal solvent—it is capable of dissolving a vast number of natural and synthetic chemicals. Increasing population and the contamination of water with municipal, agricultural, and industrial wastes has led to a deterioration of water quality and nearly all sources of water require some form of treatment before potable use. This textbook is designed to serve as an introduction to the field of water treatment and the processes that are used to make water safe to drink.

The authors of this book have collaborated on two books that are intertwined with each other, both published by John Wiley and Sons, Inc. The other book, *MWH's Water Treatment: Principles and Design,* 3rd ed. (Crittenden et al., 2012), was the source for a significant portion of the material in this book. The focus of this present book is on principles of water treatment; it is suitable as a textbook for both undergraduate and graduate courses. The other book is an expanded edition, nearly triple the length of this one, that provides more comprehensive coverage of the field of drinking water treatment and is suitable as both a textbook and a reference for practicing professionals. The unit process chapters of *MWH's Water Treatment: Principles and Design* contain a detailed analysis of the principles of treatment processes as well as in-depth material on design. *MWH's Water Treatment: Principles and Design* also provides extensive chapters on the physical, chemical, and microbiological quality of water, removal of selected contaminants, internal corrosion of water conduits, and case studies that are not included in this book. Students who use this textbook in a class on water treatment and go on to a career in design of water treatment facilities are encouraged to consult *MWH's Water Treatment: Principles and Design* on topics that were beyond the scope of this textbook.

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1 Introduction

Securing and maintaining an adequate supply of water has been one of the essential factors in the development of human settlements. The earliest communities were primarily concerned with the quantity of water available. Increasing population, however, has exerted more pressure on limited high-quality surface sources, and contamination of water with municipal, agricultural, and industrial wastes has led to a deterioration of water quality in many other sources. At the same time, water quality regulations have become more rigorous, analytical capabilities for detecting contaminants have become more sensitive, and the public has become more discriminating about water quality. Thus, the quality of a water source cannot be overlooked in water supply development. In fact, most sources of water require some form of treatment before potable use.

Water treatment can be defined as the processing of water to achieve a water quality that meets specified goals or standards set by the end user or a community through its regulatory agencies. Goals and standards can include the requirements of regulatory agencies, additional requirements set by a local community, and requirements associated with specific industrial processes.

The primary focus of this book is the principles of water treatment for the production of potable or drinking water on a municipal level. Water treatment, however, encompasses a much wider range of problems and ultimate uses, including home treatment units and facilities for industrial water treatment with a wide variety of water quality requirements that depend on the specific industry. Water treatment processes are also applicable to remediation of contaminated groundwater and other water sources and wastewater treatment when the treated wastewater is to be recycled for new uses. The issues and processes covered in this book are relevant to all of these applications.

This book thoroughly covers the fundamental principles that govern the design and operation of water treatment processes. Following this introduction, the next three chapters provide background information that is necessary to understand the scope and complexity of treatment processes. Chapter 2 describes the relationship between water quality and public health, introduces the types of constituents that are present in various water supplies, and outlines some of the challenges faced by water treatment professionals. Chapter 3 introduces how the physicochemical properties of constituents in water and other factors guide the selection of treatment processes. Chapter 4 introduces the core principles necessary for understanding treatment processes, such as chemical equilibrium and kinetics, mass balance analysis, reactor analysis, and mass transfer. Chapters 5 through 13 are the heart of the book, presenting in-depth material on each of the principal unit processes traditionally used in municipal water treatment. Chapter 14 presents material on the processing of treatment residuals, a subject that can have a significant impact on the design and operation of treatment facilities.

1-1 The Importance of Principles

From the 1850s to about the 1950s, water treatment facilities were frequently designed by experienced engineers who drew upon previous successful design practices. Improvements were made by incremental changes from one plant to the next. Treatment processes were often treated as a ‘‘black box,’’ and detailed understanding of the scientific principles governing the process was not essential in completing a successful design. In recent years, however, significant changes have taken place in the water treatment industry that require engineers to have a greater understanding of fundamental principles underlying treatment processes. Some of these changes include increasing contamination of water supplies, increasing rate of technological development, and increasing sophistication of treatment facilities.

Early treatment practices were primarily focused on the aesthetic quality of water and prevention of contamination by pathogenic organisms. These treatment goals were relatively clear-cut compared to today’s requirements. Since about the 1950s, tens of thousands of chemicals have been developed for a wide variety of purposes—about 3300 chemicals are produced in quantities greater than 454,000 kg/yr (1,000,000 lb/yr) in the United States. Some chemicals have leaked into water supplies and have carcinogenic or other negative health impacts on humans. Many water supplies are now impacted by discharges from wastewater treatment plants and urban storm sewers. Engineers may be required to identify and design treatment strategies for chemicals for which no previous experience is available. As will be demonstrated in Chap. 3, treatment processes depend on well-established physicochemical principles. If the scientific principles are understood, it is possible to identify candidate processes based on the expected interaction between the properties of the contaminants and the capabilities of the processes. For instance, by knowing the volatility and hydrophobicity of a synthetic organic chemical, it is possible to predict whether air stripping or adsorption onto activated carbon is a more suitable treatment strategy.

Technology has been accelerating the pace at which treatment equipment is being developed. Engineers are faced with situations in which equipment vendors and manufacturers have developed new or innovative processes, and the engineer is assigned the task of recommending to a client whether or not the equipment should be evaluated as a viable option. Potable water is a necessary part of modern society, properly working processes are a matter of public health, and consumers expect to have water available continuously. Practical knowledge of previous successful design practices may not be sufficient for predicting whether new equipment will work. Understanding the scientific principles that govern treatment processes gives the engineer a basis for evaluating process innovations.

Treatment plants have gotten more complex. Sometimes facilities fail to work properly and the engineer is called in to identify factors that are preventing the plant from working or to recommend strategies to improve performance. Often, the difference between effective and ineffective performance is the result of scientific principles—a coagulant dose too low to destabilize particles, a change in water density because of a change in temperature, treatment being attempted outside the effective pH range. In these instances, scientific principles can guide the decision-making process regarding why a process is not working and what changes to operation would fix the problem.

As a result, the range of knowledge and experience needed to design water treatment facilities is extensive and cannot be learned in a single semester in college; today's design engineers need both knowledge about the fundamental principles of processes and practical design experience. This book provides a solid foundation in the former; other books focus more on the latter, such as books by Kawamura (2000) and AWWA and ASCE (2004). In addition, a companion book written by the authors, *MWH's Water Treatment Principles and Design,* 3rd ed. (Crittenden et al., 2012), covers both principles and design. While the coverage of that book is broad, it is nearly triple the length of this book and is difficult to cover in detail in a single engineering course. This book takes a focused approach on principles of water treatment and does so with the perspective of applying principles during design and operation so that it will serve as a useful introduction into the field of water treatment.

1-2 The Importance of Sustainability

Another concept in this book is that sustainability and energy consumption should be considered in selecting treatment processes, designing them, and operating them. There are several reasons for this approach. First, the withdrawal, conveyance, treatment, and distribution of potable water—and subsequent collection, treatment, and discharge of domestic wastewater—is one of the most energy-intensive industries in the United States. Only the primary metal and chemical industries use more energy. A focus on sustainability and energy considerations will help the water treatment industry develop ways to be more efficient while conserving resources.

Water demand has grown in urban areas and adequate supplies of locally available, high-quality water are increasingly scarce. Simultaneously, the ability to detect contaminants has become more sophisticated, negative health effects of some constituents have become more evident, regulations have become more stringent, and consumer expectations of high-quality water have become more strident. The growing trend toward use of poor-quality water sources, coupled with these other effects, has stimulated a trend toward more advanced treatment that requires more energy and resources. Increasing energy and resource use will contribute to greater pollution and environmental degradation; incorporating sustainability and energy consumption into process and design practices will offset that trend and allow higher levels of water treatment without the negative impacts.

Ultimately, the most important reason to consider sustainability in water treatment plant design is an issue of leadership. Environmental engineering professionals—the engineers who design water treatment facilities—ought to be more knowledgeable about environmental considerations than the general public and should demonstrate to other professions that successful design can be achieved when the environmental impacts are taken into account. The section on sustainability and energy considerations at the end of each of the process chapters in this book is a small start in that direction.

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Kawamura, S. (2000) *Integrated Design and Operation of Water Treatment Facilities*, Wiley, New York.

2 Water Quality and Public Health

The primary purpose of municipal water treatment is to protect public health. Water can contain a wide array of constituents that can make people ill and has a unique ability to rapidly transmit disease to large numbers of people. The purpose of this chapter is to introduce the relationship between water quality and public health and identify the major sources of contaminants in water supplies. The basic features of drinking water regulations in the United States are introduced. The chapter ends with a description of some of the challenges, competing issues, and compromises that water treatment engineers must balance to successfully design a water treatment system.

2-1 Relationship between Water Quality and Public Health

History of Waterborne Disease

Prior to the middle of the nineteenth century, it was commonly believed that diseases such as cholera and typhoid fever were primarily transmitted by breathing miasma, vapors emanating from a decaying victim and drifting through the night. Serious engagement in treatment of public drinking water supplies began to develop in the last half of the nineteenth century after Dr. John Snow identified the connection between contamination of drinking water and waterborne disease. Snow's discovery was later supported by the advocacy of the germ theory of disease by the French scientist Louis Pasteur in the 1860s and the discovery of important microbial *pathogens* (microorganisms capable of causing disease) by the German scientist Robert Koch. These developments led to the understanding that gastrointestinal disease spreads when the pathogens in the feces of infected human beings are transported into the food and water of healthy individuals—exposure via the so-called *fecal-to-oral route*. As a result, a number of strategies were developed to break the connection between drinking water systems and systems for disposal of human waste. These strategies included the use of water sources that are not exposed to sewage contamination, the use of water treatment on contaminated supplies, the use of continuously pressurized water systems that ensure that safe water, once it is obtained, could be delivered to the consumer without exposure to further contamination, and the use of bacterial indices of human fecal contamination.

Continuous chlorination of drinking water as a means for bacteriological control was introduced at the beginning of the twentieth century. In the next four decades, the focus was on the implementation of conventional water treatment and chlorine disinfection of surface water supplies. By 1940, the vast majority of water supplies in developed countries had ''complete treatment'' and was considered microbiologically safe. The success of filtration and disinfection practices lead to the virtual elimination of the most deadly waterborne diseases in developed countries, particularly typhoid fever and cholera, as depicted on Fig. 2-1 (CDC, 2011).

In 1974, however, both in the United States and in Europe, it was discovered that chlorine, the chemical most commonly used for disinfection, reacted with the natural organic matter in the water to produce synthetic organic chemicals, particularly chloroform. Since that time, decades of research have shown that chlorine produces a large number of disinfection by-products (DBPs), and that alternate chemical disinfectants produce DBPs of their own. The challenge to protect the public from waterborne diseases continues as engineers balance disinfection and the formation of treatment by-products.

In the 1970s and 1980s, it became apparent that some waterborne diseases spread by means other than from one human to another via the fecal-to-oral route. First among these are *zoonotic diseases*, diseases that humans can contract via the fecal-to-oral route from the feces of other animals. Examples of zoonotic pathogens are *Giardia lamblia* and *Cryptosporidium parvum*. Second are diseases caused by *opportunistic pathogens* that make their home in aquatic environments but will infect humans when the opportunity arises. Examples of opportunistic pathogens are *Legionella pneumophila, Aeromonas hydrophilia, Mycobacterium avium* complex, and *Pseudomonas aeruginosa*. An opportunistic pathogen is a microorganism

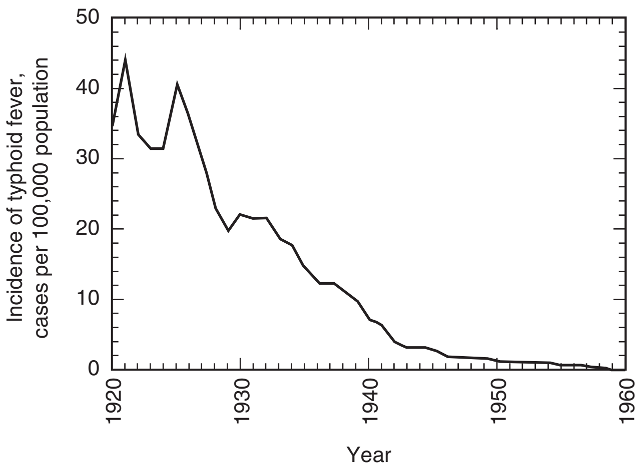

Figure 2-1
Decline in the incidence of typhoid fever in the United States due to the provision of higher quality drinking water and other sanitation and hygiene practice improvements. [Data from CDC (2011).]

that is not ordinarily able to overcome the natural defenses of a healthy human host. Under certain circumstances, however, such organisms are able to cause infection resulting in serious damage to the host. There are two circumstances when opportunistic pathogens are more successful: (a) when the immune response of the host has been compromised [e.g., persons with human immunodeficiency virus (HIV), persons on drugs that suppress the immune system, the very elderly] or (b) when the host is exposed to such high levels of the organism in question that the infection becomes overwhelming before the body can develop a suitable immune response. As a result of the possible presence of zoonotic pathogens, finding a water supply free of sewage contamination does not assure the absence of pathogens and does not obviate the need for water treatment. Also, understanding the role of opportunistic pathogens makes it clear that purifying water and transporting it under pressure does not provide complete protection, and growth of opportunistic pathogens must also be controlled in distribution systems and in water system appurtenances.

Role of Water in Transmitting Disease

A unique aspect of water as a vehicle for transmitting disease is that a contaminated water supply can rapidly expose a large number of people. When food is contaminated with a pathogen, tens to hundreds of persons are commonly infected. If a large, centralized food-packaging facility is involved, thousands might be infected. However, when drinking water is contaminated with a pathogen, typically hundreds of people are infected and occasionally hundreds of thousands are infected. For example, it is estimated that 500,000 people became ill from contaminated drinking water in the 1993 Milwaukee *Cryptosporidium* incident (MacKenzie et al., 1994).

The principal mechanisms for the transmission of *enteric* (gastrointestinal) diseases are shown on Fig. 2-2. Suppose that, while infecting an adult,

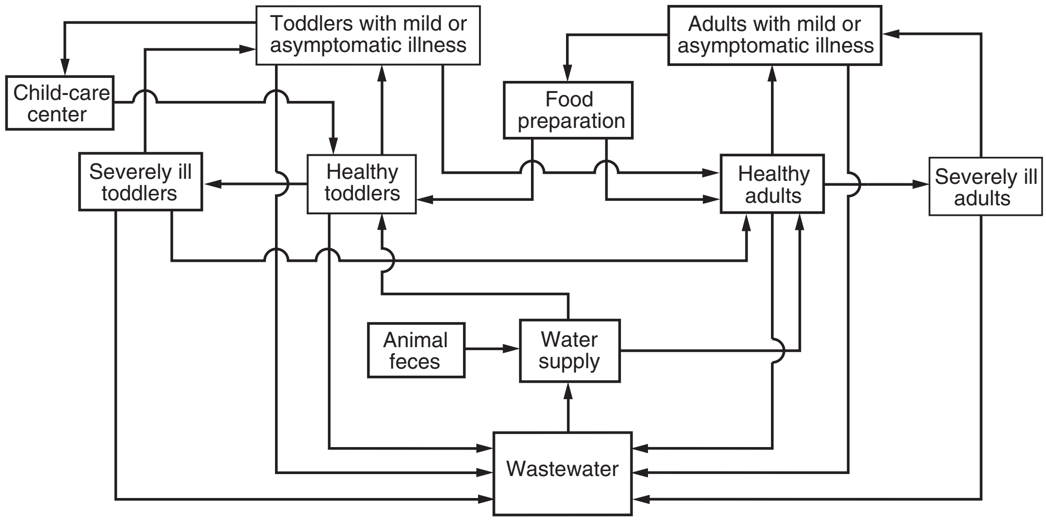

Figure 2-2
Schematic of routes of transmission for enteric disease.

a pathogen causes a severe, debilitating enteric disease that immobilizes and seriously injures the infected person. The route of transmission can be analyzed using Fig. 2-2. If an adult with severe illness is too debilitated to prepare food, the organism cannot get into the food supply. However, the organism does get in the sewer even if the sick person cannot get out of bed. Once in the sewer, the organism is then transported to the wastewater treatment plant. If the organism is not removed or inactivated at the wastewater treatment plant, it enters the receiving watercourse. If that watercourse serves as a water supply and water treatment does not remove or inactivate the organism, both healthy toddlers and adults who drink the water are exposed and may get infected. Thus, the entire population drinking the water supply is potentially exposed to the disease-causing agent. Under these conditions, an organism can successfully reproduce even if it causes a severe disease from which the host rarely recovers. According to some historical accounts, the classic form of Asiatic cholera that appeared in the middle of the nineteenth century behaved in this way. The route of transmission can be interrupted by removing or inactivating the organism from the water either at the wastewater treatment plant or at the drinking water treatment plant.

Figure 2-2 can also be used to consider the spread of the disease via the food route. Adults with mild symptoms of the disease, if they do not use adequate hygiene, may contaminate food when they prepare it. Both toddlers and adults who eat the contaminated food may then get infected. Some of those who get infected will be asymptomatic; others may exhibit mild symptoms. Infected adults may again prepare and contaminate food, and some infected toddlers will go to child-care centers. Toddlers in child-care centers will expose other toddlers. Adult caregivers can also expose themselves while handling the sick toddlers.

Debilitating diseases are less likely to spread this way because seriously ill adults are unlikely to be preparing food for others and seriously ill children are unlikely to go to child-care centers. Furthermore, the drinking water has no connection to this route of communication so treating the drinking water will not stop it. The value of a water treatment intervention is much greater where severe, debilitating disease is concerned.

Enteric organisms that cause seriously debilitating disease can be nearly eliminated through water treatment because they depend on this route of exposure for survival. When enteric organisms cause mild disease or asymptomatic infections, water treatment can prevent the largest scale epidemic events but the disease remains in the community. This is because mildly ill or asymptomatic carriers will spread the disease via food preparation and in child-care centers.

2-2 Source Waters for Municipal Drinking Water Systems

Designing on effective water treatment plant is a complex process because of the wide variety of undesireable constituents that can be in the source water. Even waters thought of as ''pristine'' might contain some constituents that should be removed. The specific constituents in water, the relative concentrations of those constituents, and other water quality parameters that affect treatment depend heavily on local conditions of geology, climate, and human activity. Thus, treatment processes must be tailored to the specific source water. The specific treatment challenges, however, are heavily influenced by the type of source water, which can include groundwater, lakes and reservoirs, rivers, seawater, and wastewater impaired waters. Each type of source will require different treatment processes and present different challenges to the water treatment engineer. Constituents can enter the water supply through several pathways, as depicted on Fig. 2-3. Potential types of contamination and general characteristics of each type of source are described in the following sections.

Groundwater

Groundwater is water that exists in the pore spaces between sand, gravel, and rocks in the earth and can be brought to the surface using wells. About 35 percent of people served by public water systems in the United States are supplied with groundwater; nearly all the rest are supplied with fresh surface water. Undesirable constituents in groundwater can be either naturally occurring or *anthropogenic* (of human origin). The natural constituents result from dissolution caused by long-term contact between the water and the rocks and minerals. Some natural constituents that might need to be removed by water treatment include:

- Iron and manganese: Depending on local conditions, groundwater can be aerobic (in the presence of oxygen gas) or anaerobic (in

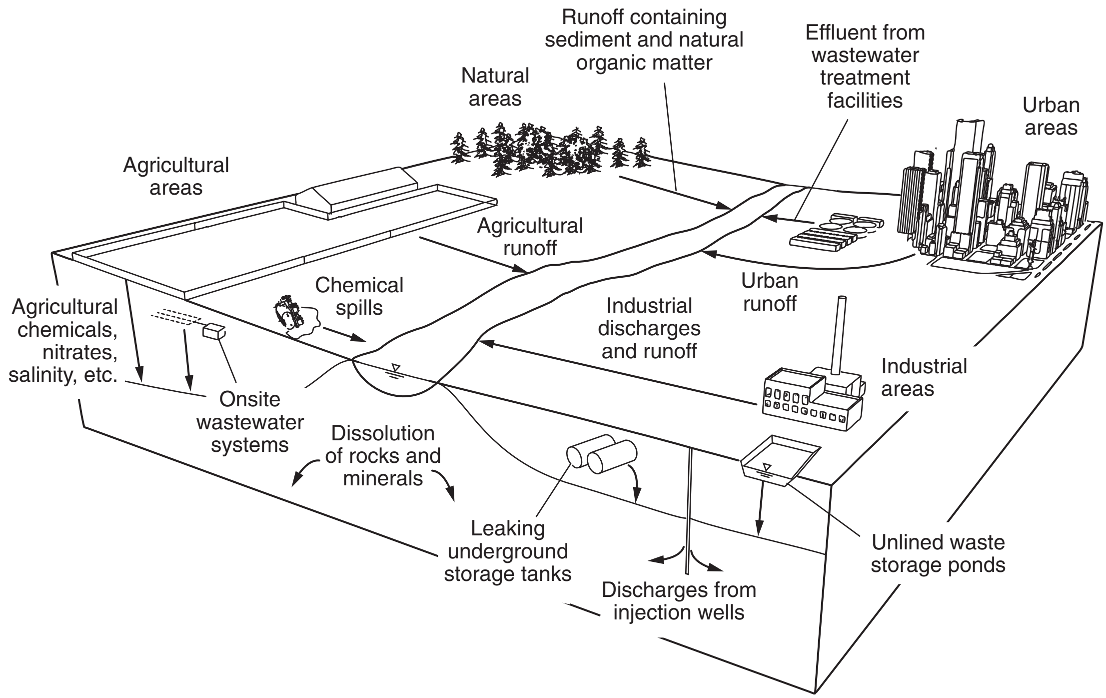

Figure 2-3
Sources of naturally occurring constituents and contaminants in drinking water supplies.

the absence of oxygen-containing electron acceptors). In anaerobic conditions, iron- and manganese-containing minerals are relatively soluble and can dissolve into the water. When the water is aerated and/or chlorinated, the iron and manganese react to form insoluble species that precipitate and cause rust- and black-colored stains on laundry and plumbing fixtures.

- Hardness: *Hardness* is a characteristic of water caused by the presence of calcium and magnesium, which are abundant in the Earth's crust. Hard water does not cause negative health impacts, but it reacts with soap to form a white precipitate (soap scum), leaves water spots on surfaces, and forms precipitates in water heaters, tea pots, heat exchangers, boilers valves, and pipes, clogging them and/or reducing their efficiency.
- Trace inorganics: Minerals can contain many trace elements, including arsenic, barium, chromium, fluoride, selenium, and species that exhibit radioactivity such as radium, radon, and uranium. Many trace inorganics exhibit toxicity, carcinogenicity, or other adverse health effects, if concentrations are too high.