



water treatment

principles and design

third edition

A photograph of a water treatment plant at night. The facility is illuminated by several tall, black light poles. In the foreground, there are several large, cylindrical tanks and a complex of pipes and machinery. In the background, there are large, circular basins and a small building. The sky is dark blue, and the ground is a mix of dirt and concrete. The overall scene is industrial and well-lit.

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Kerry J. Howe, George Tchobanoglous

MWH's Water Treatment

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Principles and Design

Third Edition

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Preface

During the 27 years since the publication of the first edition of this textbook, many changes have occurred in the field of public water supply that impact directly the theory and practice of water treatment, the subject of this book. The following are some important changes:

1. Improved techniques and new instrumental methods for the measurement of constituents in water, providing lower detection limits and the ability to survey a broader array of constituents.
2. The emergence of *new* chemical constituents in water whose significance is not understood well and for which standards are not available. Many of these constituents have been identified using the new techniques cited above, while others are continuing to find their way into water as a result of the synthesis and development of new compounds. Such constituents may include disinfection by-products, pharmaceuticals, household chemicals, and personal care products.
3. Greater understanding of treatment process fundamentals including reaction mechanisms and kinetics, through continued research. This new understanding has led to improved designs and operational strategies for many drinking water treatment processes.
4. The development and implementation of new technologies for water treatment, including membrane technologies (e.g., membrane filtration and reverse osmosis), ultraviolet light (UV) disinfection, and advanced oxidation.
5. The development and implementation of new rules to deal with the control of pathogenic microorganisms, while at the same time minimizing the formation of disinfection by-products.

6. The ever-increasing importance of the management of residuals from water treatment plants, including such issues as concentrate management from reverse-osmosis processes.

The second edition of this textbook, published in 2005, was a complete rewrite of the first edition and addressed many of these changes. This third edition continues the process of revising the book to address these changes, as well as reorganizing some topics to enhance the usefulness of this book as both a textbook and a reference for practicing professionals. Major revisions incorporated into this edition are presented below.

1. A new chapter on advanced oxidation (Chap. 18) has been added.
2. A table of important nomenclature has been added to the beginning of each chapter to provide a resource for students and practitioners learning the vocabulary of water treatment.
3. The theory and practice of mixing has been moved from the coagulation/flocculation chapter to the reactor analysis chapter to unify the discussion of hydraulics and mixing.
4. A new section on enhanced coagulation has been added to the coagulation chapter.
5. The adsorption chapter has been expanded to provide additional detail on competitive adsorption, kinetics, and modeling of both fixed-bed and flow-through adsorption systems.
6. Material has been updated on advanced treatment technologies such as membrane filtration, reverse osmosis, and side-stream reactors for ozone addition.
7. The discussion of applications for RO has been updated to include brackish groundwater, wastewater, and other impaired water sources, as well as expanded discussion of concentrate management and energy recovery devices.
8. A new section on pharmaceuticals and personal care products has been added to Chap 20.
9. New section headings have been added in several chapters to clarify topics and make it easier to find content.
10. Topics and material has been reorganized in some chapters to clarify material.
11. The final chapter in this book has been updated with new case studies that demonstrate the synthesis of full-scale treatment trains. This chapter has been included to allow students an opportunity to learn how water treatment processes are assembled to create a water treatment plant, to achieve multiple water quality objectives, starting with different raw water qualities.

Important Features of This Book

This book is written to serve several purposes: (1) an undergraduate textbook appropriate for elective classes in water treatment, (2) a graduate-level textbook appropriate for teaching water treatment, groundwater remediation, and physical chemical treatment, and (3) a reference book for engineers who are designing or operating water treatment plants.

To convey ideas and concepts more clearly, the book contains the following important elements: (1) 170 example problems worked out in detail with units, (2) 399 homework problems, designed to develop students understanding of the subject matter, (3) 232 tables that contain physical properties of chemicals, design data, and thermodynamic properties of chemicals, to name a few, and (4) 467 illustrations and photographs. Metric SI and U.S. customary units are given throughout the book. Instructors will find the example problems, illustrations, and photographs useful in introducing students to fundamental concepts and practical design issues. In addition, an instructor's solutions manual is available from the publisher.

The Use of This Book

Because this book covers a broad spectrum of material dealing with the subject of water treatment, the topics presented can be used in a variety of undergraduate and graduate courses. Topics covered in a specific course will depend on course objectives and the credit hours. Suggested courses and course outlines are provided below.

The following outline would be appropriate for a one-semester introductory course on water treatment.

Topic	Chapter	Sections
Introduction to Water Quality	1	All
Physical and Chemical Quality of Water	2	All
Microbiological Quality of Water	3	All
Introduction to Water Treatment	4	All
Chemical Oxidation	8	8-1, 8-2, 8-3
Coagulation and Flocculation	9	9-1, 9-2, 9-4, 9-5, 9-7
Gravity Separation	10	All
Granular Filtration	11	All
Membrane Filtration	12	All
Disinfection	13	All, except 13-4 and 13-5
Synthesis of Treatment Trains: Case Studies from Bench to Full Scale	23	All

The following outline would be appropriate for a two-semester course on water treatment.

First Semester		
Topic	Chapter	Sections
Introduction to Water Quality	1	All
Physical and Chemical Quality of Water	2	All
Microbiological Quality of Water	3	All
Introduction to Water Treatment	4	All
Principles of Chemical Reactions	5	All
Principles of Reactor Analysis and Mixing	6	All
Coagulation and Flocculation	9	All
Gravity Separation	10	All
Granular Filtration	11	All
Membrane Filtration	12	All
Disinfection	13	All
Synthesis of Treatment Trains: Case Studies from Bench to Full Scale	23	All
Second Semester		
Principles to Mass Transfer	7	All
Aeration and Stripping	14	All
Adsorption	15	All
Ion Exchange	16	All
Reverse Osmosis	17	All
Chemical Oxidation and Reduction	8	All
Advanced Oxidation	18	All
Disinfection/Oxidation Byproducts	19	All
Removal of Selected Constituents	20	All
Residuals Management	21	All
Internal Corrosion of Water Conduits	22	All

The following outline would be appropriate for a one-semester course on physical chemical treatment.

Topic	Chapter	Sections
Principles of Chemical Reactions	5	All
Principles of Reactor Analysis and Mixing	6	All
Chemical Oxidation and Reduction	8	All
Disinfection/Oxidation Byproducts	19	All
Coagulation and Flocculation	9	All
Gravity Separation	10	All
Granular Filtration	11	All
Membrane Filtration	12	All

(continued)

Topic	Chapter	Sections
Principles of Mass Transfer	7	All
Aeration and Stripping	14	All
Adsorption	15	All
Ion Exchange	16	All
Reverse Osmosis	17	All

The following topics would be appropriate for the physical-chemical portion of a one-semester course on ground water remediation.

Topic	Chapter	Sections
Principles of Chemical Reactions	5	All
Principles of Reactor Analysis and Mixing	6	All
Principles of Mass Transfer	7	All
Aeration and Stripping	14	All
Adsorption	15	All
Ion Exchange	16	All
Chemical Oxidation and Reduction	8	8-1, 8-2, 8-3, 8-4, 8-5, 8-6
Advanced Oxidation	18	All
Disinfection/Oxidation Byproducts	19	All

The following topics would be appropriate for a portion of a one-semester course on water quality.

Topic	Chapter	Sections
Introduction to Water Quality	1	All
Physical and Chemical Quality of Water	2	All
Microbiological Quality of Water	3	All
Introduction to Water Treatment	4	All
Disinfection	13	All
Internal Corrosion of Water Conduits	22	All

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Foreword

Since the printing of the first edition of *Water Treatment Principles and Design* in 1984, and even since the second edition in 2005, much has changed in the field of water treatment. There are new technologies and new applications of existing technologies being developed at an ever-increasing rate. These changes are driven by many different pressures, including water scarcity, regulatory requirements, public awareness, research, and our creative desire to find better, more cost-effective solutions to providing safe water.

Change is cause for optimism, as there is still so much to be done. According to the recent United Nations Report *Sick Water* (UNEP and UN-HABITAT, 2010), over half of the world's hospital beds are occupied with people suffering from illnesses linked to contaminated water and more people die as a result of polluted water than are killed by all forms of violence including wars. Perhaps our combined technologies and dedication can help change this reality.

The purpose of this third edition is to update our understanding of the technologies used in the treatment of water, with the hope that this will be more usable to students and practitioners alike. We are extremely fortunate to have assembled such an esteemed group of authors and to have received such extensive support from so many sources. We are extremely happy and proud of the result.

I would like to personally thank the principal authors Dr. Kerry J. Howe of the University of New Mexico and a former Principal Engineer at MWH, Dr. George Tchobanoglous of the University of California at Davis, Dr. John C. Crittenden of the Georgia Institute of Technology, Dr. R. Rhodes Trussell of Trussell Technologies, Inc. and a former Senior Vice President and Board Member of MWH, Dr. David W. Hand of the Michigan Technological University, and Mr. James H. Borchardt, Vice President of MWH.

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Finally, I would challenge those who read this book to consider their role in changing our world, one glass of water at a time.

Murli Tolaney
Chairman Emeritus
MWH Global, Inc.

1 Introduction

1-1 History of the Development of Water Treatment

1-2 Health and Environmental Concerns

Nineteenth Century

Twentieth Century

Looking to the Future

1-3 Constituents of Emerging Concern

Number of Possible Contaminants

Pharmaceuticals and Personal Care Products

Nanoparticles

Other Constituents of Emerging Concern

1-4 Evolution of Water Treatment Technology

Traditional Technologies

Introduction of Additional Treatment Technologies

Developments Requiring New Approaches and Technologies

Revolution Brought about by Use of Membrane Filtration

1-5 Selection of Water Treatment Processes

References

Securing and maintaining an adequate supply of water has been one of the essential factors in the development of human settlements. The earliest developments were primarily concerned with the quantity of water available. Increasing population, however, has exerted more pressure on limited high-quality surface sources, and the 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 general public has become both more knowledgeable and more discriminating about water

quality. Thus, the quality of a water source cannot be overlooked in water supply development. In fact, virtually all 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 evolution of water treatment practice has a rich history of empirical and scientific developments and challenges met and overcome.

The primary focus of this book is the application 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, community treatment plants, 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 a full range of topics associated with water treatment, starting in Chaps. 2 and 3 with an in-depth exploration of the physical, chemical, and microbiological aspects that affect water quality. Chapter 4 presents an overview of factors that must be considered when selecting a treatment strategy. Chapters 5 through 8 explain background concepts necessary for understanding the principles of water treatment, including fundamentals of chemical reactions, chemical reactors, mass transfer, and oxidation/reduction reactions. Chapters 9 through 18 are the heart of the book, presenting in-depth material on each of the principal unit processes used in municipal water treatment. Chapters 19 through 22 present supplementary material that is essential to an overall treatment system, including issues related to disinfection by-products, treatment strategies for specific contaminants, processing of treatment residuals, and corrosion in water distribution systems. The final chapter, Chap. 23, synthesizes all the previous material through a series of case studies.

The purpose of this introductory chapter is to provide some perspective on the (1) historical development of water treatment, (2) health concerns, (3) constituents of emerging concern, (4) evolution of water treatment technology, and (5) selection of water treatment processes. The material presented in this chapter is meant to serve as an introduction to the chapters that follow in which these and other topics are examined in greater detail.

1-1 History of the Development of Water Treatment

Some of the major events and developments that contributed to our understanding of the importance of water quality and the need to provide some means of improving the quality of natural waters are presented in Table 1-1. As reported in Table 1-1, one of the earliest water treatment techniques (boiling of water) was primarily conducted in containers in the households using the water. From the sixteenth century onward, however, it became increasingly clear that some form of treatment of large quantities of water was essential to maintaining the water supply in large human settlements.

1-2 Health and Environmental Concerns

The health concerns from drinking water have evolved over time. While references to filtration as a way to clarify water go back thousands of years, the relationship between water quality and health was not well understood or appreciated. Treatment in those days had as much to do with the aesthetic qualities of water (clarity, taste, etc.) as it did on preventing disease. The relationship between water quality and health became clear in the nineteenth century, and for the first 100 years of the profession of water treatment engineering, treatment was focused on preventing waterborne disease outbreaks. Since 1970, however, treatment objectives have become much more complex as public health concerns shifted from acute illnesses to the chronic health effects of trace quantities of anthropogenic (man-made) contaminants.

In the middle of the nineteenth century it was a common belief 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. This view began to change in the last half of that century. In 1854, Dr. John Snow demonstrated that an important cholera epidemic in London was the result of water contamination (Snow, 1855). Ten years later, Dr. Louis Pasteur articulated the germ theory of disease. Over the next several decades, a number of doctors, scientists, and engineers began to make sense of the empirical observations from previous disease outbreaks. By the late 1880s, it was clear that some important epidemic diseases were often waterborne, including cholera, typhoid fever, and amoebic dysentery (Olsztynski, 1988). As the nineteenth century ended, methods such as the coliform test were being developed to assess the presence of sewage contamination in a water supply (Smith, 1893), and the conventional water treatment process (coagulation/flocculation/sedimentation/filtration) was being developed as a robust way of removing contamination from municipal water supplies (Fuller, 1898).

Nineteenth Century

Table 1-1

Historical events and developments that have been precursors to development of modern water supply and treatment systems

Period	Event
4000 B.C.	Ancient Sanskrit and Greek writings recommend water treatment methods. In the Sanskrit Ousruta Sanghita it is noted that “impure water should be purified by being boiled over a fire, or being heated in the sun, or by dipping a heated iron into it, or it may be purified by filtration through sand and coarse gravel and then allowed to cool.”
3000 to 1500 B.C.	Minoan civilization in Crete develops technologies so advanced they can only be compared to modern urban water systems developed in Europe and North America in the second half of the nineteenth century. Technology is exported to Mediterranean region.
1500 B.C.	Egyptians reportedly use the chemical alum to cause suspended particles to settle out of water. Pictures of clarifying devices were depicted on the wall of the tomb of Amenophis II at Thebes and later in the tomb of Ramses II.
Fifth century B.C.	Hippocrates, the father of medicine, notes that rainwater should be boiled and strained. He invents the “Hippocrates sleeve,” a cloth bag to strain rainwater.
Third century B.C.	Public water supply systems are developed at the end of the third century B.C. in Rome, Greece, Carthage, and Egypt.
340 B.C. to 225 A.D.	Roman engineers create a water supply system that delivers water [490 megaliters per day (130 million gallons per day)] to Rome through aqueducts.
1676	Anton van Leeuwenhoek first observes microorganisms under the microscope.
1703	French scientist La Hire presents a plan to French Academy of Science proposing that every household have a sand filter and rainwater cistern.
1746	French scientist Joseph Amy is granted the first patent for a filter design. By 1750 filters composed of sponge, charcoal, and wool could be purchased for home use.
1804	The first municipal water treatment plant is installed in Paisley, Scotland. The filtered water is distributed by a horse and cart.
1807	Glasgow, Scotland, is one of the first cities to pipe treated water to consumers.
1829	Installation of slow sand filters in London, England.
1835	Dr. Robley Dunlingsen, in his book <i>Public Health</i> , recommends adding a small quantity of chlorine to make contaminated water potable.
1846	Ignaz Semmelweiss (in Vienna) recommends that chlorine be used to disinfect the hands of physicians between each visit to a patient. Patient mortality drops from 18 to 1 percent as a result of this action.
1854	John Snow shows that a terrible epidemic of Asiatic cholera can be traced to water at the Broad Street Well, which has been contaminated by the cesspool of a cholera victim recently returned from India. Snow, who does not know about bacteria, suspects an agent that replicates itself in the sick individuals in great numbers and exits through the gastrointestinal tract, and is transported by the water supply to new victims.
1854	Dr. Falipo Pacini, in Italy, identifies the organism that causes Asiatic cholera, but his discovery goes largely unnoticed.

Table 1-1 (Continued)

Period	Event
1856	Thomas Hawksley, civil engineer, advocates continuously pressurized water systems as a strategy to prevent external contamination.
1864	Louis Pasteur articulates the germ theory of disease.
1874	Slow sand filters are installed in Poughkeepsie and Hudson, New York.
1880	Karl Eberth isolates the organism (<i>Salmonella typhosa</i>) that causes typhoid fever.
1881	Robert Koch demonstrates in the laboratory that chlorine will inactivate bacteria.
1883	Carl Zeiss markets the first commercial research microscope.
1884	Professor Escherich isolates organisms from the stools of a cholera patient that he initially thought were the cause of cholera. Later it is found that similar organisms are also present in the intestinal tracts of every healthy individual as well. Organism eventually named for him (<i>Escherichia coli</i>).
1884	Robert Koch proves that Asiatic cholera is due to a bacterium, <i>Vibrio cholerea</i> , which he calls the comma bacillus because of its comma-like shape.
1892	A cholera epidemic strikes Hamburg, Germany, while its neighboring city, Altona, which treats its water using slow sand filtration, escapes the epidemic. Since that time, the value of granular media filtration has been widely recognized.
1892	The New York State Board of Health uses the fermentation tube method developed by Theobald Smith for the detection of <i>E. coli</i> to demonstrate the connection between sewage contamination of the Mohawk River and the spread of typhoid fever.
1893	First sand filter built in America for the express purpose of reducing the death rate of the population supplied is constructed at Lawrence, Massachusetts. To this end, the filter proves to be a great success.
1897	G. W. Fuller studies rapid sand filtration [5 cubic meters per square meter per day (2 gallons per square foot per day)] and finds that bacterial removals are much better when filtration is preceded by good coagulation and sedimentation.
1902	The first drinking water supply is chlorinated in Middelkerke, Belgium. Process is actually the "Ferrochlor" process wherein calcium hypochlorite and ferric chloride are mixed, resulting in both coagulation and disinfection.
1903	The iron and lime process of treating water (softening) is applied to the Mississippi River water supplied to St Louis, Missouri.
1906	First use of ozone as a disinfectant in Nice, France. First use of ozone in the United States occurs some four decades later.
1908	George Johnson, a member of Fuller's consulting firm, helps install continuous chlorination in Jersey City, New Jersey.
1911	Johnson publishes "Hypochlorite Treatment of Public Water Supplies" in which he demonstrates that filtration alone is not enough for contaminated supplies. Adding chlorination to the process of water treatment greatly reduces the risk of bacterial contamination.

(continues)

Table 1-1 (Continued)

Period	Event
1914	U.S. Public Health Service (U.S. PHS) uses Smith's fermentation test for coliform to set standards for the bacteriological quality of drinking water. The standards applied only to water systems that provided drinking water to interstate carriers such as ships and trains.
1941	Eighty-five percent of the water supplies in the United States are chlorinated, based on a survey conducted by U.S. PHS.
1942	U.S. PHS adopts the first comprehensive set of drinking water standards.
1974	Dutch and American studies demonstrate that chlorination of water forms trihalomethanes.
1974	Passage of the Safe Drinking Water Act (SDWA).

Source: Adapted from AWWA (1971), Baker (1948), Baker and Taras (1981), Blake (1956), Hazen (1909), Salvato (1992), and Smith (1893).

Twentieth Century

The twentieth century began with the development of continuous chlorination as a means for bacteriological control, and in the first 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 were considered microbiologically safe. In fact, during the 1940s and 1950s, having a microbiologically safe water supply became one of the principal signposts of an advanced civilization. The success of filtration and disinfection practices led to the virtual elimination of the most deadly waterborne diseases in developed countries, particularly typhoid fever and cholera.

FROM BACTERIA TO VIRUSES

The indicator systems and the treatment technologies for water treatment focused on bacteria as a cause of waterborne illness. However, scientists demonstrated that there were some infectious agents much smaller than bacteria (viruses) that could also cause disease. Beginning in the early 1940s and continuing into the 1960s, it became clear that viruses were also responsible for some of the diseases of the fecal–oral route, and traditional bacterial tests could not be relied upon to establish their presence or absence.

ANTHROPOGENIC CHEMICALS AND COMPOUNDS

Concern also began to build about the potential harm that anthropogenic chemicals in water supplies might have on public health. In the 1960s, the U.S. PHS developed some relatively simple tests using carbon adsorption and extraction in an attempt to assess the total mass of anthropogenic compounds in water. Then in the mid-1970s, with the development of the gas chromatograph/mass spectrometer, it became possible to detect these compounds at much lower levels. The concern about the potential

harm of man-made organic compounds in water coupled with improving analytical capabilities has led to a vast array of regulations designed to address these risks. New issues with anthropogenic chemicals will continue to emerge as new chemicals are synthesized, analytical techniques improve, and increasing population density impacts the quality of water sources.

DISINFECTION BY-PRODUCTS

A class of anthropogenic chemicals of particular interest in water treatment is chemical by-products of the disinfection process itself (disinfection by-products, or DBPs). DBPs are formed when disinfectants react with species naturally present in the water, most notably natural organic matter and some inorganic species such as bromide. The formation of DBPs increases as the dose of disinfectants or contact time with the water increases. Reducing disinfectant use to minimize DBP formation, however, has direct implications for increasing the risk of illness from microbial contamination. Thus, a trade-off has emerged between using disinfection to control microbiological risks and preventing the formation of undesirable man-made chemicals caused by disinfectants. Managing this trade-off has been one of the biggest challenges of the water treatment industry over the last 30 years.

MODERN WATERBORNE DISEASE OUTBREAKS

While severe waterborne disease has been virtually eliminated in developed countries, new sources of microbiological contamination of drinking water have surfaced in recent decades. Specifically, pathogenic protozoa have been identified that are zoonotic in origin, meaning that they can pass from animal to human. These protozoan organisms are capable of forming resistant, encysted forms in the environment, which exhibit a high level of resistance to treatment. The resistance of these organisms has further complicated the interrelationship between the requirements of disinfection and the need to control DBPs. In fact, it has become clear that processes that provide better physical removal of pathogens are required in addition to more efficient processes for disinfection.

The significance of these new sources of microbiological contamination has become evident in recent waterborne disease outbreaks, such as the outbreaks in Milwaukee, Wisconsin, in 1993 and Walkerton, Ontario, in 2000. In Milwaukee, severe storms caused contamination of the water supply and inadequate treatment allowed *Cryptosporidium* to enter the water distribution system, leading to over 400,000 cases of gastrointestinal illness and over 50 deaths (Fox and Lytle, 1996). The Walkerton incident was caused by contamination of a well in the local water system by a nearby farm. During the outbreak, estimates are that more than 2300 persons became ill due to *E. coli* O157:H7 and *Campylobacter* species (Clark et al., 2003). Of the 1346 cases that were reported, 1304 (97 percent) were considered to be directly due to the drinking water. Sixty-five

persons were hospitalized, 27 developed hemolytic uremic syndrome, and 6 people died.

Another challenge associated with microbial contamination is that the portion of the world's population that is immunocompromised is increasing over time, due to increased life spans and improved medical care. The immunocompromised portion of the population is more susceptible to health risks, including those associated with drinking water.

Looking to the Future

As the twenty-first century begins, the challenges of water treatment have become more complex. Issues include the identification of new pathogens such as *Helicobacter pylori* and the noroviruses, new disinfection by-products such as *N*-nitrosodimethylamine (NDMA), and a myriad of chemicals, including personal care products, detergent by-products, and other consumer products. As analytical techniques improve, it is likely that these issues will grow, and the water quality engineer will face ever-increasing challenges.

1-3 Constituents of Emerging Concern

Contaminants and pathogens of emerging concern are by their very nature unregulated constituents that may pose a serious threat to human health. Consequently, they pose a serious obstacle to delivering the quality and quantity of water that the public demands. Furthermore, emerging contaminants threaten the development of more environmentally responsible water resources that do not rely on large water projects involving reservoirs and dams in more pristine environments. Creating acceptable water from water resources that are of lower quality because of contaminants of emerging concern is more expensive, and there is resistance to increased spending for public water supply projects (NRC, 1999).

Number of Possible Contaminants

The sheer number of possible contaminants is staggering. The CAS (Chemical Abstracts Service, a division of the American Chemical Society) Registry lists more than 55 million unique organic and inorganic chemicals (CAS, 2010a). In the United States, about 70,000 chemicals are used commercially and about 3300 are considered by the U.S. Environmental Protection Agency (EPA) to be high-volume production chemicals [i.e., are produced at a level greater than or equal to 454,000 kg/yr (1,000,000 lb/yr)]. The CAS also maintains CHEMLIST, a database of chemical substances that are the target of regulatory activity someplace in the world; this list currently contains more than 248,000 substances (CAS, 2010b).

Pharmaceuticals and Personal Care Products

Increasing interconnectedness between surface waters used for discharge of treated wastewater and as a source for potable water systems has created concern about whether trace contaminants can pass through the wastewater treatment system and enter the water supply. Many recent investigations

have found evidence of low concentrations of pharmaceuticals and personal care products (PPCPs) and endocrine disrupting compounds (EDCs) in the source water for many communities throughout the United States and other developed nations.

Pharmaceuticals can enter the wastewater system by being excreted with human waste after medication is ingested or because of the common practice of flushing unused medication down the toilet. Pharmaceuticals include antibiotics, analgesics [painkillers such as aspirin, ibuprofen (Advil), acetaminophen (Tylenol)], lipid regulators (e.g., atorvastatin, the active ingredient in Lipitor), mood regulators (e.g., fluoxetine, the active ingredient in Prozac), antiepileptics (e.g., carbamazepine, the active ingredient in many epilepsy and bipolar disorder medications), and hundreds of other medications. Personal care products, which include cosmetics and fragrances, acne medications, insect repellants, lotions, detergents, and other products, can be washed from the skin and hair during washing or showering. Endocrine disrupting chemicals are chemicals that have the capability to interfere with the function of human hormones. EDCs include actual hormones, such as estrogens excreted by females after use of birth-control pills, or other compounds that mimic the function of hormones, such as bisphenol A. Studies have shown that some of these compounds are effectively removed by modern wastewater treatment processes, but others are not. Although the compounds are present at very low concentrations when they are detected, the public is concerned about the potential presence of these compounds in drinking water.

The manufacture of nanoparticles is a new and rapidly growing field. Nanoparticles are very small particles ranging from 1 to 100 nanometers (nm) used for applications such as the delivery of pharmaceuticals across the blood–brain barrier. Because nanomaterials are relatively new and the current market is small, a knowledge base of the potential health risks and environmental impacts of nanomaterials is lacking. As the manufacture of nanomaterials increases, along with the potential for discharge to the environment, more research to establish health risks and environmental impacts may be appropriate.

In addition to the constituents listed above, other constituents of emerging concern include (1) fuel oxygenates (e.g., methyl *tert*-butyl ether, MTBE), (2) *N*-nitrosodimethylamine (NDMA), (3) perchlorate, (4) chromate, and (5) veterinary medications that originate from concentrated animal-feeding operations.

Nanoparticles

Other Constituents of Emerging Concern

1-4 Evolution of Water Treatment Technology

To understand how the treatment methods discussed in this book developed, it is appropriate to consider their evolution. Most of the methods in use at the beginning of the twentieth century evolved out of physical

observations (e.g., if turbid water is allowed to stand, a clarified liquid will develop as the particles settle) and the relatively recent (less than 120 years) recognition of the relationship between microorganisms in contaminated water and disease. A list of plausible methods for treating water at the beginning of the twentieth century was presented in a book by Hazen (1909) and is summarized in Table 1-2. It is interesting to note that all of the treatment methods reported in Table 1-2 are still in use today. The most important modern technological development in the field of water treatment not reflected in Table 1-2 is the use of membrane technology.

Table 1-2

Summary of methods used for water treatment early in the twentieth century

Treatment Method	Agent/Objectives
I. Mechanical separation	<input type="checkbox"/> By gravity—sedimentation <input type="checkbox"/> By screening—screens, scrubbers, filters <input type="checkbox"/> By adhesion—scrubbers, filters
II. Coagulation	<input type="checkbox"/> By chemical treatment resulting in drawing matters together into groups, thereby making them more susceptible to removal by mechanical separation but without any significant chemical change in the water
III. Chemical purification	<input type="checkbox"/> Softening—by use of lime <input type="checkbox"/> Iron removal <input type="checkbox"/> Neutralization of objectionable acids
IV. Poisoning processes (now known as disinfection processes)	<input type="checkbox"/> Ozone <input type="checkbox"/> Sulfate of copper <input type="checkbox"/> The object of these processes is to poison and kill objectionable organisms without at the same time adding substances objectionable or poisonous to the users of the water
V. Biological processes	<input type="checkbox"/> Oxidation of organic matter by its use as food for organisms that thereby effect its destruction <input type="checkbox"/> Death of objectionable organisms, resulting from the production of unfavorable conditions, such as absence of food (removed by the purification processes) and killing by antagonistic organisms
VI. Aeration	<input type="checkbox"/> Evaporation of gases held in solution that are the cause of objectionable tastes and odors <input type="checkbox"/> Evaporation of carbonic acid, a food supply for some kinds of growths <input type="checkbox"/> Supplying oxygen necessary for certain chemical purifications and especially necessary to support growth of water-purifying organisms
VII. Boiling	<input type="checkbox"/> Best household method of protection from disease-carrying waters

Source: Adapted from Hazen (1909).