Stantec

**Updated Third Edition**

# Water Treatment

## Principles and Design

John C. Crittenden | R. Rhodes Trussell
David W. Hand | Kerry J. Howe
George Tchobanoglous

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# Preface

Making water safe to drink is complicated. A myriad of constituents can be present in natural waters, with different concentrations, different physical and chemical properties, and representing different hazards. Removing them requires integrating unit processes into a process train, in which each process may remove specific constituents or help another process work more effectively. This book has a rich history of helping students and professional engineers understand the fundamental principles of water treatment and provides a pathway to successful treatment plant design.

Some early practitioners of water treatment engineering relied on trial-and-error, and then replicating designs that were found to be successful. Others recognized that separation processes obey fundamental scientific principles. One in the latter camp was James M. Montgomery, who founded James M. Montgomery, Consulting Engineers, Inc. (JMM) in 1945. With the underpinning of Mr. Montgomery's scientific and engineering talents, the firm grew to be one of the leading environmental engineering firms in the United States and was widely respected as an innovator of the art, science, design, and engineering of water treatment systems.

Recognizing the exceptional expertise of the firm and wanting to honor their founder's devotion to training other engineers, the company's leadership set about to write a textbook that could serve as a resource to engineers throughout the rapidly growing – and rapidly changing – field of water treatment engineering. Over a period of several years, more than 50 employees contributed as authors or reviewers, led by Dr. Michael C. Kavanaugh, Dr. Susumu Kawamura, Dr. Carol Tate, Dr. R. Rhodes Trussell, and William W. Aultman. The first edition of *Water Treatment Principles and Design* was published in 1985 and quickly became the most prominent and respected resource for water treatment engineering among practitioners and students alike.

The 1980s and 1990s were a period of rapid change following the passage of the Safe Drinking Water Act in 1974. Within a decade, portions of the first edition were becoming dated and processes such as ozonation, adsorption, advanced oxidation, and reverse osmosis were becoming strategies for achieving more complex water treatment goals. In the mid-1990s, recognizing that an update was necessary, the company (then named Montgomery Watson, following a 1990 merger with the firm Watson Hawksley from the United Kingdom) embarked on writing a revision. Unfortunately, the challenges of engaging many experts within the company drove up the cost and dragged out the schedule, and after several years the effort was abandoned.

With efforts to write a revision with internal experts stymied and fearing the book would become obsolete, Dr. R. Rhodes Trussell convinced Montgomery Watson's leadership to engage a select group of outside experts to assist him in updating the original text. Drs. John C. Crittenden, George Tchobanoglous, David W. Hand, and Kerry J. Howe (a former JMM employee) were retained. By then, more time had passed and more new processes needed to be incorporated into the text. In the end, the new authors completely restructured the contents, and the second edition of *Water Treatment Principles and Design* emerged as an entirely new book while retaining the original book's (and James Montgomery's) commitment to grounding water treatment plant design on fundamental principles. The second edition was published in 2005, under the corporate logo of Montgomery Watson Harza (MWH), following the 2001 merger between Montgomery Watson and Harza Engineering Company.

As the water treatment industry continued to evolve, a third edition quickly became necessary. The authors, with support from James H. Borchardt of MWH, completed *MWH's Water Treatment Principles and Design, 3rd. edition* in 2012. Simultaneous with the 3rd edition, an abridged version of the text was prepared, trimmed to include only the essential principles that could be covered in a one-semester college course in water treatment. *Principles of Water Treatment*, weighing in at only 650 pages compared to the larger book's 1900 pages, was also published in 2012.

In 2016, MWH Global (which had grown to 6,800 employees) was acquired by Stantec, a Canadian engineering firm started by environmental engineer Dr. Don Stanley in 1954. The combined firm, with 22,000 employees, offers top-tier design services to water clients around the world from offices in over 400 locations. During the time of the acquisition, important changes were taking place in the water treatment industry and the world. In the industry, water scarcity was becoming an important driver of water treatment projects, and many communities began exploring alternative water sources like seawater desalination and potable reuse. Although desalination was already covered in the 3rd edition, the complexities of advanced treatment trains for potable reuse now warrant significant coverage. Another trend was the growing prominence of online resources and content as a way of learning and sharing information. Having acquired the legacy of *MWH's Water Treatment Principles and Design* in the merger, Stantec wanted to make sure that the book remained relevant in a changing world. Bill Ward of Stantec initiated discussions with the authors of the 3rd edition to update the book. Mr. Ward suggested the addition of QR codes in the book margins that link to online content and identified materials for the book's website (hosted on Stantec.com), while the 3rd edition authors wrote a new chapter on potable reuse. This book—*Stantec's Water Treatment: Principles and Design, updated 3rd. edition*—is the product of that latest collaboration. We hope you, the reader, will use it to further your knowledge in the exciting field of water treatment.

## 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) 409 homework problems, designed to develop students understanding of the subject matter, (3) 247 tables that contain physical properties of chemicals, design data, and thermodynamic properties of chemicals, to name a few, and (4) 458 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.

Errata- For corrections to the printed text, use this link:
http://www.stantec.com/wt3r/Preface-1.html

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The authors are indebted to everyone who assisted with the preparation of this latest edition of this book. Most importantly, we thank Mr. Bill Ward, PE, Director at Stantec, for being the driving force to start this revision, advocating for its publication within Stantec, serving as a liaison between Stantec and the authors, and bringing creative ideas such as the QR codes linking to online content to the project. Without his initiative, this edition would not have been published. Thanks to Dr. Amir Alansari; Dr. Laith Furatian, P.Eng.; Dr. Sanaz Imen, PE; and Dr. Ayman Shawwa, PE, BCEE, PMP, all from Stantec, and Mr. Reed Warburton of Bowdoin College for reviewing the page proofs to help ensure the accuracy of this edition.

Most of the content of this edition is held over from the 3rd edition, and those who contributed to that edition are gratefully acknowledged. Dr. Harold Leverenz prepared most of the figures, and figures for several chapters were prepared by Mr. James Howe. Dr. Zhonming Lu and Dr. Daisuke Minakata contributed to writing and revising Chapters 15 and 18, respectively. Mr. Osvaldo A. Broesicke assisted with the preparation of Figure 6-20. Mr. Carson O. Lee and Mr. Daniel Birdsell reviewed and checked many of the chapters, including the figure, table, and equation numbers, the math in example problems, and the references at the end of the chapters. Mr. James Borchardt, PE, Vice President at Stantec, served as a liaison to Stantec and coordinated technical input from Stantec staff.

For the 3rd edition, several MWH employees provided technical input, prepared case studies, gathered technical information on MWH projects, prepared graphics and photos, and provided administrative support. These include: Ms. Donna M. Arcaro; Dr. Jamal Awad, PE, BCEE; Mr. Charles O. Bromley, PE, BCEE; Dr. Arturo A. Burbano, PE, BCEE; Mr. Ronald M. Cass, PE; Mr. Harry E. Dunham, PE; Mr. Frieder H. Ehrlich, C Eng, MAIChemE; Mr. Andrew S. Findlay, PE; Mr. Mark R. Graham, PE; Mr. Jude D. Grounds, PE; Ms. Stefani O. Harrison, PE; Dr. Joseph G. Jacangelo, REHS; Ms. Karla J. Kinser, PE; Mr. Peter H. Kreft, PE; Mr. Stewart E. Lehman, PE; Mr. Richard Lin, PE; Mr. William H. Moser, PE; Mr. Michael A. One-by, PE; Mr. Michael L. Price, PE; Mr. Nigel S. Read, C Eng; Mr. Matthieu F. Roussillon, PE; Ms. Stephanie J. Sansom, PE; Mr. Gerardus J. Schers, PE; Ms. Jackie M. Silber; Mr. William A. Taplin, PE; and Dr. Timothy A. Wolfe, PE, BCEE.

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John C. Crittenden
R. Rhodes Trussell
David W. Hand
Kerry J. Howe
George Tchobanoglous

# Foreword

Looking back on this and the prior editions of "Water Treatment Principles and Design," it is apparent that the authors have been innovating, developing, and adapting continuously to a world that is always changing. The first edition of this book was published in 1985, the second edition in 2005 and the third edition in 2012. Each edition represents a significant step forward in applying good science to the pressing issues of the day. Refinement of proven technologies and introduction of new techniques have enabled practitioners to consistently deliver safe and reliable water to people, even in the face of changing climate, emerging contaminants, water scarcity, aging infrastructure, and ever tightening budgets.

As we all work to deliver drinking water to ever more people, our governments, scientists, and engineers face challenges not seen by their predecessors. Huge populations have moved to water-limited geographies; changes in weather patterns coupled with demand have caused some supplies to evaporate before our eyes; many new and emerging chemicals are already prevalent in our environment and known to be persistent, dangerous, and difficult to treat; and every year our investment in water treatment and distribution infrastructure falls farther behind. Innovation, emerging technologies, and more effective application of best engineering practices can help us bridge these gaps.

With that in mind, our goal for this revised third edition is to collaborate with the esteemed authors to update students and practitioners on the topic of potable reuse, to deliver a focused multimedia library of supplemental information via the internet, and to address some increasingly important contaminants of emerging concern.

We all owe a debt of gratitude to the principal authors: Dr. Kerry Howe of the University of New Mexico, Dr. George Tchobanoglous of the University of California at Davis, Dr. John Crittenden of the Georgia Institute of Technology, Dr. Rhodes Trussell of Trussell Technologies, Inc., and Dr. David Hand of the Michigan Technological University for collaborating to carefully develop this invaluable encyclopedic text. Thanks also to James

Borchardt, P.E. of Stantec, who contributed to the Third Edition of the text. Thank you also, Kalli Schultea of Wiley, who helped us bring this edition forward.

And we are all grateful to you, our reader, for learning more about the science of drinking water treatment. You each contribute incrementally to a noble effort that has delivered safe and reliable drinking water to large portions of humanity, contributing to a collective work that enables so many of us to enjoy a quality of life that was not available to those who came before the field developed. With your help, may we do the same for the billions of people our profession has not yet served.

***Bill Ward, J.D., P.E.***
*Senior Advisor*
*Stantec Institute for Water Technology & Policy*

# About the Authors

**Dr. John C. Crittenden** is the director of the Brook Byers Institute for Sustainable Systems and a professor in Civil and Environmental Engineering at the Georgia Institute of Technology. He holds the Hightower Chair and is a Georgia Research Alliance Eminent Scholar in Environmental Technologies. Dr. Crittenden was elected to the US National Academy of Engineering in 2002, the Chinese Academy of Engineering in 2013, and the European Academy of Sciences in 2019. He has received the NWRI Clarke Prize, the ASCE Simon W. Freese Award, and the Friendship Medal from China. He is the co-holder of five patents and is the author more than 415 articles in refereed journals, more than 100 book chapters, reports, and symposia, and has more than 30,000 citations. Dr. Crittenden has a B.S. in chemical engineering and M.S. and Ph.D. degrees in civil engineering from the University of Michigan.

**Dr. R. Rhodes Trussell** is a registered civil and corrosion engineer in the State of California with 50 years of water treatment experience. After working for 33 years for MWH, Inc. (now part of Stantec), he founded Trussell Technologies, Inc., a consulting firm specializing in the application of science to engineering. He was elected to the National Academy of Engineering in 1995. Dr. Trussell has been awarded the Boyd Award by AMWA, the Pohland Award by AEESP, the AP Black Award by AWWA, the Global Water Award by IWA, the Clarke Prize by NWRI, and the Simon W. Freese Award by ASCE. He has authored more than 200 publications, including several chapters in all editions of Stantec's Water Treatment: Principles and Design. He has B.S., M.S., and Ph.D. degrees in environmental engineering from the University of California at Berkeley.

**Dr. David W. Hand** is a professor emeritus of civil, environmental, and geospatial engineering at Michigan Technological University. His teaching and research focus on water and wastewater treatment engineering with emphasis on physicochemical treatment processes. He received the ASCE Rudolf Hering Medal, the AEESP Award for Outstanding Teaching in Environmental Engineering and Science, and a publication award from AWWA. He is a Board Certified Environmental Engineering Member of AAEES. He has authored or coauthored over 130 technical publications including six textbooks, two patents, and eight copyrighted software programs. He has B.S., M.S. and Ph.D. degrees in engineering and civil engineering from the Michigan Technological University.

**Dr. Kerry J. Howe** is a distinguished professor in Civil, Construction, and Environmental Engineering at the University of New Mexico, the director of the Center for Water and the Environment, and has over 35 years of water treatment experience. He worked for over 10 years as a design engineer at MWH, Inc., now part of Stantec. Dr. Howe is a registered professional engineer in New Mexico and Wisconsin, and a Board Certified Environmental Engineer by the AAEES. He has authored or coauthored over 180 presentations, technical reports, and peer-reviewed journal publications. He has a B.S. degree from the University of Wisconsin-Madison, an M.S. degree from the University of Texas at Austin, and a Ph.D. degree from the University of Illinois at Urbana-Champaign.

**Dr. George Tchobanoglous** is professor emeritus in the Department of Civil and Environmental Engineering at the University of California, Davis. He is a member of the US National Academy of Engineering, the European Academy of Sciences and Arts, and a corresponding member of the Academy of Athens. He has received Honorary Doctor of Engineering degrees from the Colorado School of Mines, the Aristotle University of Thessaloniki, and the Technical University of Crete, Greece. Dr. Tchobanoglous has been awarded the Clarke Prize by NWRI and the Pohland Award by AEESP. He has authored or coauthored over 600 publications, including 23 textbooks and 8 reference books, and has given more than 625 presentations. Dr. Tchobanoglous received a B.S. in civil engineering from the University of the Pacific, an M.S. in sanitary engineering from the University of California, Berkeley, and a Ph.D. in environmental engineering from Stanford University.

# 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 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.


*Stantec's Water Treatment: Principles and Design,* Updated Third Edition. John C. Crittenden, R. Rhodes Trussell, David W. Hand, Kerry J. Howe, and George Tchobanoglous.

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 (manmade) contaminants.

**Nineteenth Century**

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).

**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 *Public Health*, 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 (*Salmonella typhosa*) 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 (*Escherichia coli*). |
| 1884 | Robert Koch proves that Asiatic cholera is due to a bacterium, *Vibrio cholerea*, 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 *E. coli* 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 where in 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. |

(*Continued*)

**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

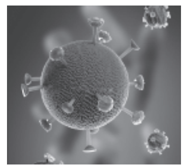
Concern also began to build about the potential harm that anthropogenic chemicals in water supplies might have on public health. In the 1960s, the U.S. PHS developed some relatively simple tests using carbon adsorption and extraction in an attempt to assess the total mass of anthropogenic compounds in 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.



Water engineers must be knowledgeable about potential risks from new pathogens.
http://www.stantec.com/wt3r/1-1.html

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.

The list of CECs is continually changing. Follow this link to see some recent chemicals of concern.

http://www.stantec.com/wt3r/1-2.html

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.

### Nanoparticles

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.

### Other Constituents of Emerging Concern

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.

## 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 | ❑ By gravity—sedimentation<br>❑ By screening—screens, scrubbers, filters<br>❑ By adhesion—scrubbers, filters |
| II. Coagulation | ❑ 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 | ❑ Softening—by use of lime<br>❑ Iron removal<br>❑ Neutralization of objectionable acids |
| IV. Poisoning processes (now known as disinfection processes) | ❑ Ozone<br>❑ Sulfate of copper<br>❑ 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 | ❑ Oxidation of organic matter by its use as food for organisms that thereby effect its destruction<br>❑ 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 | ❑ Evaporation of gases held in solution that are the cause of objectionable tastes and odors<br>❑ Evaporation of carbonic acid, a food supply for some kinds of growths<br>❑ Supplying oxygen necessary for certain chemical purifications and especially necessary to support growth of water-purifying organisms |
| VII. Boiling | ❑ Best household method of protection from disease-carrying waters |

*Source*: Adapted from Hazen (1909).