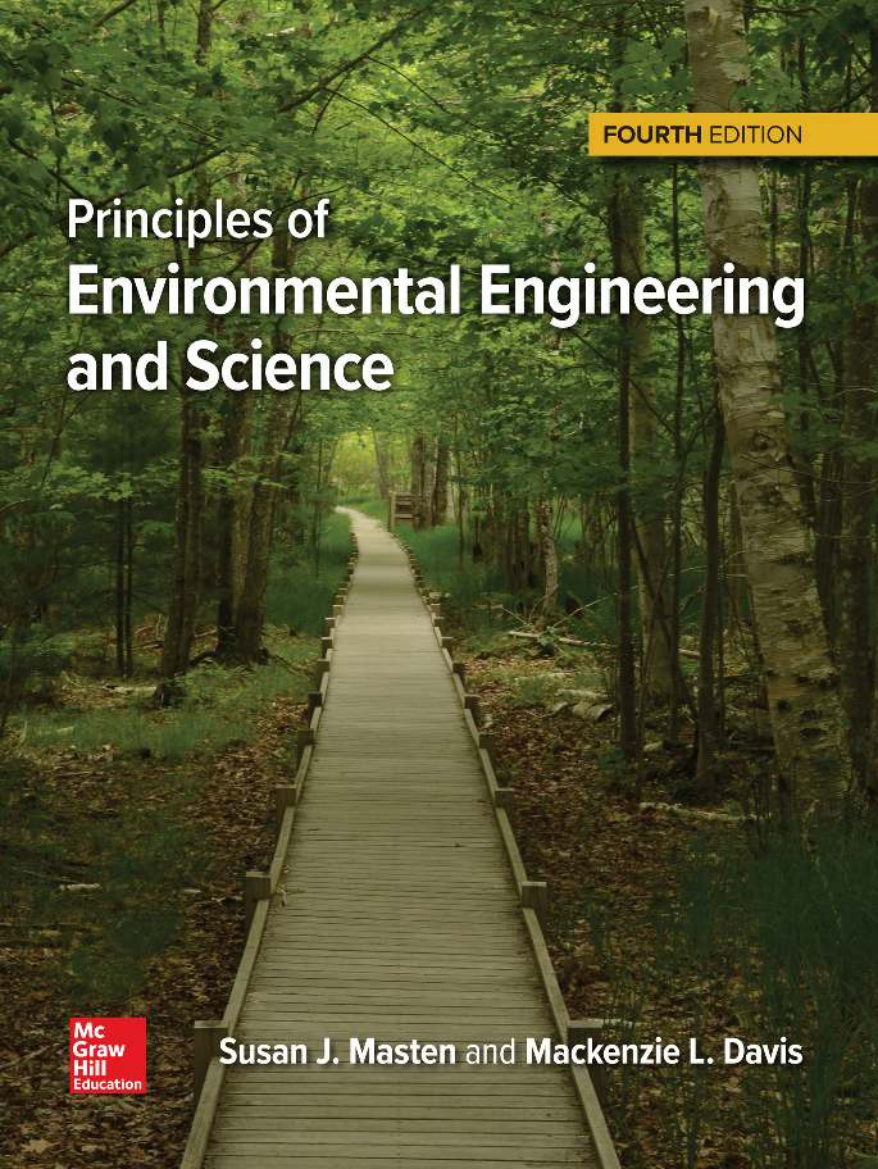

FOURTH EDITION

# Principles of Environmental Engineering and Science

Susan J. Masten and Mackenzie L. Davis

McGraw Hill Education

# Principles of Environmental Engineering and Science

**Fourth Edition**

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McGraw Hill Education

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# Preface

Following the format of previous editions, the fourth edition of *Principles of Environmental Engineering and Science* is designed for use in an introductory sophomore-level engineering course. Basic, traditional subject matter is covered. Fundamental science and engineering principles that instructors in more advanced courses may depend upon are included. Mature undergraduate students in allied fields—such as biology, chemistry, resource development, fisheries and wildlife, microbiology, and soils science—have little difficulty with the material.

We have assumed that the students using this text have had courses in chemistry, physics, and biology, as well as sufficient mathematics to understand the concepts of differentiation and integration. Basic environmental chemistry and biology concepts are introduced at the beginning of the book.

Materials and energy balance is introduced early in the text. It is used throughout the text as a tool for understanding environmental processes and solving environmental problems. It is applied in hydrology, sustainability, water quality, water and wastewater treatment, air pollution control, as well as solid and hazardous waste management.

Each chapter concludes with a list of review items, the traditional end-of-chapter problems and discussion questions. The review items have been written in the "objective" format of the Accreditation Board for Engineering and Technology (ABET). Instructors will find this particularly helpful for directing student review for exams, for assessing continuous quality improvement for ABET and for preparing documentation for ABET curriculum review.

The fourth edition has been thoroughly revised and updated. FE formatted problems have been added to the appropriate chapters. New case studies have been added to many of the chapters as well. The following summarizes the major changes in this edition:

- Introduction
  - Data on per capita water consumption has been updated
- Biology
  - Section on harmful algae blooms has been updated
  - Addition of section on Legionellosis
- Ecosystems
  - Updated figures and charts
- Risk
  - Updated tables
- Hydrology
  - Updated figures and tables
  - Addition of discussion of effect of climate change
- Sustainability
  - Updated discussion of water resources focusing on floods and droughts with examples in the United States and in other countries
  - Updated tables and figures on energy and mineral resources
  - Expanded discussion of shale gas includes flowback and earthquakes
- Water Quality Management
  - Updated figures and charts
  - Updated section on water source protection

- Water Treatment
  - Expanded overview of treatment systems
  - Updated section on regulations
  - Updated figures and charts
  - Expansion of section on disinfection to include breakpoint chlorination and UV disinfection
- Wastewater Treatment
  - Addition of direct potable reuse discussion
- Air Pollution
  - Updated ambient air pollution standards
  - Updated discussion of acidification of lakes
  - Addition of mercury control technology for power plants
  - Update of federal motor vehicle standards
  - New discussion of CAFE standards
  - New discussion of the use of coal in power plants
  - Update of global warming potential data for selected compounds
  - Updated graphs of global surface temperature
  - New graph of $CO_2$ concentration
- Solid Waste
  - Updated figures and charts

### *Online Resources*

Case Studies from the previous edition are still available for use at www.mhhe.com /davisprinciples4e. Powerpoint slides and an instructor's manual are also available. The instructor's manual includes sample course outlines, solved example exams, and detailed solutions to the end-of-chapter problems. In addition, there are suggestions for using the pedagogic aids in the next.

As always, we appreciate any comments, suggestions, corrections, and contributions for future revisions.

Susan J. Masten
Mackenzie L. Davis

# Acknowledgments

As with any other text, the number of individuals who have made it possible far exceeds those whose names grace the cover. At the hazard of leaving someone out, we would like to explicitly thank the following individuals for their contribution.

The following students helped to solve problems, proofread text, prepare illustrations, raise embarrassing questions, and generally make sure that other students could understand it: Shelley Agarwal, Stephanie Albert, Deb Allen, Mark Bishop, Aimee Bolen, Kristen Brandt, Jeff Brown, Amber Buhl, Nicole Chernoby, Rebecca Cline, Linda Clowater, Shauna Cohen, John Cooley, Ted Coyer, Marcia Curran, Talia Dodak, Kimberly Doherty, Bobbie Dougherty, Lisa Egleston, Karen Ellis, Elaheh Esfahanian, Craig Fricke, Elizabeth Fry, Beverly Hinds, Edith Hooten, Brad Hoos, Kathy Hulley, Geneva Hulslander, Lisa Huntington, Angela Ilieff, Melissa Knapp, Alison Leach, Gary Lefko, Lynelle Marolf, Lisa McClanahan, Tim McNamara, Becky Mursch, Cheryl Oliver, Kyle Paulson, Marisa Patterson, Lynnette Payne, Jim Peters, Kristie Piner, Christine Pomeroy, Susan Quiring, Erica Rayner, Bob Reynolds, Laurene Rhyne, Sandra Risley, Carlos Sanlley, Lee Sawatzki, Stephanie Smith, Mary Stewart, Rick Wirsing, Ya-yun Wu. To them a hearty thank you!

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We would also like to thank the following reviewers for their many helpful comments and suggestions: Max Anderson, University of Wisconsin–Platteville; Gregory Boardman, Virginia Tech; Jonathan Brant, University of Wyoming; Leonard W. Casson, University of Pittsburgh–Swanson School of Engineering; Andres Clarens, University of Virginia; Lubo Liu, California State University–Fresno; George Murgel, Boise State University; John Novak, Virginia Tech; Jonathan Sharp, Colorado School of Mines.

We give special thanks to Simon Davies for his contributions and unending support. His efforts are sincerely appreciated. And last, but certainly not least, we wish to thank our families who have put up with us during the writing of this book, especially Quentin and Jeffrey Masten-Davies, who gave up several Christmas vacations plus many other days during the year while their mom spent uncountable hours working on this book.

A special thanks to Mack's wife, Elaine, for putting up with the nonsense of book writing.

Susan J. Masten Mackenzie L. Davis

# About the Authors

**Susan J. Masten** is a Professor in the Department of Civil and Environmental Engineering at Michigan State University. She received her Ph.D. in environmental engineering from Harvard University in 1986. Before joining the faculty at Michigan State University in 1989, she worked for several years in environmental research at the University of Melbourne (Australia) and at the US Environmental Protection Agency's Kerr Laboratory, in Ada, Oklahoma. Professor Masten's research involves the use of chemical oxidants for the remediation of soils, water, and wastewater. Her research is presently focused on the use of ozone for reducing the concentration of disinfection by-products in drinking water, controlling fouling in membranes, and reducing the toxicity of ozonation by-products formed from the ozonation of polycyclic aromatic hydrocarbons and pesticides. She also had research projects involving the use of ozone for the reduction of odor in swine manure slurry and the elimination of chlorinated hydrocarbons and semivolatile organic chemicals from soils using in-situ ozone stripping and ozone sparging.

Dr. Masten is a member of the following professional organizations: American Water Works Association, Association of Environmental Engineering and Science Professors (AEESP), and American Chemical Society. She served on the Executive Committee of the MSU Chapter of the American Chemical Society from 1995–2005. She has served as the chair of the AEESP Publications Committee since 2013.

Professor Masten was a Lilly Teaching Fellow during the 1994–1995 academic year. She is also the recipient of the Withrow Distinguished Scholar Award, College of Engineering, MSU, March 1995, and the Teacher-Scholar Award, Michigan State University, February 1996, and the Withrow Teaching Award in 2012 and 2018. Dr. Masten was also a member of the Faculty Writing Project, Michigan State University, May 1996. In 2001, she was awarded the Association of Environmental Engineering and Science Professors/Wiley Interscience Outstanding Educator Award, and in 2013, she was awarded the Lyman A. Ripperton Environmental Educator Award by the Air and Waste Management Association. Professor Masten was awarded an Erskine Fellowship in 2018 from the University of Canterbury, Christchurch, NZ.

Dr. Masten is a registered professional engineer in the state of Michigan.

**Mackenzie L. Davis, Ph.D., P.E., BCEE,** is an Emeritus Professor of Environmental Engineering at Michigan State University. He received all his degrees from the University of Illinois. From 1968 to 1971 he served as a Captain in the U.S. Army Medical Service Corps. During his military service he conducted air pollution surveys at Army ammunition plants. From 1971 to 1973 he was Branch Chief of the Environmental Engineering Branch at the U.S. Army Construction Engineering Research Laboratory. His responsibilities included supervision of research on air, noise, and water pollution control and solid waste management for Army facilities. In 1973 he joined the faculty at Michigan State University. He has taught and conducted research in the areas of air pollution control and hazardous waste management.

In 1987 and 1989–1992, under an intergovernmental personnel assignment with the Office of Solid Waste of the U.S. Environmental Protection Agency, Dr. Davis performed technology assessments of treatment methods used to demonstrate the regulatory requirements for the land disposal restrictions ("land ban") promulgated under the Hazardous and Solid Waste Amendments.

Dr. Davis is a member of the following professional organizations: American Chemical Society, American Institute of Chemical Engineers, American Society for Engineering Education, American Meteorological Society, American Society of Civil Engineers, American Water

Works Association, Air & Waste Management Association, Association of Environmental Engineering and Science Professors, and the Water Environment Federation.

His honors and awards include the State-of-the-Art Award from the ASCE, Chapter Honor Member of Chi Epsilon, Sigma Xi, election as a Fellow in the Air & Waste Management Association, and election as a Diplomate in the American Academy of Environmental Engineers with certification in hazardous waste management. He has received teaching awards from the American Society of Civil Engineers Student Chapter, Michigan State University College of Engineering, North Central Section of the American Society for Engineering Education, Great Lakes Region of Chi Epsilon, and the Amoco Corporation. In 1998, he received the Lyman A. Ripperton Award for distinguished achievement as an educator from the Air & Waste Management Association. In 2007, he was recognized as the Educational Professional of the Year by the Michigan Water Environment Association. He is a registered professional engineer in Michigan.

Dr. Davis is the author of a student and professional edition of *Water and Wastewater Engineering* and co-author of *Introduction to Environmental Engineering* with Dr. David Cornwell.

In 2003, Dr. Davis retired from Michigan State University.

# 1

# Introduction

## 1–1 WHAT IS ENVIRONMENTAL SCIENCE?

### *Natural Science*

In the broadest sense, science is systematized knowledge derived from and tested by recognition and formulation of a problem, collection of data through observation, and experimentation. We differentiate between social science and natural science in that the former deals with the study of people and how they live together as families, tribes, communities, races, and nations, and the latter deals with the study of nature and the physical world. Natural science includes such diverse disciplines as biology, chemistry, geology, physics, and environmental science.

### *Environmental Science*

Whereas the disciplines of biology, chemistry, and physics (and their subdisciplines of microbiology, organic chemistry, nuclear physics, etc.) are focused on a particular aspect of natural science, environmental science in its broadest sense encompasses all the fields of natural science. The historical focus of study for environmental scientists has been, of course, the natural environment. By this, we mean the atmosphere, the land, the water and their inhabitants as differentiated from the built environment. Modern environmental science has also found applications to the built environment or, perhaps more correctly, to the effusions from the built environment.

### *Quantitative Environmental Science*

Science or, perhaps more correctly, the **scientific method,** deals with data, that is, with recorded observations. The data are, of course, a sample of the universe of possibilities. They may be representative or they may be skewed. Even if they are representative, they will contain some random variation that cannot be explained with current knowledge. Care and impartiality in gathering and recording data, as well as independent verification, are the cornerstones of science.

When the collection and organization of data reveal certain regularities, it may be possible to formulate a generalization or **hypothesis.** This is merely a statement that under certain circumstances certain phenomena can generally be observed. Many generalizations are statistical in that they apply accurately to large assemblages but are no more than probabilities when applied to smaller sets or individuals.

In a scientific approach, the hypothesis is tested, revised, and tested again until it is proven acceptable.

If we can use certain assumptions to tie together a set of generalizations, we formulate a theory. For example, theories that have gained acceptance over a long time are known as **laws.** Some examples are the laws of motion, which describe the behavior of moving bodies, and the gas laws, which describe the behavior of gases. The development of a **theory** is an important accomplishment because it yields a tremendous consolidation of knowledge. Furthermore, a theory gives us a powerful new tool in the acquisition of knowledge for it shows us where to look for new generalizations. "Thus, the accumulation of data becomes less of a magpie collection of facts and more of a systematized hunt for needed information. It is the existence of classification and generalization, and above all theory that makes science an organized body of knowledge" (Wright, 1964).

Logic is a part of all theories. The two types of logic are qualitative and quantitative logic. Qualitative logic is descriptive. For example we can qualitatively state that when the amount of wastewater entering a certain river is too high, the fish die. With qualitative logic we cannot identify what "too high" means—we need quantitative logic to do that.

When the data and generalizations are quantitative, we need mathematics to provide a theory that shows the quantitative relationships. For example, a quantitative statement about the river might state that "When the mass of organic matter entering a certain river equals $x$ kilograms per day, the amount of oxygen in the stream is $y$."

Perhaps more importantly, quantitative logic enables us to explore "What if?" questions about relationships. For example, "If we reduce the amount of organic matter entering the stream, how much will the amount of oxygen in the stream increase?" Furthermore, theories,

and in particular, mathematical theories, often enable us to bridge the gap between experimentally controlled observations and observations made in the field. For example, if we control the amount of oxygen in a fish tank in the laboratory, we can determine the minimum amount required for the fish to be healthy. We can then use this number to determine the acceptable mass of organic matter placed in the stream.

Given that environmental science is an organized body of knowledge about environmental relationships, then **quantitative environmental science** is an organized collection of mathematical theories that may be used to describe and explore environmental relationships.

In this book, we provide an introduction to some mathematical theories that may be used to describe and explore relationships in environmental science.

## 1–2 WHAT IS ENVIRONMENTAL ENGINEERING?

Environmental engineering is a profession that applies mathematics and science to utilize the properties of matter and sources of energy in the solution of problems of environmental sanitation. These include the provision of safe, palatable, and ample public water supplies; the proper disposal of or recycle of wastewater and solid wastes; the adequate drainage of urban and rural areas for proper sanitation; and the control of water, soil, and atmospheric pollution, and the social and environmental impact of these solutions. Furthermore, it is concerned with engineering problems in the field of public health, such as the control of arthropod-borne diseases, the elimination of industrial health hazards, the provision of adequate sanitation in urban, rural, and recreational areas, and the effect of technological advances on the environment (ASCE, 1973, 1977).

Environmental engineering is not concerned primarily with heating, ventilating, or air conditioning, nor is it concerned primarily with landscape architecture. Neither should it be confused with the architectural and structural engineering functions associated with built environments, such as homes, offices, and other workplaces.

Historically, environmental engineering has been a specialty area of civil engineering. Today it is still primarily associated with civil engineering in academic curricula. However, especially at the graduate level, students may come from a multitude of other disciplines. Examples include chemical, biosystems, electrical, and mechanical engineering as well as biochemistry, microbiology, and soil science.

### *Professional Development*

The beginning of professional development for environmental engineers is the successful attainment of the baccalaureate degree. For continued development, a degree in engineering from a program accredited by the Accreditation Board for Engineering and Technology (ABET) provides a firm foundation for professional growth. Other steps in the progression of professional development are:

- Achievement of the title “Engineer in Training” by successful completion of the Fundamentals of Engineering (FE) examination
- Achievement of the title “Professional Engineer” by successful completion of four years of applicable engineering experience and successful completion of the Principles and Practice of Engineering (PE) exam
- Achievement of the title “Board Certified Environmental Engineer” (BCEE) by successful completion of eight years of experience and successful completion of a written certification examination or 16 years of experience and successful completion of an oral examination

The FE exam and the PE exam are developed and administered by the National Council of Examiners for Engineering and Surveying (NCEES). The BCEE exams are administered by the American Academy of Environmental Engineering (AAEE). Typically, the FE examination is taken in the last semester of undergraduate academic work.

### *Professions*

Environmental engineers are professionals. Being a professional is more than being in or of a profession. True professionals are those who pursue their learned art in a spirit of public service (ASCE, 1973). True professionalism is defined by the following characteristics:

1. Professional decisions are made by means of general principles, theories, or propositions that are independent of the particular case under consideration.
2. Professional decisions imply knowledge in a specific area in which the person is expert. The professional is an expert only in his or her profession and not an expert at everything.
3. The professional's relations with his or her clients are objective and independent of particular sentiments about them.
4. A professional achieves status and financial reward by her or his accomplishments, not by inherent qualities such as birth order, race, religion, sex, or age or by membership in a union.
5. A professional's decisions are assumed to be on behalf of the client and to be independent of self-interest.
6. The professional relates to a voluntary association of professionals and accepts only the authority of those colleagues as a sanction on his or her own behavior (Schein, 1968).

A professional's superior knowledge is recognized. This puts the client into a very vulnerable position. The client retains significant authority and responsibility for decision making. The professional supplies ideas and information and proposes courses of action. The client's judgment and consent are required. The client's vulnerability has necessitated the development of a strong professional code of ethics. The code of ethics serves to protect not only the client but the public. Codes of ethics are enforced through the professional's peer group.

**Professional Codes of Ethics.** Civil engineering, from which environmental engineering is primarily, but not exclusively, derived has an established code of ethics that embodies these principles. The code is summarized in Figure 1–1. The *FE Fundamentals of Engineering Supplied-Reference Handbook,* published by the National Council of Examiners for Engineering and Surveying (NCEES) includes *Model Rules of Professional Conduct.* The NCEES amplifies the principles of the code of ethics in the *Handbook*. It is available online at www.ncees.org /Exams/Study_materials/Download_FE_supplied-Reference_Handbook.php.

## 1–3 HISTORICAL PERSPECTIVE

### *Overview*

Recognizing that environmental science has its roots in the natural sciences and that the most rudimentary forms of generalization about natural processes are as old as civilizations, then environmental science is indeed very old. Certainly, the Inca cultivation of crops and the mathematics of the Maya and Sumerians qualify as early applications of natural science. Likewise the Egyptian prediction and regulation of the annual floods of the Nile demonstrate that environmental engineering works are as old as civilization. On the other hand if you asked Archimedes or Newton or Pasteur what field of environmental engineering and science they worked in, they would have given you a puzzled look indeed! For that matter, even as late as 1687 the word *science* was not in vogue; Mr. Newton's treatise alludes only to *Philosophiae Naturalis Principa Mathematics (Natural Philosophy and Mathematical Principles).*

Engineering and the sciences as we recognize them today began to blossom in the 18th century. The foundation of environmental engineering as a discipline may be considered to

**FIGURE 1–1**

American Society of Civil Engineers code of ethics. (ASCE, 2005. Reprinted with permission.)

**AMERICAN SOCIETY OF CIVIL ENGINEERS CODE OF ETHICS**

**Fundamental Principles**

Engineers uphold and advance the integrity, honor and dignity of the engineering profession by:

1. using their knowledge and skill for the enhancement of human welfare and the environment;
2. being honest and impartial and serving with fidelity the public, their employers and clients;
3. striving to increase the competence and prestige of the engineering profession; and
4. supporting the professional and technical societies of their disciplines.

**Fundamental Canons**

1. Engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.
7. Engineers shall continue their professional development throughout their careers, and shall provide opportunities for the professional development of those engineers under their supervision.

coincide with the formation of the various societies of civil engineering in the mid-1800s (e.g., the American Society of Civil Engineers in 1852). In the first instances and well into the 20th century, environmental engineering was known as sanitary engineering because of its roots in water purification. The name changed in the late 1960s and early 1970s to reflect the broadening scope that included not only efforts to purify water but also air pollution, solid waste management, and the many other aspects of environmental protection that are included in the environmental engineer's current job description.

Although we might be inclined to date the beginnings of environmental science to the 18th century, the reality is that at any time before the 1960s there was virtually no reference to environmental science in the literature.

Although the concepts of ecology had been firmly established by the 1940s and certainly more than one individual played a role, perhaps the harbinger of environmental science as we know it today was Rachel Carson and, in particular, her book *Silent Spring* (Carson, 1962). By the mid-1970s environmental science was firmly established in academia, and by the 1980s recognized subdisciplines (environmental chemistry, environmental biology, etc.) that characterize the older disciplines of natural sciences had emerged.

### *Hydrology*

Citations for the following section originally appeared in Chow's *Handbook of Applied Hydrology* (1964). The modern science of hydrology may be considered to have begun in the 17th century with measurements. Measurements of rainfall, evaporation, and capillarity in the Seine were taken by Perrault (1678). Mariotte (1686) computed the flow in the Seine after measuring the cross section of the channel and the velocity of the flow.

The 18th century was a period of experimentation. The predecessors for some of our current tools for measurement were invented in this period. These include Bernoulli's piezometer, the Pitot tube, Woltman's current meter, and the Borda tube. Chézy proposed his equation to describe uniform flow in open channels in 1769.

The grand era of experimental hydrology was the 19th century. The knowledge of geology was applied to hydrologic problems. Hagen (1839) and Poiseulle (1840) developed the equation to describe capillary flow, Darcy published his law of groundwater flow (1856), and Dupuit developed a formula for predicting flow from a well (1863).

During the 20th century, hydrologists moved from empiricism to theoretically based explanations of hydrologic phenomena. For example, Hazen (1930) implemented the use of statistics in hydrologic analysis, Horton (1933) developed the method for determining rainfall excess based on infiltration theory, and Theis (1935) introduced the nonequilibrium theory of hydraulics of wells. The advent of high-speed computers at the end of the 20th century led to the use of finite element analysis for predicting the migration of contaminants in soil.

### Water Treatment

The provision of water and necessity of carrying away wastes were recognized in ancient civilizations: a sewer in Nippur, India, was constructed about 3750 B.C.E.; a sewer dating to the 26th century B.C.E. was identified in Tel Asmar near Baghdad, Iraq (Babbitt, 1953). Herschel (1913), in his translation of a report by Roman water commissioner Sextus Frontinus, identified nine aqueducts that carried over $3 \times 10^5$ $m^3 \cdot d^{-1}$ of water to Rome in 97 A.D.

Over the centuries, the need for clean water and a means for wastewater disposal were discovered, implemented, and lost to be rediscovered again and again. The most recent rediscovery and social awakening occurred in the 19th century.

In England, the social awakening was preceded by a water filtration process installed in Paisley, Scotland, in 1804 and the entrepreneurial endeavors of the Chelsea Water Company, which installed filters for the purpose of improving the quality of the Thames River water in 1829 (Baker, 1981; Fair and Geyer, 1954). Construction of the large Parisian sewers began in 1833, and W. Lindley supervised the construction of sewers in Hamburg, Germany, in 1842 (Babbitt, 1953). The social awakening was led by physicians, attorneys, engineers, statesmen, and even the writer Charles Dickens. "Towering above all was Sir Edwin Chadwick, by training a lawyer, by calling a crusader for health. His was the chief voice in the *Report from the Poor Law Commissioners on an Inquiry into the Sanitary Conditions of the Labouring Populations of Great Britain,* 1842" (Fair and Geyer, 1954). As is the case with many leaders of the environmental movement, his recommendations were largely unheeded.

Among the first recognizable environmental scientists were John Snow (Figure 1–2) and William Budd (Figure 1–3). Their epidemiological research efforts provided a compelling demonstration of the relationship between contaminated water and disease. In 1854, Snow demonstrated the relationship between contaminated water and cholera by plotting the fatalities from cholera and their location with reference to the water supply they used (Figures 1–4 and 1–5). He found that cholera deaths in one district of London were clustered around the Broad Street Pump, which supplied contaminated water from the Thames River (Snow, 1965). In 1857, Budd began work that ultimately showed the relationship between typhoid and water contamination. His monograph, published in 1873, not only described the sequence of events in the propagation of typhoid but also provided a succinct set of rules for prevention of the spread of the disease (Budd, 1977). These rules are still valid expedients over 133 years later. The work of these two individuals is all the more remarkable in that it preceded the discovery of the germ theory of disease by Koch in 1876.

In the United States a bold but unsuccessful start on filtration was made at Richmond, Virginia, in 1832. No further installations were made in the United States until after the Civil War. Even then, they were for the most part failures. The primary means of purification from the 1830s until the 1880s was plain sedimentation.

**FIGURE 1–2**

Dr. John Snow. (©Pictorial Press Ltd/Alamy)

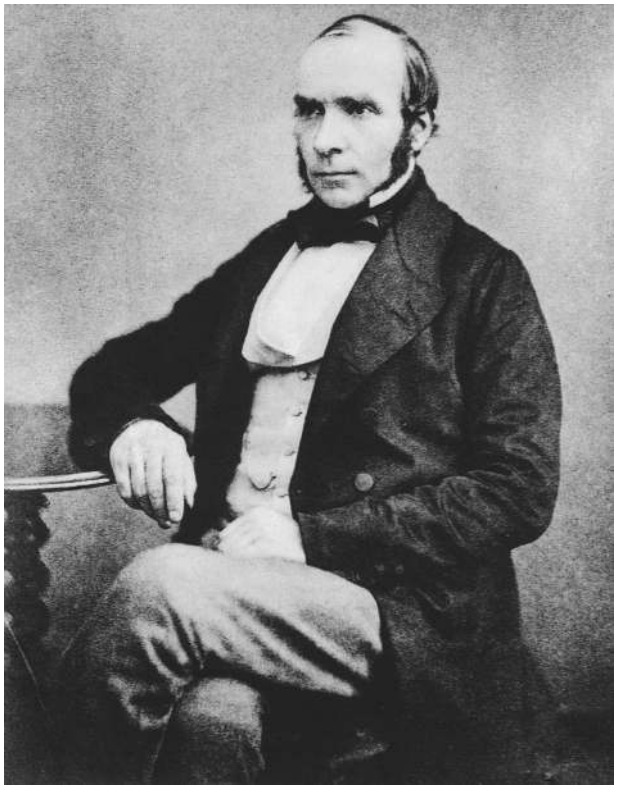
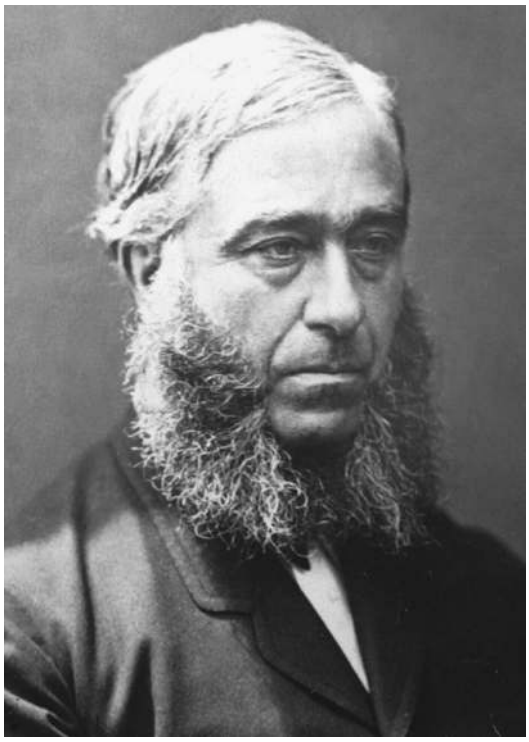


**FIGURE 1–3**

Dr. William Budd. (©Used with permission of the Library & Archives Service, London School of Hygiene & Tropical Medicine)



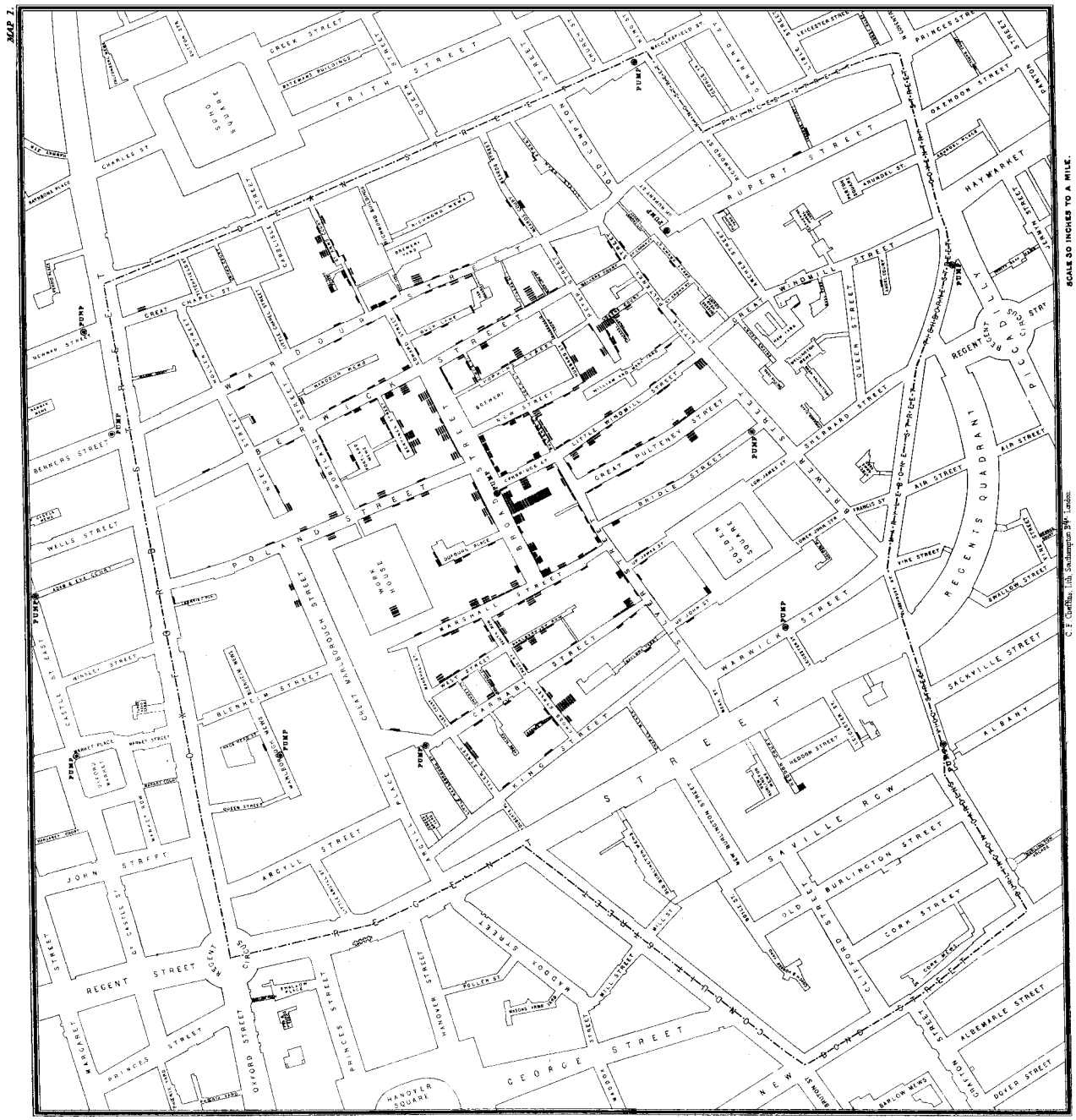
It is worthy of note that the American Water Works Association (AWWA) was established in 1881. This body of professionals joined together to share their knowledge and experience. As with other professional societies and associations formed in the late 1800s and early 1900s, the activities of the Association provide a repository for the knowledge and experience gained in purifying water. It was and is an integral part of the continuous improvement in the purification of drinking water. It serves a venue to present new ideas and challenge ineffective practices. Its journal and other publications provide a means for professionals to keep abreast of advances in the techniques for water purification.

Serious filtration research in the United States began with the establishment of the Lawrence Experiment Station by the State Board of Health in Massachusetts in 1887. On the basis of experiments conducted at the laboratory, a slow sand filter was installed in the city of Lawrence and put into operation in 1887.

At about the same time, rapid sand filtration technology began to take hold. The success here, in contrast to the failure in Britain, is attributed to the findings of Professors Austen and Wilber at Rutgers University and experiments with a full-scale plant in Cincinnati, Ohio, by George Warren Fuller. Austin and Wilber reported in 1885 that the use of alum as a coagulant when followed by plain sedimentation yielded a higher quality water than plain sedimentation alone. In 1899, Fuller reported on the results of his research. He combined the coagulation-settling process with rapid sand filtration and successfully purified Ohio River water even during its worst conditions. This work was widely disseminated.

**FIGURE 1–4**

Dr. Snow's map of cholera fatalities in London, August 19 to September 30, 1854. Each bar (▬) represents one fatality.




The first permanent water chlorination plant anywhere in the world was put into service in Middlekerrke, Belgium, in 1902. This was followed by installations at Lincoln, England, in 1905 and at the Boonton Reservoir for Jersey City, New Jersey, in 1908. Ozonation began about the same time as chlorination. However, until the end of the 20th century, the economics of disinfection by ozonation were not favorable.

## FIGURE 1–5

Map of service areas of three water companies in London, 1854. To view the original colors, go to the UCLA website: http://www.ph.ucla.edu/epi