3rd edition

Principles of **Environmental Engineering and Science**

Mackenzie L. Davis and **Susan J. Masten**

Principles of Environmental Engineering and Science

Third Edition

Mackenzie L. Davis
Emeritus, Michigan State University—East Lansing

Susan J. Masten
Michigan State University—East Lansing, MI

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PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND SCIENCE, THIRD EDITION

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To our students who make it worthwhile.

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Preface

Following the format of previous editions, the third 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 third edition has been thoroughly revised and updated. The following paragraphs summarize the major changes in this edition.

- Introduction
  Data on per capita water consumption has been updated
- Biology
  Addition of sections on enzyme kinetics and rates of cellular respiration
  Expanded section on microbial transformations
  Problems related to enzyme kinetics, rates of cellular respiration, and thermodynamics of biologically mediated reactions
- Chemistry
  New section on equilibrium among gases and liquids
- Ecosystems
  Updated figures and charts
- Risk
  Updated tables
- Hydrology
  New section on water rights
  New section on storm water management
- Sustainability
  Major revision with a detailed 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

- Water Quality Management
  Updated figures and charts
  New section on water source protection
- Water Treatment
  Expanded overview of treatment systems
  New section on coagulation theory
  New section on membranes
  Expansion of section on disinfection to include breakpoint chlorination and UV disinfection
- Wastewater Treatment
  Material dealing with on-site disposal has been moved to a student website
  Addition of a discussion of biological treatment of nitrogen and phosphorus
  Addition of a discussion of Integrated Fixed Film Activated Sludge (IFAS)
  Addition of a discussion of Moving Bed Biofilm Reactor (MBBR)
  Revised and updated discussion of anaerobic digestion
- Air Pollution
  Updated ambient air pollution standards
  Addition of EPA methods for estimating emissions from power plants
  Addition of Federal Motor Vehicle Standards
  Discussion of CAFE standards
  Update of global warming discussion
  Addition of global warming potential data for selected compounds
  Addition of air-to-fuel ratio calculations
- Solid Waste
  Updated figures and charts

Cover Photographs

The photographs were chosen to represent the diverse aspects of environmental science and engineering covered in this text. The upper photograph of Mont Blanc and the French and Italian Alps was taken from Aiguille du Midi, overlooking Chamonix, France. As discussed in Chapters 5 and 12, global climate change has had very significant effects on glaciers and alpine ecosystems.

From left to right, the figures on the bottom represent various aspects of environmental engineering. The photo on the left is taken of the Tollgate Stormwater Management System, a constructed wetland project built to handle storm water from a subdivision in Lansing, Michigan. The water is naturally filtered and cleansed, solving complex environmental and water management problems and ensuring that pollutants are not discharged to Red Cedar or Grand Rivers, which flow through Lansing. The entire project cost less than one-third of that required for traditional solutions.

The next photo is of Singapore's Ulu Pandan Water Reclamation Plant. The plant treats 361,000 m^3 of wastewater per day using membrane bioreactors. Off-gas treatment is used for odor control. The effluent from the wastewater plant is further purified using advanced membrane technologies and ultraviolet disinfection and is marketed as NEWater, primarily for nonpotable industrial uses, although a small portion is blended with reservoir water for human consumption.

The third photo from the left is of the Garreg Ddu Reservoir, which is part of the Elan Valley Reservoir system in Wales, United Kingdom. The Elan Valley Reservoirs were constructed in the 19th century to serve the rapidly growing population of Birmingham, England. The city's expansion during the Industrial Revolution had resulted in regular outbreaks of such waterborne diseases as typhoid, cholera, and dysentery, resulting in the need for a source of clean, pure water. The reservoir system, although now privately owned by Glas Cymru, continues to serve Birmingham.

The photo on the far right is taken in the filtration room of the John Dye Water Conditioning Plant, which was built during the Great Depression and continues to serve the Lansing area. It opened in 1940, and with its art deco architecture and three sets of Depression-era murals, including one by Charles Pollock, brother to renowned artist Jackson Pollock, it is recognized as an architectural icon. It produces 87,000 m^3 of softened, clean drinking water to its customers every day.

Online Resources

An instructor's manual and set of PowerPoint slides are available online at www.mhhe.com/davis for qualified instructors. Please inquire with your McGraw-Hill representative for the necessary access password. 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.

Mackenzie L. Davis
Susan J. Masten

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.

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Mackenzie L. Davis Susan J. Masten

About the Authors

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.

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: Air and Waste Management Association, International Ozone Association, and the American Society for Engineering Education. She served on the Executive Committee of the MSU Chapter of the American Chemical Society from 1995–2005.

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. 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.

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

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?

Engineering

Engineering is a profession that applies science and mathematics to make the properties of matter and sources of energy useful in structures, machines, products, systems, and processes.

Environmental Engineering

The Environmental Engineering Division of the American Society of Civil Engineers (ASCE) has published the following statement of purpose that may be used to show the relationship between environmental science and environmental engineering:

> Environmental engineering is manifest by sound engineering thought and practice in the solution of problems of environmental sanitation, notably in 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 control of arthropod-borne diseases, the elimination of industrial health hazards, and the provision of adequate sanitation in urban, rural, and recreational areas, and the effect of technological advances on the environment (ASCE, 1977).

Neither environmental science nor environmental engineering should be confused with heating, ventilating, or air conditioning (HVAC), nor with landscape architecture. Neither should they be confused with the architectural and structural engineering functions associated with built environments, such as homes, offices, and other workplaces.

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 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 $3 \times 10^5\ \mathrm{m^3 \cdot d^{-1}}$ 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

FIGURE 1–1

Dr. John Snow.

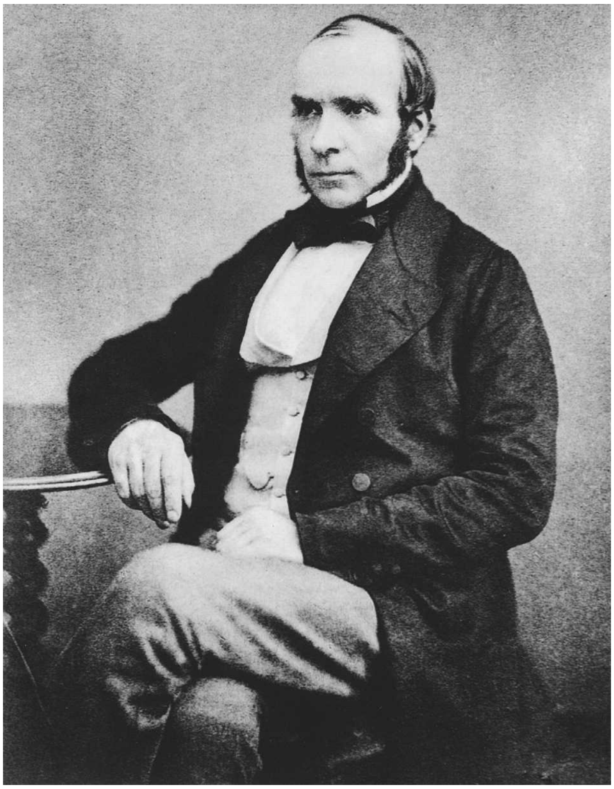
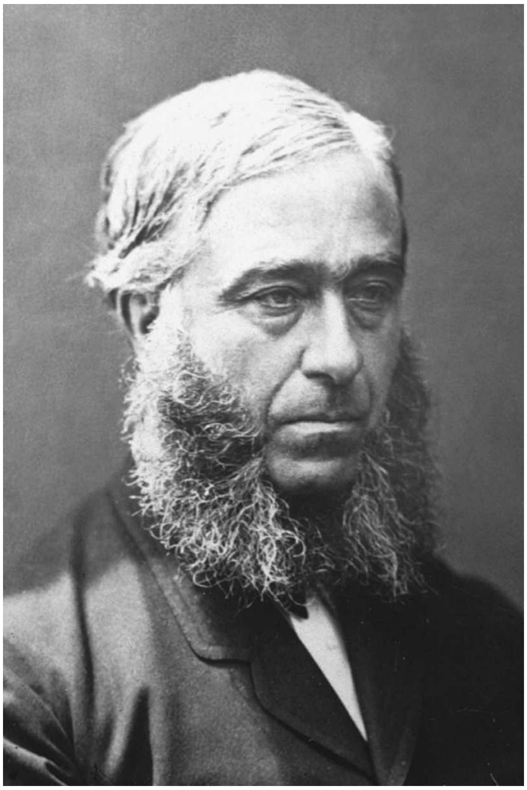


FIGURE 1–2

Dr. William Budd.



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 1–1) and William Budd (Figure 1–2). 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 1–3 and 1–4). 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.

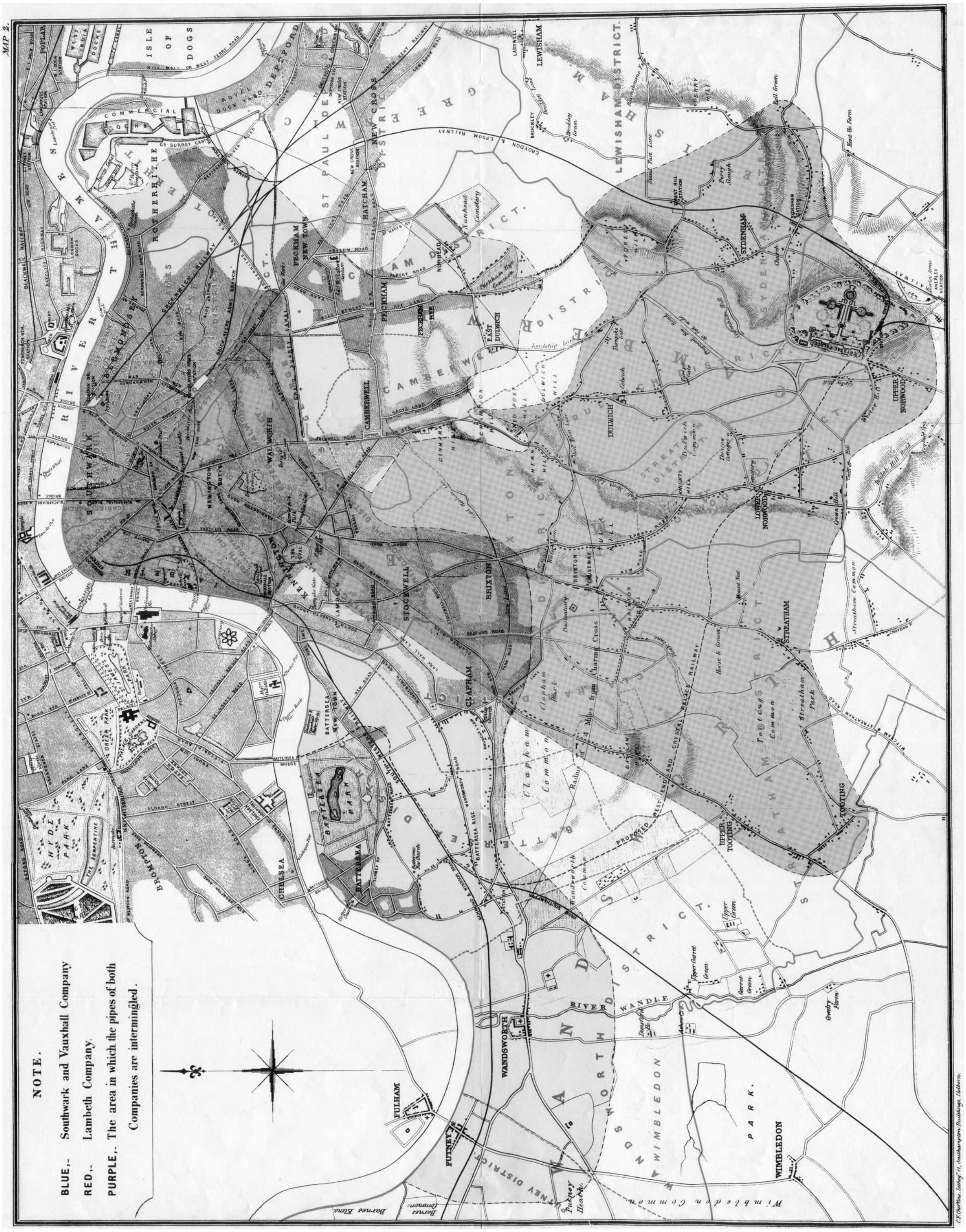
FIGURE 1–3

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

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 1–4

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



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.

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.

Fluoridation of water was first used for municipal water at Grand Rapids, Michigan, in 1945. The objective was to determine whether or not the level of dental cavities could be reduced if the fluoride level were raised to levels near those found in the water supplies of populations having a low prevalence of cavities. The results demonstrated that proper fluoridation results in a substantial reduction in tooth decay (AWWA, 1971).

The most recent major technological advance in water treatment is filtration with synthetic membranes. First introduced in the 1960s, membranes became economical for application in special municipal applications in the 1990s.

Wastewater Treatment

Early efforts at sewage treatment involved carrying the sewage to the nearest river or stream. Although the natural biota of the stream did indeed consume and thus treat part of the sewage, in general, the amount of sewage was too large and the result was an open sewer.

In England, the Royal Commission on Rivers Pollution was appointed in 1868. Over the course of their six reports, they provided official recognition (in decreasing order of preference) of sewage filtration, irrigation, and chemical precipitation as acceptable methods of treatment (Metcalf and Eddy, 1915).

At this point in time, events began to move rather quickly in both the United States and England. The first U.S. treatment of sewage by irrigation was attempted at the State Insane Asylum in August, Maine, in 1872.

The first experiments on aeration of sewage were carried out by W. D. Scott-Monctieff at Ashtead, England, in 1882 (Metcalf and Eddy, 1915). He used a series of nine trays over which the sewage percolated. After about 2 days operation, bacterial growths established themselves on the trays and began to effectively remove organic waste material.

With the establishment of the Lawrence Laboratory in Massachusetts in 1887, work on sewage treatment began in earnest. Among the notables who worked at the laboratory were Allen

Hazen, who was in charge of the lab in its formative years, and the team of Ellen Richards and George Whipple, who were among the first to isolate the organisms that oxidized nitrogen compounds in wastewater.

In 1895, the British collected methane gas from septic tanks and used it for gas lighting in the treatment plant. After successful development by the British, the tricking filter was installed in Reading, Pennsylvania, Washington, Pennsylvania, and Columbus, Ohio in 1908 (Emerson, 1945).

In England, Arden and Lockett conducted the first experiments that led to the development of the activated sludge process in 1914. The first municipal activated sludge plant in the United States was installed in 1916 (Emerson, 1945).

The progress of the state of the art of wastewater treatment has been recorded by the Sanitary Engineering Division (later the Environmental Engineering Division) of the American Society of Civil Engineers. It was formed in June 1922. The *Journal of the Environmental Engineering Division* is published monthly. The Federation of Sewage and Industrial Wastes Association, also known as the Water Pollution Control Federation, was established in October 1928 and publishes reports on the advancement of the state of the art. Now called the Water Environment Federation (WEF), its journal is *Water Environment Research.*

Air Pollution Control

Although there were royal proclamations and learned essays about air pollution as early as 1272, these were of note only for their historic value. The first experimental apparatus for clearing particles from the air was reported in 1824 (Hohlfeld, 1824). Hohlfeld used an electrified needle to clear fog in a jar. This effect was rediscovered in 1850 by Guitard and again in 1884 by Lodge (White, 1963).

The latter half of the 19th century and early 20th century were watershed years for the introduction of the forerunners of much of the current technology now in use: fabric filters (1852), cyclone collectors (1895), venturi scrubbers (1899), electrostatic precipitator (1907), and the plate tower for absorption of gases (1916). It is interesting to note that unlike water and wastewater treatment where disease and impure water were recognized before the advent of treatment technologies, these developments preceded the recognition of the relationship between air pollution and disease.

The Air & Waste Management Association was founded as the International Union for Prevention of Smoke in 1907. The organization grew from its initial 12 members to more than 9000 in 65 countries.

The 1952 air pollution episode in London that claimed 4000 lives (WHO, 1961), much like the cholera epidemic of 1849 that claimed more than 43,000 lives in England and Wales, finally stimulated positive legislation and technical attempts to rectify the problem.

The end of the 20th century saw advances in chemical reactor technology to control sulfur dioxide, nitrogen oxides, and mercury emissions from fossil-fired power plants. The struggle to control the air pollution from the explosive growth in use of the automobile for transportation was begun.

Environmental scientists made major discoveries about global air pollution at the end of the 20th century. In 1974, Molina and Rowland identified the chemical mechanisms that cause destruction of the ozone layer (Molina and Rowland, 1974). By 1996, the Intergovernmental Panel on Climate Change (IPCC) agreed that "(t)he balance of evidence suggests a discernable human influence on global climate" (IPCC, 1996).

Solid and Hazardous Waste

From as early as 1297, there was a legal obligation on householders in London to ensure that the pavement within the frontage of their tenements was kept clear (GLC, 1969). The authorities