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INTRODUCTION TO ENVIRONMENTAL ENGINEERING

Sixth Edition

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Michigan State University

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To Elaine, my critic, my cheerleader, my wife . . . lo these 50 years, and my love . . . forever

—Mackenzie L. Davis

To my wife Nancy, who not only puts up with me in life, but has to put up with me in business too . . . without you neither I nor Cornwell Engineering Group would be the same. Thank you for being my wife, companion, and partner.

—David A. Cornwell

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 *Principles of Environmental Engineering* with Dr. Susan Masten.

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David A. Cornwell, Ph.D., P.E., BCEE, is a registered professional engineer in over 20 states and is the founder and CEO of the consulting firm Cornwell Engineering Group headquartered in Newport News, VA. He attended the University of Florida in Gainesville, FL, where he received his Ph.D. in civil/environmental engineering and has remained a loyal Gator fan ever since, serving as a Bull Gator, Dean's Advisory Board, and on the President's Council. He is also currently a Full Adjunct Professor at UF. He was an associate professor in the Civil Environmental Engineering Department at Michigan State University prior to entering the consulting field. Many of Dr. Cornwell's students now are active members of the water profession.

During his career as a consultant, Dr. Cornwell has provided process, design, and operational troubleshooting services to water utilities around the world. He has lectured and written on many aspects of water treatment, including over 75 peer-reviewed technical articles and reports. Much of his work has included the development of new and optimized water treatment processes. His non-profit corporation, Cornwell Research Group is dedicated to *safe water for all* and is actively working to reduce lead exposure to children. He has won three *JAWWA* Division best paper awards and the overall *JAWWA* publication award. Dr. Cornwell has an extensive record of service to the water profession. He has been an active member of American Water Works Association (AWWA) since the early 1970s and has served on numerous committees in that organization. He has chaired the Research Division and the Technical and Education Council, and served on the board of directors and executive committee of AWWA.

In 2005, Dr. Cornwell was the recipient of the A.P. Black Research Award given by AWWA to recognize excellence in water treatment research, recognizing his contributions to bridging the gap between research and application. He recently received the Water Research Foundation Dr. Pankaj Parekh Research Innovation Award. Dr. Cornwell has been a principal investigator on over 20 Water Research Foundation research projects.

PREFACE

Following the format of previous editions, the sixth edition of *Introduction to Environmental Engineering* is designed for use in an introductory sophomore-level environmental engineering course with sufficient depth to allow its use in more advanced courses. We assume that the book will be used in one of the first environmental engineering courses encountered by the student. We have provided sufficient depth that it may also be used for more advanced courses. It covers the basic, traditional subject matter that forms the foundation of more advanced courses. As such, it provides the fundamental science and engineering principles that instructors in more advanced courses may assume are common knowledge for an advanced undergraduate.

The Fundamentals of Engineering (FE) examination for civil and environmental engineering has been highlighted as a focal point in this edition. Seventy percent of the topics included in the environmental engineering specific Fundamentals of Engineering (FE) examination are covered in *Introduction to Environmental Engineering*. These include the following subject areas: ethics in Chapter 1, mass balance in Chapter 2, hydrology and watershed processes in Chapter 4, water and wastewater engineering in Chapters 6, 7, and 8, air quality engineering in Chapter 9, the noise pollution aspects of occupational and health safety in Chapter 10, solid and hazardous waste engineering in Chapters 11 and 12, and radiological health, safety, and waste management in Chapter 13. To highlight the Fundamental of Engineering connections, we have identified over 112 equations, 12 tables, and 6 figures in *Introduction to Environmental Engineering* that also appear in the *Fundamentals of Engineering Supplied-Reference Handbook*.

FE

Because the FE exam uses both SI units and U.S. Customary System (USCS) units, USCS units are introduced in Chapter 1 and then utilized in numerous example problems as well as the FE Exam Formatted Problems. A conversion factor table is presented in Appendix C.

Specific examples of revisions that appear in the sixth edition include: updated ASCE code of ethics in Chapter 1; updated discussion of risk perception; annual risk of death; revised slope factors for inhalation risk and revised slope factors for inhalation risk in Chapter 3; addition of a discussion of nanoparticles in Chapter 7; update of NAAQS; update of auto emission standards; discussion of the use of bromine to enhance fabric filter's removal of mercury; new global warming data; development of new refrigerant gases to lower global warming potential; update of CO_2 levels and new end of chapter problems in Chapter 9; addition of a discussion of direct and indirect potable reuse and tables of communities that have implemented direct and indirect reuse; examples of reuse standards implemented by California, Arizona, New Mexico and Texas; graphs of coal use in recent years in Chapter 13.

Each chapter concludes with a list of review items, the traditional end of chapter problems, and, perhaps less traditional, discussion questions and FE formatted problems. 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. We have found the discussion questions useful as a 'minute check' or spot quiz item to see if the students understand concepts as well as number crunching.

An instructor's manual and set of PowerPoint® slides are available online 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 text.

Numerous Michigan State University alumni have indicated that *Introduction to Environmental Engineering* is an excellent text for review and preparation for the Professional Engineers examination. It is both readable for self-study as well as a good source of sufficient example problems and data for practical application in the exam. Many have taken it to the exam as one of their reference resources. And they have used it!

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

Mackenzie L. Davis
David A. Cornwell

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.

Over the many years of the six editions, the following students helped to solve problems, proofread text, prepare illustrations, raise embarrassing questions, and generally make sure that other students could understand the material: 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, Craig Fricke, Elizabeth Fry, Beverly Hinds, Edith Hooten, Brad Hoos, Kathy Hulley, Geneva Hulslander, Lisa Huntington, Angela Ilieff, 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, Glenna Wood, and Ya-yun Wu. To them a hearty thank you!

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To John Eastman, our now deceased esteemed friend and former colleague, we offer our sincere appreciation. His contribution to the initial work of Chapter 5 in the first edition, as well as constructive criticism and "independent" testing of the material was exceptionally helpful. Kristin Erickson, Radiation Safety Officer, Office of Radiation, Chemical and Biological Safety, Michigan State University, contributed to the Chapter 11 revisions for the third edition. To her we offer our hearty thanks. We especially want to thank Dave's wife, Nancy McTigue, for all her work on making revisions to the Solid Waste Management chapter and her help in reviewing the Water Treatment chapter.

And last, but certainly not least, we wish to thank our families, who have put up with the nonsense of book writing.

CONTENTS

1 Introduction

1-1 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 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, 1973, 1977).

Environmental engineering is not concerned primarily with heating, ventilating, or air conditioning (HVAC), 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, such as chemical, bio-systems, 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 8 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.

It is noteworthy that this edition of *Introduction to Environmental Engineering* has been written by Board Certified Environmental Engineers. In addition, we note that we have made a special effort to flag equations that appear in the NCEES *FE Fundamentals of Engineering Supplied-Reference Handbook*.

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 accomplishment, 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.

1-2 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 on line at www.ncees.org/Exams/Study_materials/Download_FE_supplied-Reference_Handbook.php

FIGURE 1-1

American Society of Civil Engineers code of ethics. (ASCE, 2018. 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.
8. Engineers shall, in all matters related to their profession, treat all persons fairly and encourage equitable participation without regard to gender or gender identity, race, national origin, ethnicity, religion, age, sexual orientation, disability, political affiliation, or family, marital, or economic status.

1-3 ENVIRONMENTAL ETHICS

The birth of environmental ethics as a force is partly a result of concern for our own long-term survival, as well as our realization that humans are but one form of life, and that we share our earth with other forms of life (Vesilind, 1975).

Although it seems a bit unrealistic for us to set a framework for a discussion of environmental ethics in this short introduction, we have summarized a few salient points in Table 1-1.

TABLE 1-1 An Environmental Code of Ethics

1. Use knowledge and skill for the enhancement and protection of the environment.
2. Hold paramount the health, safety, and welfare of the environment.
3. Perform services only in areas of personal expertise.
4. Be honest and impartial in serving the public, your employers, your clients, and the environment.
5. Issue public statements only in an objective and truthful manner.

Although these few principles seem straightforward, real-world problems offer distinct challenges. Here is an example for each of the principles listed:

- The first principle may be threatened when it comes into conflict with the need for food for a starving population and the country is overrun with locusts. Will the use of pesticides enhance and protect the environment?
- The EPA has stipulated that wastewater must be disinfected where people come into contact with the water. However, the disinfectant may also kill naturally occurring beneficial microorganisms. Is this consistent with the second principle?
- Suppose your expertise is water and wastewater chemistry. Your company has accepted a job to perform air pollution analysis and asks you to perform the work in the absence of a colleague who is the company's expert. Do you decline and risk being fired?
- The public, your employers, and your client believe that dredging a lake to remove weeds and sediment will enhance the lake. However, the dredging will destroy the habitat for muskrats. How can you be impartial to *all* these constituencies?
- You believe that a new regulation proposed by EPA is too expensive to implement but you have no data to confirm that opinion. How do you respond to a local newspaper reporter asking for your opinion? Do you violate the fifth principle even though it is "your opinion" that is being sought?

We think it is important to point out that many environmentally related decisions such as those described above are much more difficult than the problems presented in the remaining chapters of this book. Frequently these problems are related more to ethics than to engineering. The problems arise when there are several courses of action with no *a priori* certainty as to which is best. Decisions related to safety, health, and welfare are easily resolved. Decisions as to which course of action is in the best interest of the public are much more difficult to resolve. Furthermore, decisions as to which course of action is in the best interest of the environment are at times in conflict with those that are in the best interest of the public. Whereas decisions made in the public interest are based on professional ethics, decisions made in the best interest of the environment are based on environmental ethics.

Ethos, the Greek word from which "ethic" is derived, means the character of a person as described by his or her actions. This character was developed during the evolutionary process and was influenced by the need for adapting to the natural environment. Our ethic is our way of doing things. Our ethic is a direct result of our natural environment. During the latter stages of the evolutionary process, *Homo sapiens* began to modify the environment rather than submit to what, millennia later, became known as Darwinian natural selection. As an example, consider the cave dweller who, in the chilly dawn of prehistory, realized the value of the saber-toothed tiger's coat and appropriated it for personal use. Inevitably a pattern of appropriation developed, and our ethic became more self-modified than environmentally adapted. Thus, we are no longer adapted to our natural environment but rather to our self-made environment. In the ecological context, such maladaptation results in one of two consequences: (1) the organism (*Homo sapiens*) dies out; or (2) the organism evolves to a form and character that is once again compatible with the natural environment (Vesilind, 1975). Assuming that we choose the latter course, how can this change in character (ethic) be brought about? Each individual must change his or her character or ethic, and the social system must change to become compatible with the global ecology.

The acceptable system is one in which we learn to share our exhaustible resources—to regain a balance. This requires that we reduce our needs and that the materials we use must be replenishable. We must treat all of the earth as a sacred trust to be used so that its content is neither diminished nor permanently changed; we must release no substances that cannot be reincorporated without damage to the natural system. The recognition of the need for such adaptation (as a means of survival) has developed into what we now call the *environmental ethic* (Vesilind, 1975).

1-4 ENGINEERING DIMENSIONS AND UNITS

The *FE Fundamentals of Engineering Supplied-Reference Handbook* uses the metric system of units. Ultimately, the FE examination will be entirely metric. However, currently some of the FE examination problems use both metric and U.S. Customary System (USCS) units. This text uses the metric system of units. Because the FE examination has some problems in U.S. Customary units, we have included some example problems and some FE formatted end-of-chapter problems in U.S. Customary units.

Our experience is that U.S. students are very familiar with the metric system of units and have an adequate knowledge of fundamental U.S. Customary System (USCS) units such as feet per second (ft/s or fps), miles per hour (mph), pounds mass (lb_m), and gallons (gal) that we need not elaborate more than this brief reminder. However, there are a small number of units and abbreviations that are particular to environmental engineering that we feel should be addressed here. They will be used without further elaboration in the following chapters. At appropriate places, we will provide examples of the use of handy equivalences.

The following are USCS definitions:

acre-ft (or ac-ft): a volume of water that has a surface area of one acre and a depth of one foot or an equivalent volume by other measurements, for example, an area of ½ acre and a depth of 2 feet or an area of 2 acres and a depth of ½ foot.

Btu: British thermal unit

cfs: cubic feet per second

gal: U.S. gallon(s)

gpm: U.S. gallon(s) per minute

gpcd: U.S. gallons per capita per day

hp: horsepower

mgd: million U.S. gallons per day

TABLE 1-2 U.S. Customary System conversions factors

Multiply	by	To obtain
acre (ac)	43,560	square feet (ft^2)
acre-ft	325,851	U.S. gallons
Btu	2.930×10^{-4}	kW-hour
Btu/min	0.02358	hp
Btu/min	0.01758	kW
ft^3 of water	62.4	lb_m of water
ft^3 of water	7.48	U.S. gallons of water
gal of water	0.1337	ft^3 of water
gal of water	8.34	lb_m of water
gpd/ft^2	0.04074	$m^3/d \cdot m^2$
gpm/ft^2	2.445	$m^3/h \cdot m^2$
hp	0.7457	kW
psi	2.307	ft of water
$lb_m/ft^2 \cdot d$	0.2048	$kg/m^2 \cdot d$
lb_m/U.S. ton	0.4999	g/kg
U.S. short tons	2,000	lb_m
U.S. tons/acre	0.2242	kg/ha

ppb: parts (mass) per billion parts of fluid; the fluid is understood to be water. Alternatively it may be parts (mass) per billion parts of soil. ppb is equivalent to µg/kg or µg/L.

ppm: parts (mass) of substance per million parts of the fluid. Alternatively it may be parts (mass) per billion parts of soil. ppm is equivalent to mg/kg or mg/L.

ppm(v/v): volume of substance per million volumes of fluid

psi: a pressure; pounds force per square inch of surface area

sf: square feet

U.S. ton: 2,000 lb_m

Conversion factors for the USCS are given in Table 1-2 and in Appendix C. Conversions from SI units to USCS units are given inside the back cover of this book.

1-5 ENVIRONMENTAL SYSTEMS OVERVIEW

Systems

Before we begin in earnest, we thought it worth taking a look at the problems to be discussed in this text in a larger perspective. Engineers like to call this the "systems approach," that is, looking at all the interrelated parts and their effects on one another. In environmental systems it is doubtful that mere mortals can ever hope to identify all the interrelated parts, to say nothing of trying to establish their effects on one another. The first thing the systems engineer does, then, is to simplify the system to a tractable size that behaves in a fashion similar to the real system. The simplified model does not behave in detail as the system does, but it gives a fair approximation of what is going on.

We have followed this pattern of simplification in our description of three environmental systems: the water resource management system, the air resource management system, and the solid waste management system. Pollution problems that are confined to one of these systems are called single-medium problems if the medium is either air, water, or soil. Many important environmental problems are not confined to one of these simple systems but cross the boundaries from one to the other. These problems are referred to as *multimedia* pollution problems.

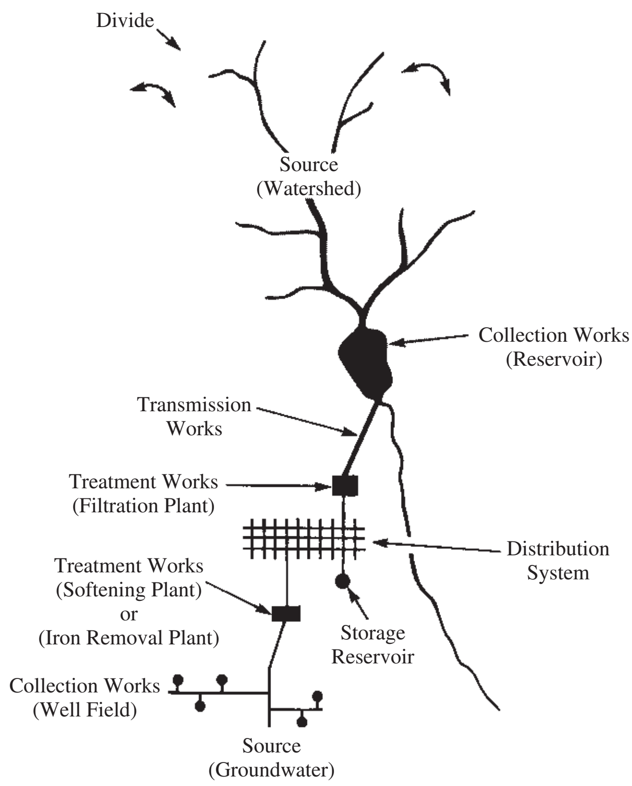
Water Resource Management System

Water Supply Subsystem. The nature of the water source commonly determines the planning, design, and operation of the collection, purification, transmission, and distribution works.* The two major sources used to supply community and industrial needs are referred to as *surface water* and *groundwater.* Streams, lakes, and rivers are the surface water sources. Groundwater sources are those pumped from wells.

Figure 1-2 depicts an extension of the water resource system to serve a small community. The source in each case determines the type of collection works and the type of treatment works. The pipe network in the city is called the distribution system. The

FIGURE 1-2

An extension of the water supply resource system.



***Works* is a noun used in the plural to mean "engineering structures." It is used in the same sense as *art works.*

pipes themselves are often referred to as *water mains*. Water in the mains generally is kept at a pressure between 200 and 860 kilopascals (kPa). Excess water produced by the treatment plant during periods of low *demand** (usually the nighttime hours) is held in a storage reservoir. The storage reservoir may be elevated (the ubiquitous water tower), or it may be at ground level. The stored water is used to meet high demand during the day. Storage compensates for changes in demand and allows a smaller treatment plant to be built. It also provides emergency backup in case of a fire.

Population and water-consumption patterns are the prime factors that govern the quantity of water required and hence the source and the whole composition of the water resource system. One of the first steps in the selection of a suitable water-supply source is determining the demand that will be placed on it. The essential elements of water demand include average daily water consumption and peak rate of demand. Average daily water consumption must be estimated for two reasons: (1) to determine the ability of the water source to meet continuing demands over critical periods when surface flows are low or groundwater tables are at minimum elevations, and (2) for purposes of estimating quantities of stored water that would satisfy demands during these critical periods. The peak demand rates must be estimated in order to determine plumbing and pipe sizing, pressure losses, and storage requirements necessary to supply sufficient water during periods of peak water demand.

Many factors influence water use for a given system. For example, the mere fact that water under pressure is available stimulates its use, often excessively, for watering lawns and gardens, for washing automobiles, for operating air-conditioning equipment, and for performing many other activities at home and in industry. The following factors have been found to influence water consumption in a major way:

1. Climate
2. Industrial activity
3. Meterage
4. System management
5. Standard of living

The following factors also influence water consumption but to a lesser degree: extent of sewerage, system pressure, water price, and availability of private wells.

If the demand for water is measured on a *per capita*† basis, climate is the most important factor influencing demand. This is shown dramatically in Table 1-3. The average annual precipitation for the "wet" states is about 100 cm per year while the average annual precipitation for the "dry" states is only about 25 cm per year. Of course, the dry states are also considerably warmer than the wet states.

**Demand* is the use of water by consumers. This use of the word derives from the economic term meaning "the desire for a commodity." The consumers express their desire by opening the faucet or flushing the water closet (W.C.).

†Per capita is a Latin term that means "by heads." Here it means "per person." This assumes that each person has one head (on the average).

TABLE 1-3 Total fresh water withdrawals for public supply[a]

State	Withdrawal (Lpcd)[b]
"Wet"	
Connecticut	680
Michigan	598
New Jersey	465
Ohio	571
Pennsylvania	543
Average	571
"Dry"	
Nevada	1,450
New Mexico	698
Utah	926
Average	1,025

[a]Compiled from Kenny et al., 2009.
[b]Lpcd = liters per capita per day.

The influence of industry is to increase per capita water demand. Small rural and suburban communities will use less water per person than industrialized communities.

The third most important factor in water use is whether individual consumers have water meters. Meterage imposes a sense of responsibility not found in unmetered residences and businesses. This sense of responsibility reduces per capita water consumption because customers repair leaks and make more conservative water-use decisions almost regardless of price. For residential consumers, water is so inexpensive, price is not much of a factor in water use. Water price is extremely important for industrial and farming operations that use large volumes of water.

Following meterage closely is the aspect called system management. If the water distribution system is well managed, per capita water consumption is less than if it is not well managed. Well-managed systems are those in which the managers know when and where leaks in the water main occur and have them repaired promptly.

Climate, industrial activity, meterage, and system management are more significant factors controlling water consumption than the standard of living. The rationale for the last factor is straightforward. Per capita water use increases with an increased standard of living. Highly developed countries use much more water than the less developed nations. Likewise, higher socioeconomic status implies greater per capita water use than lower socioeconomic status.

The total U.S. water withdrawal for all uses (agricultural, commercial, domestic, mining, and thermoelectric power), including both fresh and saline water, was estimated to be approximately 5,000 liters per capita per day (Lpcd) in 2010. The amount for U.S. public supply (domestic, commercial, and industrial use) was estimated to be 590 Lpcd in 2010 (Maupin et al., 2014). The American Water Works Association estimated that