

A photograph of a wooden boardwalk or path winding through a dense, green forest. The path is made of wooden planks and leads the eye from the foreground into the distance, where it disappears into the trees. The forest is filled with various shades of green, and the lighting is soft, suggesting a dappled sunlight effect.

FOURTH EDITION

Principles of Environmental Engineering and Science

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Principles of Environmental Engineering and Science

Fourth Edition

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PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND SCIENCE, FOURTH EDITION

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To our students who make it worthwhile.

Contents

<i>Preface</i>	xii	Chapter Review	25
<i>Acknowledgments</i>	xiv	Problems	26
<i>About the Authors</i>	xv	Discussion Questions	27
		FE Exam Formatted Problems	31
		References	31
1 Introduction	1		
1-1 WHAT IS ENVIRONMENTAL SCIENCE?	2	2 Chemistry	35
<i>Natural Science</i>	2	<i>Case Study: Leaded Gasoline: Corporate Greed Versus Chemistry</i>	36
<i>Environmental Science</i>	2	2-1 INTRODUCTION	37
<i>Quantitative Environmental Science</i>	2	2-2 BASIC CHEMICAL CONCEPTS	38
1-2 WHAT IS ENVIRONMENTAL ENGINEERING?	3	<i>Atoms, Elements, and the Periodic Table</i>	38
<i>Professional Development</i>	3	<i>Chemical Bonds and Intermolecular Forces</i>	39
<i>Professions</i>	4	<i>The Mole, Molar Units, and Activity Units</i>	41
1-3 HISTORICAL PERSPECTIVE	4	<i>Chemical Reactions and Stoichiometry</i>	42
<i>Overview</i>	4	<i>Chemical Equilibrium</i>	49
<i>Hydrology</i>	5	<i>Reaction Kinetics</i>	61
<i>Water Treatment</i>	6	2-3 ORGANIC CHEMISTRY	66
<i>Wastewater Treatment</i>	10	<i>Alkanes, Alkenes, and Alkynes</i>	67
<i>Air Pollution Control</i>	10	<i>Aryl (Aromatic) Compounds</i>	68
<i>Solid and Hazardous Waste</i>	11	<i>Functional Groups and Classes of Compounds</i>	68
1-4 HOW ENVIRONMENTAL ENGINEERS AND ENVIRONMENTAL SCIENTISTS WORK TOGETHER	12	2-4 WATER CHEMISTRY	69
1-5 INTRODUCTION TO PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND SCIENCE	12	<i>Physical Properties of Water</i>	69
<i>Where Do We Start?</i>	12	<i>States of Solution Impurities</i>	70
<i>A Short Outline of This Book</i>	13	<i>Concentration Units in Aqueous Solutions or Suspensions</i>	71
1-6 ENVIRONMENTAL SYSTEMS OVERVIEW	13	<i>Buffers</i>	74
<i>Systems</i>	13	2-5 SOIL CHEMISTRY	80
<i>Water Resource Management System</i>	14	2-6 ATMOSPHERIC CHEMISTRY	82
<i>Air Resource Management System</i>	19	<i>Fundamentals of Gases</i>	83
<i>Solid Waste Management System</i>	19	Chapter Review	86
<i>Multimedia Systems</i>	19	Problems	87
<i>Sustainability</i>	21	Discussion Questions	92
1-7 ENVIRONMENTAL LEGISLATION AND REGULATION	21	FE Exam Formatted Problems	92
<i>Acts, Laws, and Regulations</i>	21	References	94
1-8 ENVIRONMENTAL ETHICS	23		
<i>Case 1: To Add or Not to Add</i>	24	3 Biology	95
<i>Case 2: You Can't Do Everything At Once</i>	24	<i>Case Study: Lake Erie is Dead</i>	96
		3-1 INTRODUCTION	97

3-2	CHEMICAL COMPOSITION OF LIFE	97	4-3	MATERIALS BALANCES	153
	<i>Carbohydrates</i>	97		<i>Fundamentals</i>	153
	<i>Nucleic Acids</i>	99		<i>Time as a Factor</i>	154
	<i>Proteins</i>	102		<i>More Complex Systems</i>	155
	<i>Lipids</i>	106		<i>Efficiency</i>	158
3-3	THE CELL	107		<i>The State of Mixing</i>	161
	<i>Prokaryotes and Eukaryotes</i>	107		<i>Including Reactions and Loss Processes</i>	163
	<i>Cell Membrane</i>	107		<i>Reactors</i>	167
	<i>Cell Organelles of Eukaryotes</i>	112		<i>Reactor Analysis</i>	168
	<i>Cell Organelles of Plant Cells</i>	115	4-4	ENERGY BALANCES	176
	<i>Cell Organelles of Prokaryotes</i>	118		<i>First Law of Thermodynamics</i>	176
3-4	ENERGY AND METABOLISM	118		<i>Fundamentals</i>	177
	<i>Cells, Matter, and Energy</i>	118		<i>Second Law of Thermodynamics</i>	185
3-5	CELLULAR REPRODUCTION	123		Chapter Review	187
	<i>The Cell Cycle</i>	123		Problems	187
	<i>Asexual Reproduction</i>	124		Discussion Questions	195
	<i>Sexual Reproduction</i>	125		FE Exam Formatted Problems	195
3-6	DIVERSITY OF LIVING THINGS	126		References	196
3-7	BACTERIA AND ARCHAEA	126	5	Ecosystems	197
	<i>Archaea</i>	127		<i>Case Study: Ecosystems</i>	198
	<i>Bacteria</i>	128	5-1	INTRODUCTION	199
3-8	PROTISTS	131		<i>Ecosystems</i>	199
	<i>Protozoa</i>	131	5-2	HUMAN INFLUENCES ON ECOSYSTEMS	200
	<i>Algae</i>	133	5-3	ENERGY AND MASS FLOW	201
	<i>Slime Molds and Water Molds</i>	136		<i>Bioaccumulation</i>	205
3-9	FUNGI	136	5-4	NUTRIENT CYCLES	207
	<i>Chytridiomycota</i>	136		<i>Carbon Cycle</i>	207
	<i>Zygomycota</i>	136		<i>Nitrogen Cycle</i>	209
	<i>Ascomycota</i>	136		<i>Phosphorus Cycle</i>	210
	<i>Basidiomycota</i>	137		<i>Sulfur Cycle</i>	212
	<i>Deuteromycota</i>	137	5-5	POPULATION DYNAMICS	213
3-10	VIRUSES	137		<i>Bacterial Population Growth</i>	214
3-11	MICROBIAL DISEASE	139		<i>Animal Population Dynamics</i>	216
3-12	MICROBIAL TRANSFORMATIONS	141		<i>Human Population Dynamics</i>	220
	Chapter Review	143	5-6	LAKES: AN EXAMPLE OF MASS AND ENERGY CYCLING IN AN ECOSYSTEM	224
	Problems	145		<i>Stratification and Turnover in Deep Lakes</i>	224
	Discussion Questions	147		<i>Biological Zones</i>	225
	FE Exam Formatted Problems	147		<i>Lake Productivity</i>	227
	References	149		<i>Eutrophication</i>	230
4	Materials and Energy Balances	151	5-7	ENVIRONMENTAL LAWS TO PROTECT ECOSYSTEMS	233
4-1	INTRODUCTION	152		Chapter Review	234
4-2	UNIFYING THEORIES	152		Problems	235
	<i>Conservation of Matter</i>	152			
	<i>Conservation of Energy</i>	152			
	<i>Conservation of Matter and Energy</i>	152			

	Discussion Questions	237			
	FE Exam Formatted Problems	238			
	References	239			
6	Risk Perception, Assessment, and Management	243			
	<i>Case Study: Imposed Risk Versus Assumed Risk</i>	244			
6-1	INTRODUCTION	244			
6-2	RISK PERCEPTION	244			
6-3	RISK ASSESSMENT	246			
	<i>Data Collection and Evaluation</i>	246			
	<i>Toxicity Assessment</i>	246			
	<i>Exposure Assessment</i>	252			
	<i>Risk Characterization</i>	258			
6-4	RISK MANAGEMENT	259			
	Chapter Review	259			
	Problems	260			
	Discussion Questions	262			
	FE Exam Formatted Problems	262			
	References	263			
7	Hydrology	265			
	<i>Case Study: Potential Failure of the Oroville Dam</i>	266			
7-1	FUNDAMENTALS OF HYDROLOGY	267			
	<i>The Hydrological Cycle</i>	267			
7-2	MEASUREMENT OF PRECIPITATION, EVAPORATION, INFILTRATION, AND STREAMFLOW	277			
	<i>Precipitation</i>	277			
	<i>Evaporation</i>	280			
	<i>Infiltration</i>	283			
	<i>Streamflow</i>	286			
7-3	GROUNDWATER HYDROLOGY	287			
	<i>Aquifers</i>	287			
7-4	GROUNDWATER FLOW	292			
7-5	WELL HYDRAULICS	296			
	<i>Definition of Terms</i>	296			
	<i>Cone of Depression</i>	297			
7-6	SURFACE WATER AND GROUNDWATER AS A WATER SUPPLY	302			
7-7	DEPLETION OF GROUNDWATER AND SURFACE WATER	303			
	<i>Water Rights</i>	303			
	<i>Water Use</i>	305			
	<i>Land Subsidence</i>	307			
7-8	STORMWATER MANAGEMENT	308			
	<i>Low Impact Development</i>	309			
	<i>Wet Weather Green Infrastructure</i>	310			
	Chapter Review	310			
	Problems	311			
	Discussion Questions	313			
	FE Exam Formatted Problems	313			
	References	314			
8	Sustainability	317			
	<i>Case Study: A New Precious Metal—Copper!</i>	318			
8-1	INTRODUCTION	319			
	<i>Sustainability</i>	319			
	<i>The People Problem</i>	319			
	<i>There Are No Living Dinosaurs</i>	320			
	<i>Go Green</i>	321			
8-2	WATER RESOURCES	322			
	<i>Water, Water, Everywhere</i>	322			
	<i>Frequency from Probability Analysis</i>	322			
	<i>Floods</i>	323			
	<i>Droughts</i>	328			
8-3	ENERGY RESOURCES	345			
	<i>Fossil Fuel Reserves</i>	345			
	<i>Nuclear Energy Resources</i>	349			
	<i>Environmental Impacts</i>	350			
	<i>Sustainable Energy Sources</i>	354			
	<i>Green Engineering and Energy Conservation</i>	359			
8-4	MINERAL RESOURCES	366			
	<i>Reserves</i>	366			
	<i>Environmental Impacts</i>	367			
	<i>Resource Conservation</i>	369			
8-5	SOIL RESOURCES	372			
	<i>Energy Storage</i>	372			
	<i>Plant Production</i>	372			
8-6	PARAMETERS OF SOIL SUSTAINABILITY	373			
	<i>Nutrient Cycling</i>	373			
	<i>Soil Acidity</i>	374			
	<i>Soil Salinity</i>	375			
	<i>Texture and Structure</i>	376			
8-7	SOIL CONSERVATION	376			
	<i>Soil Management</i>	376			
	<i>Soil Erosion</i>	377			
	Chapter Review	383			
	Problems	384			
	Discussion Questions	385			
	FE Exam Formatted Problems	386			
	References	386			

9	Water Quality Management	393	10	Water Treatment	471
	<i>Case Study: Deepwater Horizon: The Largest Oil Spill Disaster in U.S. History</i>	394		<i>Case Study: The Flint Water Crisis</i>	472
9-1	INTRODUCTION	395	10-1	INTRODUCTION	474
9-2	WATER POLLUTANTS AND THEIR SOURCES	396		<i>Water Quality</i>	475
	<i>Point Sources</i>	396		<i>Physical Characteristics</i>	476
	<i>Nonpoint Sources</i>	396		<i>Chemical Characteristics</i>	476
	<i>Oxygen-Demanding Material</i>	397		<i>Microbiological Characteristics</i>	477
	<i>Nutrients</i>	397		<i>Radiological Characteristics</i>	477
	<i>Pathogenic Organisms</i>	399	10-2	RAPID MIXING, FLOCCULATION, AND COAGULATION	482
	<i>Suspended Solids</i>	400		<i>Colloid Stability and Destabilization</i>	483
	<i>Salts</i>	400		<i>The Physics of Coagulation</i>	483
	<i>Pesticides</i>	401		<i>Coagulants</i>	484
	<i>Pharmaceuticals and Personal Care Products</i>	403		<i>Mixing and Flocculation</i>	487
	<i>Endocrine-Disrupting Chemicals</i>	404	10-3	SOFTENING	490
	<i>Other Organic Chemicals</i>	405		<i>Hardness</i>	490
	<i>Arsenic</i>	405		<i>Lime-Soda Softening</i>	496
	<i>Toxic Metals</i>	407		<i>Ion-Exchange Softening</i>	499
	<i>Heat</i>	408	10-4	SEDIMENTATION	501
	<i>Nanoparticles</i>	408		<i>Overview</i>	501
9-3	WATER QUALITY MANAGEMENT IN RIVERS	409		<i>Determination of Settling Velocity (v_s)</i>	502
	<i>Effect of Oxygen-Demanding Wastes on Rivers</i>	409		<i>Determination of Overflow Rate (v_o)</i>	504
	<i>Biochemical Oxygen Demand</i>	410	10-5	FILTRATION	505
	<i>Laboratory Measurement of Biochemical Oxygen Demand</i>	414	10-6	DISINFECTION	508
	<i>Additional Notes on Biochemical Oxygen Demand</i>	417		<i>Disinfection Kinetics</i>	509
	<i>Nitrogen Oxidation</i>	418		<i>Disinfectants and Disinfection By-Products</i>	510
	<i>DO Sag Curve</i>	420		<i>Chlorine Reactions in Water</i>	511
	<i>Effect of Nutrients on Water Quality in Rivers</i>	436		<i>Chloramines</i>	513
9-4	WATER QUALITY MANAGEMENT IN LAKES	437		<i>Chlorine Dioxide</i>	514
	<i>Control of Phosphorus in Lakes</i>	437		<i>Ozonation</i>	514
	<i>Acidification of Lakes</i>	441		<i>Ultraviolet Radiation</i>	514
9-5	WATER QUALITY IN ESTUARIES	448	10-7	OTHER TREATMENT PROCESSES FOR DRINKING WATER	515
9-6	WATER QUALITY IN OCEANS	449		<i>Membrane Processes</i>	515
9-7	GROUNDWATER QUALITY	452		<i>Advanced Oxidation Processes (AOPs)</i>	519
	<i>Contaminant Migration in Groundwaters</i>	452		<i>Carbon Adsorption</i>	519
9-8	SOURCE WATER PROTECTION	456		<i>Aeration</i>	519
	Chapter Review	457	10-8	WATER PLANT RESIDUALS MANAGEMENT	520
	Problems	458		<i>Mass-Balance Analysis</i>	521
	Discussion Questions	463		<i>Sludge Treatment</i>	522
	FE Exam Formatted Problems	465		<i>Ultimate Disposal</i>	526
	References	466		Chapter Review	527
				Problems	528
				Discussion Questions	534
				FE Exam Formatted Problems	535
				References	537

11	Wastewater Treatment	539	11-12	SLUDGE TREATMENT	583
	<i>Case Study: Tenafly Sewage Treatment Plant: A Plant Decades Ahead of Its Time</i>	540		<i>Sources and Characteristics of Various Sludges</i>	583
11-1	INTRODUCTION	541		<i>Solids Computations</i>	583
	<i>Wastewater Treatment Perspective</i>	541		<i>Sludge Treatment Processes</i>	585
11-2	CHARACTERISTICS OF DOMESTIC WASTEWATER	541	11-13	SLUDGE DISPOSAL	591
	<i>Physical Characteristics</i>	541		<i>Ultimate Disposal</i>	591
	<i>Chemical Characteristics</i>	542		<i>Land Spreading</i>	591
	<i>Characteristics of Industrial Wastewater</i>	542		<i>Landfilling</i>	592
11-3	WASTEWATER TREATMENT STANDARDS	545		<i>Dedicated Land Disposal Utilization</i>	592
	<i>Pretreatment of Industrial Wastes</i>	546		<i>Sludge Disposal Regulations</i>	592
11-4	ON-SITE DISPOSAL SYSTEMS	547	11-14	DIRECT POTABLE REUSE	592
11-5	MUNICIPAL WASTEWATER TREATMENT SYSTEMS	547		<i>Description</i>	592
11-6	UNIT OPERATIONS OF PRETREATMENT	548		<i>Public Perception</i>	593
	<i>Bar Racks</i>	548		<i>Health Issues</i>	593
	<i>Grit Chambers</i>	548		<i>Technological Capability</i>	594
	<i>Macerators</i>	551		Chapter Review	594
	<i>Equalization</i>	551		Problems	595
11-7	PRIMARY TREATMENT	555		Discussion Questions	599
11-8	UNIT PROCESSES OF SECONDARY TREATMENT	557		FE Exam Formatted Problems	599
	<i>Overview</i>	557		References	600
	<i>Role of Microorganisms</i>	557	12	Air Pollution	603
	<i>Population Dynamics</i>	557		<i>Case Study: Killer Smog Blankets Town</i>	604
	<i>Activated Sludge</i>	559	12-1	INTRODUCTION	605
	<i>Trickling Filters</i>	570		<i>Air Pollution Perspective</i>	605
	<i>Oxidation Ponds</i>	572	12-2	FUNDAMENTALS	605
	<i>Rotating Biological Contactors</i>	574		<i>Pressure Relationships and Units of Measure</i>	605
	<i>Integrated Fixed-Film Activated Sludge (IFAS)</i>	575		<i>Relativity</i>	605
	<i>Moving Bed Biofilm Reactor</i>	575		<i>Adiabatic Expansion and Compression</i>	605
11-9	DISINFECTION	576	12-3	AIR POLLUTION STANDARDS	606
11-10	TERTIARY WASTEWATER TREATMENT	576	12-4	EFFECTS OF AIR POLLUTANTS	611
	<i>Filtration</i>	576		<i>Effects on Materials</i>	611
	<i>Carbon Adsorption</i>	577		<i>Effects on Vegetation</i>	612
	<i>Chemical Phosphorus Removal</i>	577		<i>Effects on Health</i>	614
	<i>Biological Phosphorus Removal</i>	579	12-5	ORIGIN AND FATE OF AIR POLLUTANTS	618
	<i>Nitrogen Control</i>	579		<i>Carbon Monoxide</i>	618
11-11	LAND TREATMENT FOR SUSTAINABILITY	580		<i>Hazardous Air Pollutants</i>	619
	<i>Slow Rate</i>	581		<i>Lead</i>	619
	<i>Overland Flow</i>	582		<i>Nitrogen Dioxide</i>	619
	<i>Rapid Infiltration</i>	582		<i>Photochemical Oxidants</i>	620
	<i>Potential Adverse Affects</i>	582		<i>Sulfur Oxides</i>	620
				<i>Particulates</i>	623
			12-6	MICRO AND MACRO AIR POLLUTION	625
				<i>Indoor Air Pollution</i>	625
				<i>Acid Rain</i>	628

	<i>Ozone Depletion</i>	630		<i>Public Health and Environmental Issues</i>	698
	<i>Global Warming</i>	631		<i>Other Thermal Treatment Processes</i>	700
12-7	AIR POLLUTION METEOROLOGY	640	13-7	DISPOSAL BY SANITARY LANDFILL	700
	<i>The Atmospheric Engine</i>	640		<i>Site Selection</i>	701
	<i>Turbulence</i>	640		<i>Operation</i>	702
	<i>Stability</i>	641		<i>Environmental Considerations</i>	704
	<i>Terrain Effects</i>	644		<i>Leachate</i>	704
12-8	ATMOSPHERIC DISPERSION	646		<i>Methane and Other Gas Production</i>	708
	<i>Factors Affecting Dispersion of Air</i>			<i>Landfill Design</i>	711
	<i>Pollutants</i>	646		<i>Landfill Closure</i>	711
	<i>Dispersion Modeling</i>	647		Chapter Review	712
12-9	INDOOR AIR QUALITY MODEL	654		Problems	713
12-10	AIR POLLUTION CONTROL OF STATIONARY SOURCES	656		Discussion Questions	715
	<i>Gaseous Pollutants</i>	656		FE Exam Formatted Problems	715
	<i>Flue Gas Desulfurization</i>	659		References	716
	<i>Control Technologies for Nitrogen Oxides</i>	660			
	<i>Particulate Pollutants</i>	661			
	<i>Control Technologies for Mercury</i>	664	14	Hazardous Waste Management	719
12-11	AIR POLLUTION CONTROL OF MOBILE SOURCES	665		<i>Case Study: Don't Cry over Spilled Milk but Do Cry over Contaminated Milk</i>	720
	<i>Engine Fundamentals</i>	665			
	<i>Control of Automobile Emissions</i>	668	14-1	INTRODUCTION	721
12-12	WASTE MINIMIZATION FOR SUSTAINABILITY	669		<i>Dioxins and PCBs</i>	721
	Chapter Review	671	14-2	EPA'S HAZARDOUS WASTE DESIGNATION SYSTEM	723
	Problems	672			
	Discussion Questions	674	14-3	RCRA AND HSWA	725
	FE Exam Formatted Problems	674		<i>Congressional Actions on Hazardous Waste</i>	725
	References	675		<i>Cradle-to-Grave Concept</i>	726
				<i>Generator Requirements</i>	726
				<i>Transporter Regulations</i>	728
13	Solid Waste Engineering	679		<i>Treatment, Storage, and Disposal Requirements</i>	728
	<i>Case Study: Too Much Waste, Too Little Space</i>	680		<i>Underground Storage Tanks</i>	730
13-1	INTRODUCTION	681	14-4	CERCLA AND SARA	730
	<i>Magnitude of the Problem</i>	681		<i>The Superfund Law</i>	730
13-2	CHARACTERISTICS OF SOLID WASTE	683		<i>The National Priority List</i>	731
13-3	SOLID WASTE MANAGEMENT	686		<i>The Hazard Ranking System</i>	731
13-4	SOLID WASTE COLLECTION	687		<i>The National Contingency Plan</i>	732
13-5	WASTE AS RESOURCE	687		<i>Liability</i>	733
	<i>Background and Perspective</i>	687		<i>Superfund Amendments and Reauthorization Act</i>	733
	<i>Green Chemistry and Green Engineering</i>	689	14-5	HAZARDOUS WASTE MANAGEMENT	734
	<i>Recycling</i>	689		<i>Waste Minimization</i>	734
	<i>Composting</i>	693		<i>Waste Exchange</i>	737
	<i>Source Reduction</i>	693		<i>Recycling</i>	737
13-6	SOLID WASTE REDUCTION	695	14-6	TREATMENT TECHNOLOGIES	738
	<i>Combustion Processes</i>	695		<i>Biological Treatment</i>	738
	<i>Types of Incinerators</i>	696		<i>Chemical Treatment</i>	740

	<i>Physical/Chemical Treatment</i>	743			
	<i>Incineration</i>	748			
	<i>Stabilization–Solidification</i>	755			
14–7	LAND DISPOSAL	755			
	<i>Deep Well Injection</i>	755			
	<i>Land Treatment</i>	756			
	<i>The Secure Landfill</i>	756			
14–8	GROUNDWATER CONTAMINATION AND REMEDIATION	760			
	<i>The Process of Contamination</i>	760			
	<i>EPA’s Groundwater Remediation Procedure</i>	760			
	<i>Mitigation and Treatment</i>	762			
	Chapter Review	769			
	Problems	770			
	Discussion Questions	775			
	FE Exam Formatted Problems	775			
	References	776			
15	Noise Pollution	779			
	<i>Case Study: The Noise, The Noise, The Noise!</i>	780			
15–1	INTRODUCTION	780			
	<i>Properties of Sound Waves</i>	782			
	<i>Sound Power and Intensity</i>	783			
	<i>Levels and the Decibel</i>	783			
	<i>Characterization of Noise</i>	786			
15–2	EFFECTS OF NOISE ON PEOPLE	790			
	<i>The Hearing Mechanism</i>	790			
	<i>Normal Hearing</i>	793			
	<i>Hearing Impairment</i>	794			
	<i>Damage-Risk Criteria</i>	796			
	<i>Speech Interference</i>	796			
	<i>Annoyance</i>	797			
	<i>Sleep Interference</i>	799			
	<i>Effects on Performance</i>	800			
	<i>Acoustic Privacy</i>	800			
15–3	RATING SYSTEMS	800			
	<i>Goals of a Noise-Rating System</i>	800			
	<i>The L_N Concept</i>	801			
	<i>The L_{eq} Concept</i>	801			
	<i>The L_{dn} Concept</i>	802			
15–4	COMMUNITY NOISE SOURCES AND CRITERIA	803			
	<i>Transportation Noise</i>	803			
	<i>Other Internal Combustion Engines</i>	805			
	<i>Construction Noise</i>	805			
	<i>Zoning and Siting Considerations</i>	805			
	<i>Levels to Protect Health and Welfare</i>	805			
15–5	TRANSMISSION OF SOUND OUTDOORS	806			
	<i>Inverse Square Law</i>	806			
	<i>Radiation Fields of a Sound Source</i>	808			
	<i>Directivity</i>	809			
	<i>Airborne Transmission</i>	809			
15–6	TRAFFIC NOISE PREDICTION	811			
	<i>L_{eq} Prediction</i>	811			
	<i>L_{dn} Prediction</i>	811			
15–7	NOISE CONTROL	811			
	<i>Source-Path-Receiver Concept</i>	811			
	<i>Control of Noise Source by Design</i>	812			
	<i>Noise Control in the Transmission Path</i>	813			
	<i>Control of Noise Source by Redress</i>	815			
	<i>Protect the Receiver</i>	815			
	Chapter Review	816			
	Problems	817			
	Discussion Questions	821			
	FE Exam Formatted Problems	821			
	References	822			
16	Ionizing Radiation	825			
	<i>Case Study: Chernobyl: A Land Lost Forever?</i>	826			
16–1	FUNDAMENTALS	827			
	<i>Atomic Structure</i>	827			
	<i>Radioactivity and Radiation</i>	828			
	<i>Radioactive Decay</i>	830			
	<i>Radioisotopes</i>	833			
	<i>Fission</i>	834			
	<i>The Production of X-Rays</i>	835			
	<i>Radiation Dose</i>	837			
16–2	BIOLOGICAL EFFECTS OF IONIZING RADIATION	839			
	<i>Sequential Pattern of Biological Effects</i>	839			
	<i>Determinants of Biological Effects</i>	839			
	<i>Acute Effects</i>	841			
	<i>Relation of Dose to Type of Acute Radiation Syndrome</i>	841			
	<i>Delayed Effects</i>	842			
	<i>Genetic Effects</i>	844			
16–3	RADIATION STANDARDS	845			
16–4	RADIATION EXPOSURE	847			
	<i>External and Internal Radiation Hazards</i>	847			
	<i>Natural Background</i>	847			
	<i>X-Rays</i>	848			
	<i>Radionuclides</i>	849			
	<i>Nuclear Reactor Operations</i>	849			
	<i>Radioactive Wastes</i>	850			

16–5	RADIATION PROTECTION	850		
	<i>Reduction of External Radiation Hazards</i>	850		
	<i>Reduction of Internal Radiation Hazards</i>	854		
16–6	RADIOACTIVE WASTE	855		
	<i>Types of Waste</i>	855		
	<i>Management of High-Level Radioactive Waste</i>	856		
	<i>Waste Isolation Pilot Plant</i>	857		
	<i>Management of Low-Level Radioactive Waste</i>	857		
	<i>Long-Term Management and Containment</i>	860		
	Chapter Review	862		
	Problems	863		
	Discussion Questions	864		
	References	864		
			Appendices	
			A	PROPERTIES OF AIR, WATER, AND SELECTED CHEMICALS 867
			B	LIST OF ELEMENTS WITH THEIR SYMBOLS AND ATOMIC MASSES 873
			C	PERIODIC TABLE OF CHEMICAL ELEMENTS 875
			D	USEFUL UNIT CONVERSION AND PREFIXES 876
			E	GREEK ALPHABET 878
				Index 879

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 CO₂ 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

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Susan J. Masten

Mackenzie L. Davis

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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? 2 <i>Natural Science 2</i> <i>Environmental Science 2</i> <i>Quantitative Environmental Science 2</i>
1-2	WHAT IS ENVIRONMENTAL ENGINEERING? 3 <i>Professional Development 3</i> <i>Professions 4</i>
1-3	HISTORICAL PERSPECTIVE 4 <i>Overview 4</i> <i>Hydrology 5</i> <i>Water Treatment 6</i> <i>Wastewater Treatment 10</i> <i>Air Pollution Control 10</i> <i>Solid and Hazardous Waste 11</i>
1-4	HOW ENVIRONMENTAL ENGINEERS AND ENVIRONMENTAL SCIENTISTS WORK TOGETHER 12
1-5	INTRODUCTION TO PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND SCIENCE 12 <i>Where Do We Start? 12</i> <i>A Short Outline of This Book 13</i>
1-6	ENVIRONMENTAL SYSTEMS OVERVIEW 13 <i>Systems 13</i> <i>Water Resource Management System 14</i> <i>Air Resource Management System 19</i> <i>Solid Waste Management System 19</i> <i>Multimedia Systems 19</i> <i>Sustainability 21</i>
1-7	ENVIRONMENTAL LEGISLATION AND REGULATION 21 <i>Acts, Laws, and Regulations 21</i>
1-8	ENVIRONMENTAL ETHICS 23 <i>Case 1: To Add or Not to Add 24</i> <i>Case 2: You Can't Do Everything At Once 24</i>
	CHAPTER REVIEW 25
	PROBLEMS 26
	DISCUSSION QUESTIONS 27
	FE EXAM FORMATTED PROBLEMS 31
	REFERENCES 31

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 Mathematica* (*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:	
<ol style="list-style-type: none"> 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	
<ol style="list-style-type: none"> 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 Poiseuille (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 $3 \times 10^5 \text{ m}^3 \cdot \text{d}^{-1}$ 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.

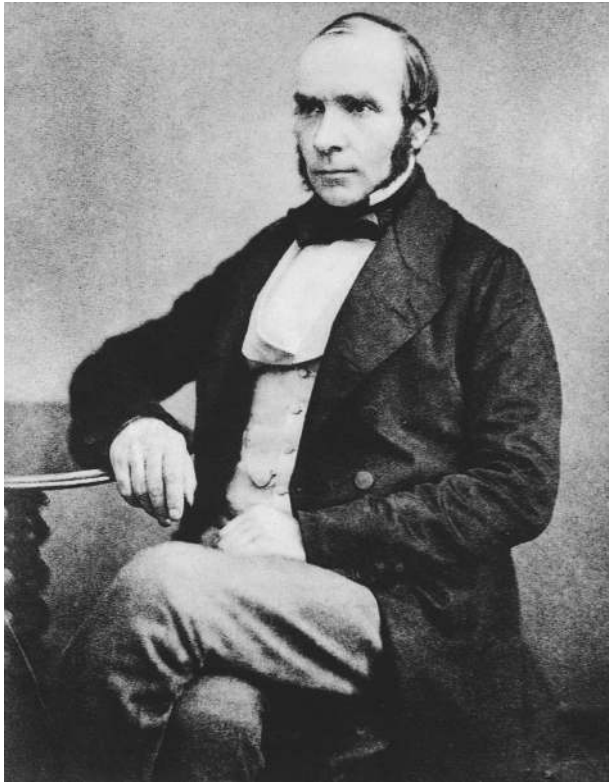
In England, the social awakening was preceded by a water filtration process installed in Paisley, Scotland, in 1804 and the entrepreneurial endeavors of the Chelsea Water Company, which installed filters for the purpose of improving the quality of the Thames River water in 1829 (Baker, 1981; Fair and 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.

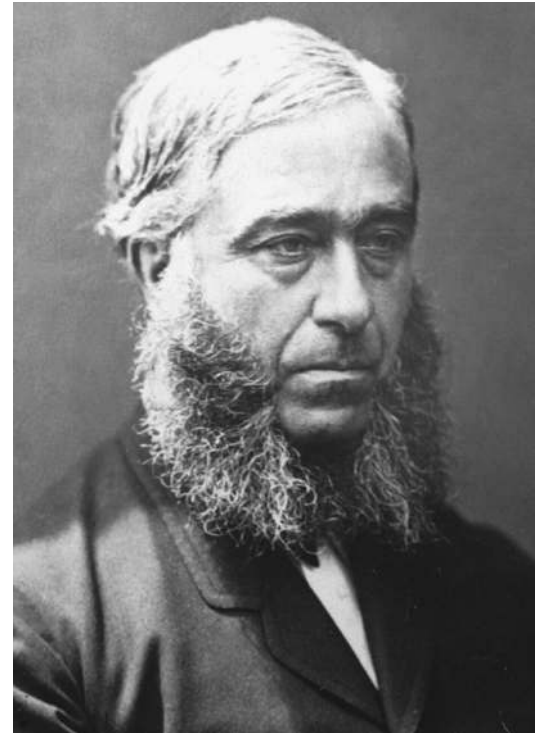
In the United States a bold but unsuccessful start on filtration was made at Richmond, Virginia, in 1832. No further installations were made in the United States until after the Civil War. Even then, they were for the most part failures. The primary means of purification from the 1830s until the 1880s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



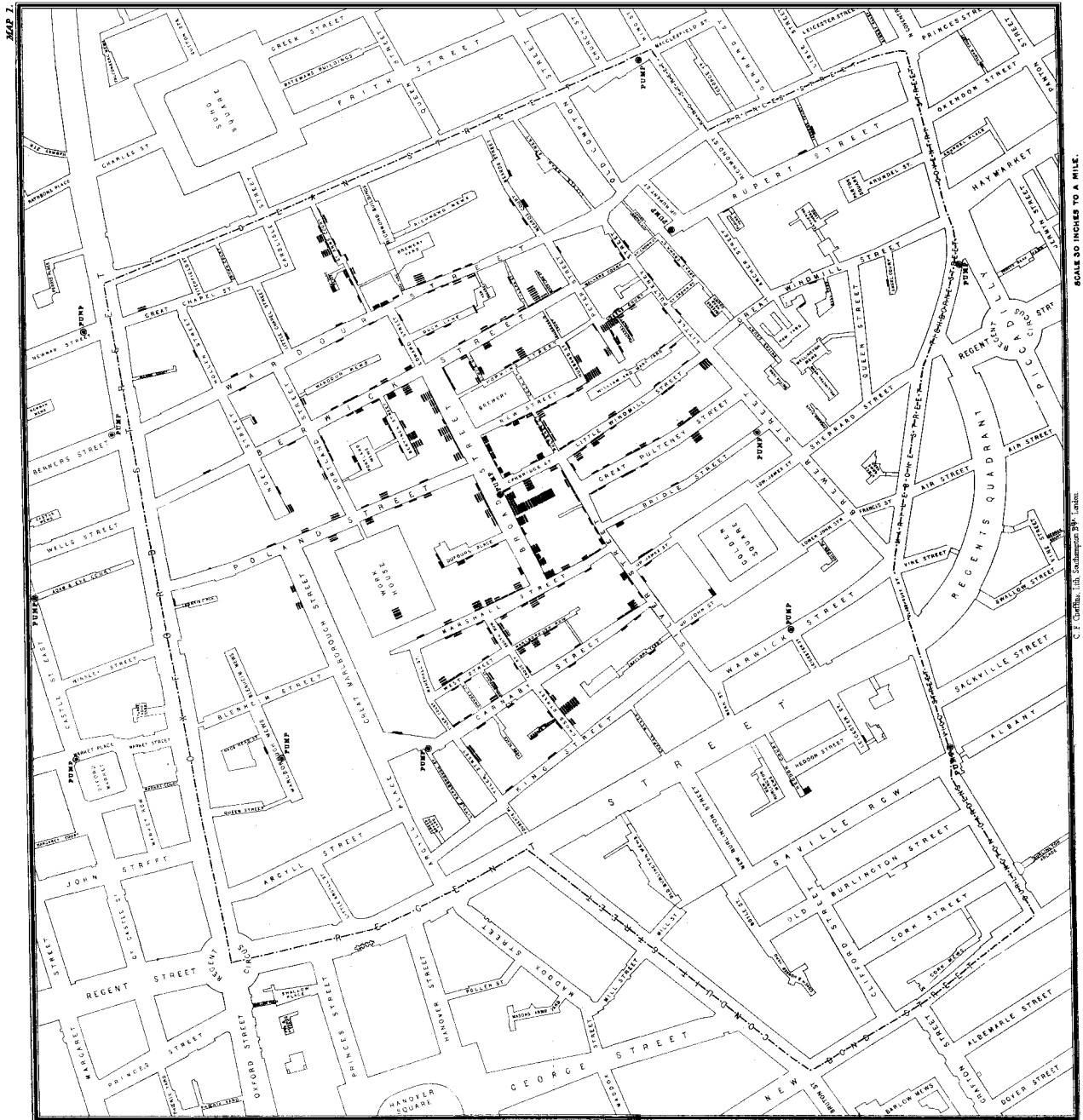
It is worthy of note that the American Water Works Association (AWWA) was established in 1881. This body of professionals joined together to share their knowledge and experience. As with other professional societies and associations formed in the late 1800s and early 1900s, the activities of the Association 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>

