

CONTENTS

Preface

xvii

PART I BASIC PRINCIPLES

1

INTRODUCTION

3

- 1.1 Emergence of Geoenvironmental Engineering, *3*
- 1.2 Types of Geoenvironmental Problems, *4*
 - 1.2.1 Contaminated Site Remediation, *4*
 - 1.2.2 Waste Containment, *5*
 - 1.2.3 Waste Minimization by Recycling, *6*
- 1.3 Book Organization, *7*
- 1.4 Summary, *7*
 - Questions/Problems, *7*
 - References, *8*

2

RELEVANT ENVIRONMENTAL LAWS AND REGULATIONS

9

- 2.1 Introduction, *9*
- 2.2 Development of Laws and Regulations, *9*
- 2.3 Federal Environmental Laws and Regulations, *10*
 - 2.3.1 Rivers and Harbors Act, *10*
 - 2.3.2 Atomic Energy Act, *10*
 - 2.3.3 Solid Waste Disposal Act, *12*
 - 2.3.4 National Environmental Policy Act, *12*

- 2.3.5 Occupational Safety and Health Act, *12*
- 2.3.6 Marine Protection, Research and Sanctuaries Act, *13*
- 2.3.7 Federal Insecticide, Fungicide and Rodenticide Act, *13*
- 2.3.8 Clean Air Act, *13*
- 2.3.9 Clean Water Act, *14*
- 2.3.10 Safe Drinking Water Act, *14*
- 2.3.11 Toxic Substances Control Act, *16*
- 2.3.12 Resource Conservation and Recovery Act, *16*
- 2.3.13 Hazardous and Solid Waste Amendments, *16*
- 2.3.14 Comprehensive Environmental Response, Compensation and Liabilities Act or Superfund, *17*
- 2.3.15 Superfund Amendments and Reauthorization Act, *18*
- 2.3.16 Pollution Prevention Act, *18*
- 2.3.17 Small Business Liability Relief and Brownfields Revitalization Act, *19*
- 2.4 State and Local Laws and Regulations, *19*
- 2.5 Impact of Regulations on Geoenvironmental Practice, *19*
- 2.6 Summary, *21*
 - Questions/Problems, *21*
 - References, *23*

3			
CHEMICAL BACKGROUND	24		
3.1 Introduction, <i>24</i>			
3.2 Toxic Chemicals, <i>24</i>			
3.2.1 Toxic Inorganic Chemicals, <i>24</i>			
3.2.2 Toxic Organic Chemicals, <i>24</i>			
3.2.3 Toxic Radionuclides, <i>25</i>			
3.3 Inorganic Chemistry Background, <i>25</i>			
3.3.1 Atoms, Elements, and the Periodic Table, <i>25</i>			
3.3.2 Molecules and Chemical Compounds, <i>25</i>			
3.3.3 Concentration of Chemical Compounds, <i>28</i>			
3.3.4 Chemical Reaction, <i>28</i>			
3.3.5 Chemical Reaction Balance, <i>28</i>			
3.3.6 Equilibrium, <i>29</i>			
3.3.7 Types of Chemical Reactions, <i>29</i>			
3.3.8 Chemical Kinetics, <i>35</i>			
3.3.9 Gas Laws, <i>36</i>			
3.4 Organic Chemistry Background, <i>36</i>			
3.4.1 Characteristics of Organic Compounds, <i>37</i>			
3.4.2 Classification of Organic Compounds, <i>38</i>			
3.4.3 Properties of Organic Compounds, <i>40</i>			
3.5 Nuclear Chemistry Background, <i>40</i>			
3.6 Chemical Analysis Methods, <i>40</i>			
3.6.1 Methods Used to Measure Toxic Inorganic Chemicals, <i>41</i>			
3.6.2 Methods Used to Measure Toxic Organic Chemicals, <i>41</i>			
3.7 Summary, <i>41</i>			
Questions/Problems, <i>42</i>			
References, <i>42</i>			
4			
COMPOSITION OF SOILS	44		
4.1 Introduction, <i>44</i>			
4.2 Soil Formation, <i>44</i>			
4.3 Soil Composition, <i>46</i>			
4.3.1 Solid Phase, <i>46</i>			
4.3.2 Liquid Phase, <i>57</i>			
4.3.3 Gas Phase, <i>62</i>			
4.4 Soil Fabric, <i>63</i>			
4.5 Summary, <i>65</i>			
Questions/Problems, <i>65</i>			
References, <i>66</i>			
5			
SOIL PROPERTIES	68		
5.1 Introduction, <i>68</i>			
5.2 Geotechnical Properties, <i>68</i>			
5.2.1 Mass–Volume Relationships, <i>68</i>			
5.2.2 Index Properties and Soil Classification, <i>68</i>			
5.2.3 Compaction Characteristics, <i>70</i>			
5.2.4 Hydraulic Characteristics, <i>75</i>			
5.2.5 Consolidation (Compressibility) Characteristics, <i>76</i>			
5.2.6 Shear Strength, <i>81</i>			
5.3 Chemical Properties, <i>82</i>			
5.3.1 pH or Hydrogen-Ion Activity, <i>84</i>			
5.3.2 Surface Charge and Point of Zero Charge, <i>85</i>			
5.3.3 Cation Exchange Capacity, <i>86</i>			
5.3.4 Anion Exchange Capacity, <i>87</i>			
5.3.5 Specific Surface, <i>87</i>			
5.4 Summary, <i>88</i>			
Questions/Problems, <i>88</i>			
References, <i>94</i>			
6			
GEOCHEMISTRY BACKGROUND	95		
6.1 Introduction, <i>95</i>			
6.2 Inorganic Geochemistry, <i>95</i>			
6.2.1 Metal Contamination, <i>95</i>			
6.2.2 Distribution of Metals in Soils, <i>95</i>			
6.2.3 Geochemical Processes Controlling the Distribution of Metals in Soils, <i>96</i>			
6.2.4 Predictive Methods for Metal Distribution in Soils, <i>100</i>			

- 6.2.5 Chemical Analysis of Metals in Soils, *100*
- 6.3 Organic Geochemistry, *101*
 - 6.3.1 Organic Contamination, *104*
 - 6.3.2 Distribution of NAPLs in Soils, *109*
 - 6.3.3 Processes Controlling Distribution of NAPLs in Soils, *109*
 - 6.3.4 Chemical Analysis of NAPLs in Soils, *114*
- 6.4 Summary, *116*
 - Questions/Problems, *116*
 - References, *117*

7

GROUNDWATER FLOW

119

- 7.1 Introduction, *119*
- 7.2 Hydrologic Cycle and Groundwater, *119*
- 7.3 Aquifer, Aquiclude, and Aquitard, *119*
- 7.4 Hydraulic Head and Aquifer Properties, *121*
 - 7.4.1 Hydraulic Head, *121*
 - 7.4.2 Porosity, *122*
 - 7.4.3 Specific Yield, *122*
 - 7.4.4 Hydraulic Conductivity, *123*
 - 7.4.5 Transmissivity, *123*
 - 7.4.6 Specific Storage and Storativity, *123*
- 7.5 Groundwater Flow in Aquifers, *124*
 - 7.5.1 Flow in Confined Aquifer, *124*
 - 7.5.2 Flow in Unconfined Aquifer, *125*
 - 7.5.3 Methods to Solve Groundwater Flow Equation, *126*
- 7.6 One-Dimensional Steady Flow, *126*
 - 7.6.1 Uniform Aquifer, *126*
 - 7.6.2 Stratified Aquifer, *126*
 - 7.6.3 Spatial Variation of Hydraulic Conductivity, *127*
- 7.7 Flow Toward a Pumping Well, *128*
 - 7.7.1 Confined Aquifer, *129*
 - 7.7.2 Unconfined Aquifer, *132*
 - 7.7.3 Effects of Multiple Wells and Boundaries, *134*
- 7.8 Pumping and Slug Testing, *135*
 - 7.8.1 Pumping Tests, *136*
 - 7.8.2 Slug Tests, *140*
- 7.9 Two- and Three-Dimensional Groundwater Flow, *147*
 - 7.9.1 Groundwater Flow Nets, *149*
 - 7.9.2 Groundwater Flow Modeling, *153*
- 7.10 Summary, *158*
 - Questions/Problems, *158*
 - References, *165*

8

CONTAMINANT TRANSPORT AND FATE 167

- 8.1 Introduction, *167*
- 8.2 Transport Processes, *167*
 - 8.2.1 Advection, *167*
 - 8.2.2 Diffusion, *168*
 - 8.2.3 Dispersion, *171*
- 8.3 Chemical Mass Transfer Processes, *174*
 - 8.3.1 Sorption and Desorption, *175*
 - 8.3.2 Precipitation and Dissolution, *180*
 - 8.3.3 Oxidation–Reduction (Redox) Reactions, *181*
 - 8.3.4 Acid–Base Reactions, *183*
 - 8.3.5 Complexation, *188*
 - 8.3.6 Ion Exchange, *188*
 - 8.3.7 Volatilization, *188*
 - 8.3.8 Hydrolysis, *190*
- 8.4 Biological Process (Biodegradation), *190*
- 8.5 Contaminant Transport and Fate Modeling, *192*
 - 8.5.1 Analytical Methods, *193*
 - 8.5.2 Numerical Methods, *196*
- 8.6 Applications, *199*
 - 8.6.1 Landfills and Surface Impoundments, *199*
 - 8.6.2 In-Situ Barriers, *201*
 - 8.6.3 Groundwater Contamination, *203*
- 8.7 Summary, *204*
 - Questions/Problems, *208*
 - References, *209*

PART II REMEDIATION TECHNOLOGIES

- 9**
SUBSURFACE CONTAMINATION: SOURCES, CONTAMINANTS, REGULATIONS, AND REMEDIAL APPROACH **215**
- 9.1 Introduction, *215*
- 9.2 Sources of Contamination, *215*
- 9.2.1 Sources Originating on the Ground Surface, *215*
- 9.2.2 Sources Originating above the Water Table (Vadose Zone), *217*
- 9.2.3 Sources Originating below the Water Table (Saturated Zone), *218*
- 9.3 Types of Contaminants, *218*
- 9.4 Relevant Regulations, *221*
- 9.4.1 Comprehensive Environmental Response, Compensation and Liabilities Act, *221*
- 9.4.2 Resource Conservation and Recovery Act, *223*
- 9.4.3 State Voluntary Site Remediation Programs, *224*
- 9.5 Other Considerations, *224*
- 9.6 Remediation Approach, *226*
- 9.6.1 Site Characterization, *226*
- 9.6.2 Risk (Impact) Assessment, *230*
- 9.6.3 Remedial Action, *230*
- 9.7 Summary, *231*
- Questions/Problems, *232*
- References, *232*
- 10**
CONTAMINATED SITE CHARACTERIZATION **234**
- 10.1 Introduction, *234*
- 10.2 General Methodology, *234*
- 10.3 Preliminary Site Assessment, *236*
- 10.3.1 Literature Review, *236*
- 10.3.2 Site Visit, *236*
- 10.4 Exploratory Site Investigation, *237*
- 10.5 Detailed Site Investigation, *237*
- 10.5.1 Methods of Obtaining Soil and Rock Data, *237*
- 10.5.2 Methods of Obtaining Hydrogeologic Data, *249*
- 10.5.3 Methods of Obtaining Chemical Data, *264*
- 10.5.4 Data Analysis and Evaluation, *273*
- 10.6 Expedited or Accelerated Site Characterization, *273*
- 10.7 Summary, *281*
- Questions/Problems, *281*
- References, *282*
- 11**
RISK ASSESSMENT AND REMEDIAL STRATEGY **284**
- 11.1 Introduction, *284*
- 11.2 Risk Assessment Procedures, *284*
- 11.3 USEPA Procedure, *284*
- 11.3.1 Data Collection and Evaluation, *284*
- 11.3.2 Exposure Assessment, *285*
- 11.3.3 Toxicity Assessment, *285*
- 11.3.4 Risk Characterization, *286*
- 11.4 ASTM Procedure, *290*
- 11.4.1 Tier 1 Evaluation, *292*
- 11.4.2 Tier 2 Evaluation, *292*
- 11.4.3 Tier 3 Evaluation, *296*
- 11.5 Other Risk Assessment Methods, *300*
- 11.6 Remedial Strategy, *307*
- Questions/Problems, *328*
- References, *329*
- 12**
IN-SITU WASTE CONTAINMENT **331**
- 12.1 Introduction, *331*
- 12.2 Vertical Barriers, *331*
- 12.2.1 Description, *331*
- 12.2.2 Compacted Clay Barriers, *333*

- 12.2.3 Slurry Trench Barriers, 333
- 12.2.4 Grouted Barriers, 350
- 12.2.5 Mixed-in-Place Barriers, 358
- 12.2.6 Steel Sheet Pile Barriers, 359
- 12.3 Bottom Barriers, 361
 - 12.3.1 Description, 361
 - 12.3.2 Permeation Grouting, 361
 - 12.3.3 Jet Grouting, 362
 - 12.3.4 Bottom Barriers by Directional Drilling and Grouting, 364
 - 12.3.5 Bottom Barriers Using Hydrofracturing and Block Displacement Method, 364
 - 12.3.6 Sheet Pile Combined with Injection Grouting, 365
- 12.4 Surface Caps or Covers, 366
 - 12.4.1 Description, 366
 - 12.4.2 Configuration and Materials, 366
 - 12.4.3 Design, 368
 - 12.4.4 Construction, 370
 - 12.4.5 Performance and Economic Considerations, 371
- 12.5 Groundwater Pumping Systems, 371
 - 12.5.1 Description, 371
 - 12.5.2 Design, 374
 - 12.5.3 Construction, 377
 - 12.5.4 Performance Assessment: A Case History, 377
- 12.6 Subsurface Drains, 377
 - 12.6.1 Description, 377
 - 12.6.2 Design, 379
 - 12.6.3 Construction, 389
 - 12.6.4 Performance and Economic Considerations, 391
- 12.7 Summary, 392
 - Questions/Problems, 395
 - References, 395
- 13**
- SOIL REMEDIATION TECHNOLOGIES 398**
- 13.1 Introduction, 398
- 13.2 Soil Vapor Extraction, 399
 - 13.2.1 Technology Description, 399
 - 13.2.2 Fundamental Processes, 399
 - 13.2.3 System Design and Implementation, 401
 - 13.2.4 Predictive Modeling, 409
 - 13.2.5 Modified or Complementary Technologies, 409
 - 13.2.6 Economic and Regulatory Considerations, 412
 - 13.2.7 Case Studies, 412
- 13.3 Soil Washing, 413
 - 13.3.1 Technology Description, 413
 - 13.3.2 Fundamental Processes, 416
 - 13.3.3 System Design and Implementation, 416
 - 13.3.4 Predictive Modeling, 417
 - 13.3.5 Modified or Complementary Technologies, 417
 - 13.3.6 Economic and Regulatory Considerations, 418
 - 13.3.7 Case Studies, 418
- 13.4 Stabilization and Solidification, 421
 - 13.4.1 Technology Description, 421
 - 13.4.2 Fundamental Processes, 422
 - 13.4.3 System Design and Implementation, 422
 - 13.4.4 Predictive Modeling, 427
 - 13.4.5 Modified or Complementary Technologies, 427
 - 13.4.6 Economic and Regulatory Considerations, 428
 - 13.4.7 Case Studies, 430
- 13.5 Electrokinetic Remediation, 432
 - 13.5.1 Technology Description, 432
 - 13.5.2 Fundamental Processes, 434
 - 13.5.3 System Design and Implementation, 437
 - 13.5.4 Predictive Modeling, 439
 - 13.5.5 Modified or Complementary Technologies, 439
 - 13.5.6 Economic and Regulatory Considerations, 439
 - 13.5.7 Case Studies, 441
- 13.6 Thermal Desorption, 445
 - 13.6.1 Technology Description, 445

- 13.6.2 Fundamental Processes, *446*
 - 13.6.3 System Design and Implementation, *447*
 - 13.6.4 Modified or Complementary Technologies, *451*
 - 13.6.5 Economic and Regulatory Considerations, *454*
 - 13.6.6 Case Studies, *454*
 - 13.7 Vitrification, *456*
 - 13.7.1 Technology Description, *456*
 - 13.7.2 Fundamental Processes, *459*
 - 13.7.3 System Design and Implementation, *460*
 - 13.7.4 Predictive Modeling, *464*
 - 13.7.5 Modified or Complementary Technologies, *464*
 - 13.7.6 Economic and Regulatory Considerations, *465*
 - 13.7.7 Case Studies, *465*
 - 13.8 Bioremediation, *467*
 - 13.8.1 Technology Description, *467*
 - 13.8.2 Fundamental Processes, *468*
 - 13.8.3 System Design and Implementation, *469*
 - 13.8.4 Predictive Modeling, *475*
 - 13.8.5 Modified or Complementary Technologies, *475*
 - 13.8.6 Economic and Regulatory Considerations, *475*
 - 13.8.7 Case Studies, *477*
 - 13.9 Phytoremediation, *478*
 - 13.9.1 Technology Description, *478*
 - 13.9.2 Fundamental Processes, *480*
 - 13.9.3 System Design and Implementation, *482*
 - 13.9.4 Predictive Modeling, *484*
 - 13.9.5 Modified or Complementary Technologies, *484*
 - 13.9.6 Economic and Regulatory Considerations, *484*
 - 13.9.7 Case Studies, *485*
 - 13.10 Soil Fracturing, *485*
 - 13.10.1 Technology Description, *485*
 - 13.10.2 Fundamental Processes, *487*
 - 13.10.3 System Design and Implementation, *491*
 - 13.10.4 Predictive Modeling, *494*
 - 13.10.5 Modified or Complementary Technologies, *495*
 - 13.10.6 Economic and Regulatory Considerations, *495*
 - 13.10.7 Case Studies, *495*
 - 13.11 Summary, *496*
 - Questions/Problems, *497*
 - References, *499*
- 14**
- GROUNDWATER REMEDIATION TECHNOLOGIES** **505**
- 14.1 Introduction, *505*
 - 14.2 Pump and Treat, *505*
 - 14.2.1 Technology Description, *505*
 - 14.2.2 Fundamental Processes, *506*
 - 14.2.3 System Design and Implementation, *510*
 - 14.2.4 Predictive Modeling, *513*
 - 14.2.5 Modified or Complementary Technologies, *519*
 - 14.2.6 Economic and Regulatory Considerations, *522*
 - 14.2.7 Case Studies, *523*
 - 14.3 In-Situ Flushing, *524*
 - 14.3.1 Technology Description, *524*
 - 14.3.2 Fundamental Processes, *526*
 - 14.3.3 System Design and Implementation, *527*
 - 14.3.4 Predictive Modeling, *529*
 - 14.3.5 Modified or Complementary Technologies, *532*
 - 14.3.6 Economic and Regulatory Considerations, *534*
 - 14.3.7 Case Studies, *536*
 - 14.4 Permeable Reactive Barriers, *538*
 - 14.4.1 Technology Description, *538*
 - 14.4.2 Fundamental Processes, *542*

- 14.4.3 System Design and Implementation, *544*
- 14.4.4 Predictive Modeling, *553*
- 14.4.5 Modified or Complementary Technologies, *554*
- 14.4.6 Economic and Regulatory Considerations, *554*
- 14.4.7 Case Studies, *554*
- 14.5 In-Situ Air Sparging, *555*
 - 14.5.1 Technology Description, *555*
 - 14.5.2 Fundamental Processes, *556*
 - 14.5.3 System Design and Implementation, *560*
 - 14.5.4 Predictive Modeling, *565*
 - 14.5.5 Modified or Complementary Technologies, *566*
 - 14.5.6 Economic and Regulatory Considerations, *568*
 - 14.5.7 Case Studies, *568*
- 14.6 Monitored Natural Attenuation, *574*
 - 14.6.1 Technology Description, *574*
 - 14.6.2 Fundamental Processes, *575*
 - 14.6.3 System Design and Implementation, *577*
 - 14.6.4 Predictive Modeling, *584*
 - 14.6.5 Modified or Complementary Technologies, *585*
 - 14.6.6 Economic and Regulatory Considerations, *585*
 - 14.6.7 Case Studies, *587*
- 14.7 Bioremediation, *587*
 - 14.7.1 Technology Description, *587*
 - 14.7.2 Fundamental Processes, *592*
 - 14.7.3 System Design and Implementation, *593*
 - 14.7.4 Predictive Modeling, *594*
 - 14.7.5 Modified or Complementary Technologies, *595*
 - 14.7.6 Economic and Regulatory Considerations, *595*
 - 14.7.7 Case Studies, *595*
- 14.8 Summary, *596*
Questions/Problems, *597*
References, *598*

PART III LANDFILLS AND SURFACE IMPOUNDMENTS

- 15**
- SOURCES AND CHARACTERISTICS OF WASTES**
- 15.1 Introduction, *605*
- 15.2 Sources of Wastes, *605*
 - 15.2.1 Dredging and Irrigation, *605*
 - 15.2.2 Mining and Quarrying, *605*
 - 15.2.3 Farming and Ranching, *605*
 - 15.2.4 Residential, Commercial, and Institutional, *606*
 - 15.2.5 Industrial, *606*
 - 15.2.6 Nuclear Power and Nuclear Defense, *607*
- 15.3 Classification of Wastes, *607*
 - 15.3.1 Solid Waste, *607*
 - 15.3.2 Hazardous Waste, *610*
 - 15.3.3 Radioactive Waste, *612*
 - 15.3.4 Infectious (Medical) Waste, *613*
- 605 15.4 Waste Characterization, *613*
 - 15.4.1 Chemical Characterization, *614*
 - 15.4.2 Physical Characterization: Engineering Properties of Wastes, *614*
- 15.5 Environmental Concerns with Wastes, *624*
 - 15.5.1 Growing Quantities, *626*
 - 15.5.2 Improper Handling and Disposal, *626*
 - 15.5.3 Toxic Chemicals, *626*
 - 15.5.4 Health Effects, *629*
 - 15.5.5 Effects on Ecosystems, *629*
- 15.6 Waste Management Strategies, *630*
 - 15.6.1 Pollution Prevention, *630*
 - 15.6.2 Waste Minimization, *630*
 - 15.6.3 Recycling, *630*

- 15.6.4 Incineration, *630*
- 15.6.5 Landfilling, *630*
- 15.7 Engineered Waste Disposal Facilities, *631*
- 15.8 Summary, *632*
 - Questions/Problems, *632*
 - References, *633*

- 16**
- LANDFILL REGULATIONS, SITING, AND CONFIGURATIONS 635**

- 16.1 Introduction, *635*
- 16.2 Federal Regulations, *635*
 - 16.2.1 Resource Conservation and Recovery Act, *635*
 - 16.2.2 Clean Water Act, *640*
 - 16.2.3 Clean Air Act, *640*
 - 16.2.4 Comprehensive Environmental Response, Compensation and Liability Act, *640*
- 16.3 State and Local Regulations, *640*
- 16.4 Siting Methodology, *641*
 - 16.4.1 Calculating Landfill Acreage, *641*
 - 16.4.2 Review of the Literature, *642*
 - 16.4.3 Regulatory Location Restrictions, *643*
 - 16.4.4 Map Overlay Procedure to Identify Potential Sites, *645*
 - 16.4.5 Identification of Specific Sites Based on Local Features, *645*
 - 16.4.6 Preliminary Site Exploration to Determine Site Hydrogeology, *646*
 - 16.4.7 Conceptual Design of a Landfill, *646*
- 16.5 Site Permit Application, *646*
- 16.6 Landfill Configurations, *646*
 - 16.6.1 Footprint and Cell Layout, *647*
 - 16.6.2 Base Grading, *648*
 - 16.6.3 Final Cover Grading, *656*
 - 16.6.4 Other Facilities and Site Development Master Plan, *656*
- 16.7 Summary, *656*
 - Questions/Problems, *656*
 - References, *657*

- 17**
- WASTE CONTAINMENT LINER SYSTEMS 659**

- 17.1 Introduction, *659*
- 17.2 Low-Permeability Soil Liners, *662*
 - 17.2.1 Hydraulic Conductivity, *662*
 - 17.2.2 Laboratory Hydraulic Conductivity Testing, *669*
 - 17.2.3 Laboratory Compatibility Testing, *672*
 - 17.2.4 Field Hydraulic Conductivity Testing, *672*
 - 17.2.5 Low-Permeability Compacted Clay Liners, *681*
 - 17.2.6 Low-Permeability Soil-Admixed Liners, *686*
- 17.3 Geomembrane Liners, *687*
 - 17.3.1 Material Properties and Tests, *689*
 - 17.3.2 Geomembrane Seams and Their Properties, *696*
- 17.4 Geotextiles, *700*
 - 17.4.1 Material Properties and Tests, *700*
 - 17.4.2 Geotextile Seams and Their Properties, *710*
- 17.5 Geosynthetic Clay Liners, *711*
 - 17.5.1 Technical Equivalency Issues of GCLs and CCLs, *711*
 - 17.5.2 Material Properties and Tests, *713*
- 17.6 Geonets and Geocomposite Drains, *715*
 - 17.6.1 Material Properties and Tests for Geonets, *715*
 - 17.6.2 Geocomposite Drains, *716*
- 17.7 Geogrids, *717*
 - 17.7.1 Material Properties and Tests, *717*
- 17.8 Interface Strengths among Various Liner Components, *718*
 - 17.8.1 Direct Shear Test Methods: ASTM D 5321 and ASTM D 6243, *719*
 - 17.8.2 Interface Shear Strength: Shear Strength Envelopes, *719*
- 17.9 Manufacturing and Construction Quality Assurance, *721*
- 17.10 Estimation of Leakage through Liner Systems, *722*

17.10.1	Leakage Mechanisms, 722		
17.10.2	Leakage through Composite Liners, 724		
17.11	Performance of Liners in Waste Containment Systems, 725		
17.12	Summary, 726		
	Questions/Problems, 726		
	References, 728		
18			
LEACHATE COLLECTION AND REMOVAL SYSTEMS AND LINER DESIGN		733	
18.1	Introduction, 733		
18.2	Design Criteria, 733		
18.3	Leachate Generation and Management, 734		
18.3.1	Leachate Quantity Estimation, 735		
18.3.2	Leachate Collection Pipes, 744		
18.3.3	Selection of Drainage Layer Material and Thickness, 747		
18.3.4	Leachate Management, 751		
18.4	Containment System Liner Design, 752		
18.4.1	Material Stresses, 752		
18.4.2	Geomembrane Puncture Resistance, 762		
18.5	Summary, 765		
	Questions/Problems, 765		
	References, 768		
19			
FINAL COVER SYSTEMS		770	
19.1	Introduction, 770		
19.2	Purpose and Design Criteria, 770		
19.3	Regulatory Minimum Requirements, 770		
19.3.1	Cover System for MSW Landfills, 770		
19.3.2	Cover System for Hazardous Waste Landfills, 772		
19.3.3	Alternative Final Cover Systems, 774		
19.4	Design Procedure, 775		
19.4.1	Layout and Grading, 775		
19.4.2	Cover Profile and Material Selection, 776		
19.4.3	Infiltration Analysis, 777		
19.4.4	Erosion Assessment, 778		
19.4.5	Drainage Layer Capacity, 779		
19.4.6	Cover Geomembrane Analysis, 781		
19.4.7	Cover Slope Stability Analysis, 784		
19.5	Summary, 788		
	Questions/Problems, 788		
	References, 789		
20			
GAS GENERATION AND MANAGEMENT		791	
20.1	Introduction, 791		
20.2	Gas Generation Mechanisms, 792		
20.3	Gas Characteristics, 794		
20.4	Gas Production Rates, 795		
20.5	Gas Migration, 797		
20.6	Gas Collection Systems, 801		
20.6.1	Passive Gas Collection Systems, 802		
20.6.2	Active Gas Collection Systems, 806		
20.6.3	Comparison of Various Gas Collection Systems, 809		
20.7	Gas Flaring and Energy Recovery, 810		
20.7.1	Gas Flaring, 810		
20.7.2	Energy Recovery, 812		
20.8	Summary, 814		
	Questions/Problems, 816		
	References, 816		
21			
GROUNDWATER MONITORING		818	
21.1	Introduction, 818		
21.2	Regulatory Requirements, 818		
21.3	Groundwater Monitoring Systems, 820		
21.3.1	Characterization of Site Hydrogeology, 820		
21.3.2	Placement of Monitoring Wells, 822		
21.3.3	Monitoring Well Design and Construction, 824		
21.3.4	Sampling and Analysis, 824		
21.3.5	Statistical Analysis of Monitoring Data, 827		
21.4	Detection Monitoring Program, 831		
21.5	Assessment Monitoring Program, 831		

21.6 Corrective Action Program, *832*

21.7 Summary, *834*

Questions/Problems, *834*

References, *835*

22

SURFACE IMPOUNDMENTS

837

22.1 Introduction, *837*

22.2 Regulatory Setting, *837*

22.2.1 Design and Operating

Requirements, *837*

22.2.2 Action Leakage Rate, *838*

22.2.3 Response Action Plan, *838*

22.2.4 Monitoring and Inspection, *838*

22.2.5 Emergency Repairs: Contingency
Plans, *838*

22.2.6 Closure and Postclosure Care, *839*

22.3 Liner Systems, *839*

22.4 Surface Impoundment Design, *841*

22.4.1 Predesign Activities, *841*

22.4.2 Surface Impoundment
Configuration, *842*

22.4.3 Component Design, *843*

22.5 Cover Design, *845*

22.5.1 Nonremovable Covers, *845*

22.5.2 Removable Covers, *847*

22.6 Closure and Postclosure Care, *847*

22.7 Summary, *850*

Questions/Problems, *854*

References, *854*

PART IV EMERGING TECHNOLOGIES

23

BENEFICIAL USE OF WASTE MATERIALS: RECYCLING

857

23.1 Introduction, *857*

23.2 Types and Evaluation of Waste
Materials, *857*

23.2.1 Types of Waste Materials, *857*

23.2.2 Evaluation Process, *858*

23.2.3 Common Waste Materials, *858*

23.3 Fly Ash, *859*

23.3.1 Sources and Quantities
Generated, *859*

23.3.2 Problems with Disposal, *859*

23.3.3 Potential Reuses, *859*

23.3.4 Chemical Composition and
Engineering Properties, *860*

23.3.5 Environmental Concerns, *860*

23.3.6 Economic Considerations, *861*

23.3.7 Field Applications and
Demonstrations, *861*

23.3.8 Summary, *862*

23.4 Blast Furnace Slag, *862*

23.4.1 Sources and Quantities
Generated, *862*

23.4.2 Problems with Disposal, *863*

23.4.3 Potential Reuses, *863*

23.4.4 Chemical Composition and
Engineering Properties, *863*

23.4.5 Environmental Concerns, *863*

23.4.6 Economic Considerations, *864*

23.4.7 Field Applications and
Demonstrations, *864*

23.4.8 Summary, *865*

23.5 Foundry Sand, *865*

23.5.1 Sources and Quantities
Generated, *865*

23.5.2 Problems with Disposal, *865*

23.5.3 Potential Reuses, *865*

23.5.4 Chemical Composition and
Engineering Properties, *865*

23.5.5 Environmental Concerns, *866*

23.5.6 Economic Considerations, *866*

23.5.7 Field Applications and
Demonstrations, *866*

23.5.8 Summary, *867*

23.6 Papermill Sludge, *867*

23.6.1 Sources and Quantities
Generated, *867*

23.6.2 Problems with Disposal, *867*

23.6.3 Potential Reuses, *867*

- 23.6.4 Physical and Chemical Properties, 867
- 23.6.5 Environmental Concerns, 867
- 23.6.6 Economic Considerations, 867
- 23.6.7 Field Applications and Demonstrations, 868
- 23.6.8 Summary, 868
- 23.7 Municipal Sludge, 868
 - 23.7.1 Sources and Quantities Generated, 868
 - 23.7.2 Problems with Disposal, 869
 - 23.7.3 Potential Reuses, 869
 - 23.7.4 Physical and Chemical Properties, 869
 - 23.7.5 Environmental Concerns, 869
 - 23.7.6 Economic Considerations, 870
 - 23.7.7 Field Applications and Demonstrations, 870
 - 23.7.8 Summary, 872
- 23.8 Incinerator Ash (Sewage Sludge Ash), 872
 - 23.8.1 Sources and Quantities Generated, 872
 - 23.8.2 Problems with Disposal, 872
 - 23.8.3 Potential Reuses, 873
 - 23.8.4 Physical and Chemical Properties, 873
 - 23.8.5 Environmental Concerns, 873
 - 23.8.6 Economical Considerations, 873
 - 23.8.7 Field Applications and Demonstrations, 874
 - 23.8.8 Summary, 874
- 23.9 Glass, 874
 - 23.9.1 Sources and Quantities Generated, 874
 - 23.9.2 Problems with Disposal, 875
 - 23.9.3 Potential Reuses, 875
 - 23.9.4 Physical and Chemical Properties, 876
 - 23.9.5 Environmental Concerns, 876
 - 23.9.6 Economic Considerations, 877
 - 23.9.7 Field Applications and Demonstrations, 877
 - 23.9.8 Summary, 878
- 23.10 Plastics, 879
 - 23.10.1 Sources and Quantities Generated, 879
 - 23.10.2 Problems with Disposal, 879
 - 23.10.3 Potential Reuses, 879
 - 23.10.4 Physical and Chemical Properties, 880
 - 23.10.5 Environmental Concerns, 880
 - 23.10.6 Economic Considerations, 880
 - 23.10.7 Field Applications and Demonstrations, 880
 - 23.10.8 Summary, 881
- 23.11 Scrap Tires, 881
 - 23.11.1 Sources and Quantities Generated, 881
 - 23.11.2 Problems with Disposal, 881
 - 23.11.3 Potential Reuses, 881
 - 23.11.4 Physical and Chemical Properties, 883
 - 23.11.5 Environmental Concerns, 884
 - 23.11.6 Economic Considerations, 887
 - 23.11.7 Field Applications and Demonstrations, 887
 - 23.11.8 Summary, 888
- 23.12 Demolition Debris and Recycled Concrete, 888
 - 23.12.1 Sources and Quantities Generated, 888
 - 23.12.2 Problems with Disposal, 888
 - 23.12.3 Potential Reuses, 888
 - 23.12.4 Physical and Chemical Properties, 889
 - 23.12.5 Environmental Concerns, 889
 - 23.12.6 Economic Considerations, 889
 - 23.12.7 Field Applications and Demonstrations, 889
 - 23.12.8 Summary, 890
- 23.13 Wood Wastes, 890
 - 23.13.1 Sources and Quantities Generated, 890
 - 23.13.2 Problems with Disposal, 890
 - 23.13.3 Potential Reuses, 890
 - 23.13.4 Physical and Chemical Properties, 891
 - 23.13.5 Environmental Concerns, 891
 - 23.13.6 Economic Considerations, 892
 - 23.13.7 Field Applications and Demonstrations, 892
 - 23.13.8 Summary, 892

23.14	Summary, 892		
	Questions/Problems, 892		
	References, 893		
24			
END USES OF CLOSED LANDFILLS		898	
24.1	Introduction, 898		
24.2	Various End Uses of Closed Landfills, 898		
	24.2.1 Methane Gas Energy Generation Uses, 899		
	24.2.2 Reopening after Closure, 900		
	24.2.3 Recreational Uses, 901		
	24.2.4 Commercial and Industrial Uses, 903		
24.3	Design Considerations, 903		
	24.3.1 Design Process, 903		
	24.3.2 Design Issues, 906		
24.4	Case Studies, 910		
24.5	Summary, 912		
	Questions/Problems, 912		
	References, 912		
25			
BIOREACTOR LANDFILLS		915	
25.1	Introduction, 916		
25.2	Types and Advantages of Bioreactor Landfills, 916		
25.3	Regulatory Issues, 918		
25.4	Bioreactor Design, 919		
	25.4.1 Cell Size, 919		
	25.4.2 Liner and Leachate Collection System, 919		
	25.4.3 Liquid Injection System, 919		
	25.4.4 Gas Extraction System, 921		
	25.4.5 Final Cover System, 921		
	25.4.6 Slope Stability, 922		
	25.4.7 Settlement, 924		
25.5	Bioreactor Landfill Operations and Maintenance, 926		
	25.5.1 Solid Waste Pretreatment or Segregation, 926		
	25.5.2 Leachate Seeps, 926		
	25.5.3 Daily and Intermediate Cover, 926		
	25.5.4 Management of Nutrients and Other Supplement Addition, 927		
	25.5.5 Monitoring Program, 927		
25.6	Case Studies, 927		
25.7	Research Issues, 933		
25.8	Summary, 935		
	Questions/Problems, 935		
	References, 936		
26			
SUBAQUATIC SEDIMENT WASTE: IN-SITU CAPPING		938	
26.1	Introduction, 938		
26.2	Relevant Terminology and Definitions, 941		
	26.2.1 Water Properties, 941		
	26.2.2 Soil or Sediment Properties, 941		
	26.2.3 Flux Properties or Flux-Determining Properties, 942		
26.3	Site Evaluation, 943		
	26.3.1 Site and Surrounding Area Characterization, 944		
	26.3.2 Evaluation of Hydrodynamic Conditions, 944		
	26.3.3 Geotechnical and Geological Conditions, 944		
	26.3.4 Characterization of the Sediments, 944		
	26.3.5 Chemical Characterization, 944		
26.4	Cap Design, 944		
	26.4.1 Selection of Capping Materials, 946		
	26.4.2 Cap Components, 946		
	26.4.3 Erosion Potential, 946		
	26.4.4 Settlement Analysis, 947		
	26.4.5 Stability Analysis, 948		
	26.4.6 Contaminant Release Analysis, 950		
26.5	Construction and Monitoring, 952		
	26.5.1 Construction Methods, 952		
	26.5.2 Monitoring, 953		
26.6	Regulatory and Economic Considerations, 954		
26.7	Case Studies, 954		
26.8	Summary, 957		
	Questions/Problems, 958		
	References, 959		
	Index		961