

Contents

VOLUME I

PREFACE..	xv
FOREWORDS	xix
ACKNOWLEDGEMENTS	xxvii
ACRONYMS	xxxiii
CHAPTER 1: The Vadose Zone:	
What It Is, Why It Matters, and How It Works	3
WHAT IS THE VADOSE ZONE?	3
WHY IS THE VADOSE ZONE IMPORTANT?	8
FUNDAMENTAL PROCESSES	13
GEOLOGIC MEDIA AND FLUID PROPERTIES	14
VADOSE ZONE FLUID STATICS	19
FLUID FLOW IN THE VADOSE ZONE	28
VADOSE ZONE CHEMICAL TRANSPORT	32
MULTIPHASE THERMODYNAMICS AND HEAT TRANSFER	41
HEAT TRANSFER BY CONVECTION AND	
CONDUCTION IN POROUS MEDIA	44
SUMMARY	45
REFERENCES	48
CASE STUDY	
TRITIUM SOURCE CHARACTERIZATION AT THE HIGH FLUX	
BEAM F&ACTOR, BROOKHAVEN NATIONAL LABORATORY	50

CHAPTER 2: Managing an Effective Vadose Zone Project	61
INTRODUCTION	61
VADOSE ZONE MANAGEMENT: WHY IT’S HARD AND WHY WE CARE	61
PRINCIPLE ONE: ESTABLISH AND MANAGE TO ENDPOINTS	68
WHY IS THIS HARD?	68
BUILDING BLOCKS	70
TOOLBOX	73
TRAPS AND GAPS	77
PRINCIPLE TWO: DEVELOP A ROADMAP	79
WHY IS THIS HARD?	80
BUILDING BLOCKS	81
TOOLBOX	88
TRAPS AND GAPS	97
PRINCIPLE THREE: PRACTICE DELIBERATE, DISCIPLINED ENGAGEMENT	99
WHY IS THIS HARD?.	100
BUILDING BLOCKS	101
TOOLBOX..	107
TRAPS AND GAPS	111
CONCLUSIONS	117
REFERENCES	119
CASE STUDIES	
HANFORD GROUNDWATER/VADOSE ZONE INTEGRATION PROJECT “DEPENDENCY WEBS”	125
THE COLUMBIA RIVER COMPREHENSIVE IMPACT ASSESSMENT .	127
 CHAPTER 3: Vadose Zone Characterization and Monitoring: Current Technologies, Applications and Future Developments	133
INTRODUCTION	133
NEEDS FOR VADOSE ZONE CHARACTERIZATION AND MONITORING	133
OBJECTIVES	134

CONCEPTUALIZATION OF VADOSE ZONE SYSTEMS	13.5
WATER FLOW AND CHEMICAL TRANSPORT PROCESSES	
IN DEEP AND SHALLOW VADOSE ZONES	137
SPATIAL AND TEMPORAL SCALES OF VADOSE ZONE	
INVESTIGATIONS AND SCALING	137
EVIDENCE OF PREFERENTIAL FLOW IN HETEROGENEOUS SOILS	
AND FRACTURED ROCKS	145
CONTAMINANT TRANSPORT	152
BIOLOGICAL PROCESSES	157
FIELD VADOSE ZONE CHARACTERISTICS	
AND MONITORING	163
TYPES OF DATA FOR SITE CHARACTERIZATION AND	
MONITORING METHODS	163
GENERAL APPROACH TO SELECTION OF SITE	
CHARACTERIZATION AND MONITORING METHODS	167
SELECTION OF DRILLING AND SOIL SAMPLING METHODS	183
CONE PENETROMETER AND DIRECT PUSH TOOLS	
FOR VADOSE ZONE CHARACTERIZATION	186
ENVIRONMENTAL MEASUREMENT - WHILE-DRILLING SYSTEM	
FOR REAL-TIME SCREENING OF CONTAMINANTS	201
WELL COMPLETION AND INSTRUMENTATION	204
HYDROGEOLOGICAL CHARACTERIZATION USING	
GEOPHYSICAL METHODS	215
FIELD MEASUREMENTS OF WATER POTENTIAL	236
FIELD MEASUREMENTS OF WATER CONTENT IN	
UNSATURATED SOILS	247
CHEMICAL DISTRIBUTION AND TRANSPORT MONITORING	260
SOIL GAS CHARACTERIZATION AND MONITORING	271
MONITORING FOR NONAQUEOUS PHASE LIQUIDS	292
ISOTOPIC TRACERS OF FLOW AND TRANSPORT THROUGH	
THE VADOSE ZONE	298
CHARACTERIZATION AND MONITORING FOR BIOREMEDIATION .	303
DETERMINATION OF UNSATURATED HYDRAULIC	
PROPERTIES OF VARIABLY SATURATED SOILS	
AND ROCKS	310

FACTORS AND PROCESSES AFFECTING	
HYDRAULIC PARAMETERS	3 11
LABORATORY METHODS	323
INVERSE METHODS	335
INDIRECT METHODS	3 36
REFERENCES	347
CASE STUDIES	
LARGE-SCALE FIELD INVESTIGATIONS IN FRACTURED BASALT IN IDAHO: LESSONS LEARNED	396
GROUNDWATER CONTAMINATION IN THE PERCHED AQUIFER AT THE DOE PANTEX PLANT	406
COMPARISON OF VADOSE ZONE SOIL AND WATER ANALYTICAL DATA FOR CHARACTERIZATION OF EXPLOSIVES CONTAMINATION	423
CONE PENETROMETER (CPT)-BASED SOIL MOISTURE PROBES	428
CONE PENETROMETER -BASED RAMAN SPECTROSCOPY FOR NAPL CHARACTERIZATION IN THE VADOSE ZONE	43 1
GAMMA BOREHOLE LOGGING FOR VADOSE ZONE CHARACTERIZATION AROUND THE HANFORD HIGH-LEVEL WASTE TANKS	445
NEAR SURFACE INFILTRATION MONITORING USING NEUTRON MOISTURE LOGGING, YUCCA MOUNTAIN, NEVADA	457
CHARACTERIZATION AND MONITORING OF UNSATURATED FLOW AND TRANSPORT PROCESSES IN STRUCTURED SOILS	475
DNAPL AND RESIDUAL WATER CHARACTERIZATION IN THE VADOSE ZONE USING THE PARTITIONING INTERWELL TRACER TEST (PITT)	493
ESTIMATION OF THE SOIL HYDRAULIC PROPERTIES	501
CHAPTER 4: Performance Monitoring	511
BACKGROUND/SCOPE	5 11
CHARACTERIZING CONTAMINATION THROUGH MONITORING	5 12
DETERMINING THAT REMEDIATION OBJECTIVES ARE BEING MET	513
KEEPING AN EYE ON TREATED SITES	513

PROCESS OPTIMIZATION MONITORING OF THE VADOSE ZONE	5 14
LONG-TERM MONITORING OF THE VADOSE ZONE	516
CONTAMINANT LOCATION IN VADOSE SOILS	5 18
FUNCTIONAL REQUIREMENTS AND CONSEQUENCES OF FAILURE .	5 18
TEMPORAL, SPATIAL, AND OTHER DATA REQUIREMENTS	5 18
VADOSE ZONE MONITORING	52 1
REDUCING LONG-TERM MONITORING COSTS	522
SENSOR TECHNOLOGY	523
THE EMERGENCE OF MICROSENSOR TECHNOLOGY	524
VADOSE ZONE MOISTURE SENSORS	540
SENSOR LIMITATION	543
GEOPHYSICAL MEASUREMENTS	543
GROUND-PENETRATING RADAR	546
ELECTRIC RESISTIVITY/TOMOGRAPHY	547
COMPATIBILITY PROBLEMS WITH GEOPHYSICAL METHODS AND SENSORS	550
PLACING, REPLACING, AND CALIBRATING OF SENSORS	550
A LOOK AT LONG-TERM MONITORING	
SYSTEM DESIGN	552
MEASUREMENT SYSTEM DESIGN	553
SYSTEM ASSEMBLY	555
SUMMARY OF NEEDS AND GAPS	557
REFERENCES	558
CASE STUDIES	
AN INTEGRATED APPROACH TO MONITORING A FIELD TEST OF IN <i>Situ</i> CONTAMINANT DESTRUCTION	564
THE VADOSE ZONE MONITORING SYSTEM FOR THE CAMU PROJECT AT SANDIA NATIONAL LABORATORIES ...	576
IN <i>Situ</i> FIELD SCREENING OF VOLATILE ORGANIC COMPOUNDS USING A PORTABLE ACOUSTIC WAVE SENSOR SYSTEM	580

VOLUME II

CHAPTER 5: Flow and Transport Modeling of the Vadose Zone	591
INTRODUCTION	59 1
PHYSICAL PROCESSES AND SETTING FOR CONTAMINANT FLOW AND TRANSPORT IN THE VADOSE ZONE	596
INTRODUCTION	596
PHYSICAL PROCESSES	597
TRANSPORT	605
MATHEMATICAL MODELS AND NUMERICAL FORMULATIONS	6 18
INTRODUCTION	6 18
FLOW AND TRANSPORT EQUATIONS	628
UNSATURATED FLOW AND TRANSPORT EQUATIONS	647
ISOTHERMAL MULTIPHASE FLOW AND TRANSPORT EQUATIONS .	648
NUMERICAL FORMULATIONS	65 1
LIMITATIONS AND RESEARCH DIRECTIONS	665
DATA NEEDS AND PRIORITIZATION	667
INTRODUCTION	667
DIFFERENT TYPES OF DATA	667
PRIORITIZATION OF DATA COLLECTION	682
METHODOLOGY OF MODEL GUIDANCE IN DATA COLLECTION .	684
UPSCALING ISSUES	685
CONCLUDING REMARKS	689
DEVELOPMENT OF SITE-SPECIFIC MODELS	690
INTRODUCTION	690
OBJECTIVES	69 1
CONCEPTUAL MODEL	692
GEOMETRIC DESCRIPTION	693
NUMERICAL SIMULATION	696
MODEL VALIDATION/CALIBRATION USING GEOCHEMICAL AND ISOTOPIC DATA	700
MODEL ASSESSMENT: PREDICTIONS, UNCERTAINTIES, AND LIMITATIONS	70 1
CURRENT RESEARCH DIRECTIONS	702

MODEL CALIBRATION	703
INTRODUCTION	703
METHODOLOGY	714
ERROR AND UNCERTAINTY ANALYSIS	731
MODEL PREDICTIONS AND THEIR UNCERTAINTIES	735
EXAMPLES	739
CONCLUDING REMARKS	747
FUTURE RESEARCH DIRECTIONS	755
REFERENCES	759
CASE STUDIES	
MODELING FAST FLOW PATHS IN UNSATURATED	
FRACTURED ROCK	785
TCE CONTAMINATION AT THE SAVANNAH RIVER SITE	792
AQUEOUS DIFFUSION IN THE VADOSE ZONE	796
MEASUREMENT OF UNSATURATED-ZONE WATER FLUXES	
ADJACENT TO A RADIOACTIVE-WASTE-MANAGEMENT UNIT .	797
INTEGRATED GEOLOGICAL INTERPRETATION FOR	
COMPUTATIONAL MODELING	799
A VADOSE ZONE INJECTION EXPERIMENT FOR TESTING	
FLOW AND TRANSPORT MODELS	804
INVERSE ESTIMATION OF UNSATURATED SOIL HYDRAULIC	
AND SOLUTE TRANSPORT PARAMETERS USING THE	
HYDRUS 1-D CODE	815
CHAPTER 6: Biogeochemical Considerations and	
Complexities	829
INTRODUCTION	829
GEJOCHEMICAL REACTIONS AND PROCESSES	831
COMPLEXATION	834
CONTAMINANT-SURFACE INTERACTIONS	841
PRECIPITATION-DISSOLUTION	845
OXIDATION-REDUCTION	849
ORGANIC CONTAMINANT-SOIL INTERACTIONS	851
THE EFFECT OF COLLOIDS	852

VADOSE ZONE MICROBIOLOGY	858
OVERVIEW	858
MICROBIOLOGICAL PROCESSES IN THE VADOSE ZONE	860
CONTAMINANT BIOTRANSFORMATION IN THE VADOSE ZONE .	870
INFLUENCE OF HYDROLOGIC PROCESSES ON ALL BIOGEOCHEMICAL REACTIONS IN THE VADOSE ZONE	876
MECHANISMS OF PREFERENTIAL FLOW AND MATRIX DIFFUSION	877
INFLUENCE OF SUBSURFACE HYDROLOGIC PROCESSES ON BIOGEOCHEMICAL REACTIONS	883
TECHNIQUES FOR QUANTIFYING THE EFFECTS OF PREFERENTIAL FLOW AND THE INFLUENCE OF NONEQUILIBRIUM PROCESSES	888
CONCLUSIONS	899
REFERENCES	901
CASE STUDIES	
OBSERVATIONS OF MULTIPLE ACTINIDE SPECIES WITH DISTINCT MOBILITIES	924
THE EFFECT OF COLLOID SIZE, COLLOID HYDROPHOBICITY, AND VOLUMETRIC WATER CONTENT ON THE TRANSPORT OF COLLOIDS THROUGH UNSATURATED POROUS MEDIA	928
SUMMARY OF COLLOID GENERATION AND STABILIZATION IN RESPONSE TO INDUCED WATER CHEMISTRY CHANGES . . .	939
UNDERSTANDING THE FATE AND TRANSPORT OF MULTIPHASE FLUID AND COLLOIDAL CONTAMINANTS IN THE VADOSE ZONE USING AN INTERMEDIATE-SCALE FIELD EXPERIMENT	943
 CHAPTER 7: Remediation of Organic Chemicals in the Vadose Zone	 949
INTRODUCTION	949
REMEDICATION TECHNOLOGIES	95 1
CONVENTIONAL VAPOR EXTRACTION	95 1
BAROMETRIC PUMPING: PASSIVE SOIL VAPOR EXTRACTION . .	970
HEATING TECHNOLOGIES	979

BIOREMEDIATION ..	1015
INJECTION OF LIQUID OXIDANTS ..	1029
DELIVERY BY LANCE INJECTION ..	1045
INJECTION OF GAS-PHASE OXIDANTS: OZONE GAS ..	1049
REACTIVE BARRIERS ..	1054
DEEP SOIL MIXING: RECOVERY AND DESTRUCTION PROCESSES ..	1064
IMMOBILIZING ORGANIC CONTAMINANTS BY STABILIZATION AND SOLIDIFICATION ..	1075
PHYTOREMEDIATION ..	1090
THE PERFORMANCE OF AVAILABLE REMEDIAION TECHNOLOGIES ..	1097
EVALUATION STRATEGY ..	1101
GAPS IN CURRENT CAPABILITIES ..	1129
REFERENCES ..	1132
CASE STUDIES	
MODELING THE PERFORMANCE OF AN SVE FIELD TEST	1157
SCALE-DEPENDENT MASS TRANSFER DURING SVE ..	1170
PASSIVE SOIL VAPOR EXTRACTION AT THE SRS MISCELLANEOUS CHEMICAL BASIN ..	1177
CASE HISTORY: PCB DESTRUCTION AND REMOVAL ..	1178
A CASE STUDY OF STEAM FLOODING: THE VISALIA PROJECT ..	1181
VADOSE ZONE REMEDIATION USING SIX-PHASE HEATING ..	1187
CASE HISTORY OF LIQUID OXIDANT INJECTION INTO THE VADOSE ZONE ..	1191
VADOSE ZONE <i>IN SITU</i> OZONATION OF POLYNUCLEAR AROMATIC HYDROCARBONS AND PENTACHLOROPHENOL ..	1200
CASE HISTORY OF REACTIVE BARRIERS USING Fe^0 METAL AND $KMnO_4$ TO DEGRADE CHLORINATED SOLVENTS	1206
CASE HISTORY OF REACTIVE BARRIERS OF POROUS CERAMICS USED TO ENHANCE BIODEGRADATION OF PETROLEUM HYDROCARBONS ..	1216
CASE HISTORY OF MIXED-REGION VAPOR STRIPPING IN A SILTY CLAY VADOSE ZONE ..	1224
PHYTOREMEDIATION OF PETROLEUM CONTAMINATED SOIL ..	1234

CHAPTER 8: Remediation of Inorganic Contamination in the Vadose Zone	123 9
INTRODUCTION AND GENERAL BACKGROUND	1239
TECHNICAL CHALLENGES	124 1
ENHANCED REMOVAL	1242
PHYSICAL/CHEMICAL METHODS	1243
ELECTROCHEMICAL METHODS	1247
BIOLOGICAL METHODS	125 8
OTHER BIOLOGICAL METHODS	126 1
STABILIZATION	126 1
IN <i>SITU</i> VITRIFICATION (ISV)	1262
SOIL-MIXING WITH CHEMICAL REAGENTS	1265
JET GROUTING	126 8
GASEOUS REDOX MANIPULATION	1268
PHYTOSTABILIZATION	1270
NATURAL ATTENUATION	1270
SUMMARY OF METHODS	1273
REFERENCES	127 4
CASE STUDIES	
ELECTROKINETIC DEMONSTRATION AT THE UNLINED CHROMIC ACID PIT	1279
FIELD DEMONSTRATIONS OF PHYTOREMEDIATION OF LEAD CONTAMINATED SOILS	1287
DEMONSTRATION OF <i>IN SITU</i> STABILIZATION OF BURIED WASTE AT PIT G-1 1 AT THE BROOKHAVEN NATIONAL LABORATORY GLASS PITS DISPOSAL SITE	1291
<i>IN SITU</i> GASEOUS REDUCTION	1302
CHAPTER 9: Barriers and Containment Methods	1309
INTRODUCTION	1309
TYPES OF PHYSICAL BARRIERS	1310
HYDRAULIC CONTAINMENT	13 13
COMPARISON OF CONTAINMENT IN THE VADOSE ZONE WITH CONTAINMENT IN THE SATURATED ZONE	13 15

CAPS	1316
SIX BASIC COMPONENTS OF CAPS	1317
TYPICAL CAP DESIGNS	1332
ALTERNATIVE CAP DESIGNS	1335
CASEHISTORIES	1340
VERTICAL BARRIERS	1363
TYPES OF WALLS	1365
HYDRAULIC CONDUCTIVITY	1383
FLOORS	1387
NATURALBOTTOM BARRIERS	1388
GROUTEDBARRIERS	1388
TUNNELS	1390
HYDRAULIC CONTAINMENT	1390
SOIL VAPOR EXTRACTION	1390
RELATIVEHUMIDITYCONTROL	1391
PERFORMANCE MODELING	1391
CAPS	1392
WALLS AND FLOORS	1392
PERFORMANCE MONITORING	1393
COSTS	1393
SUMMARY OF KNOWLEDGE GAPS AND RESEARCH NEEDS	1394
REFERENCES	1399
CASE STUDY	
HANFORD SITE SURFACE BARRIER TECHNOLOGY	1414
CHAPTER 10: Future Science and Technology Focus	1425
INTRODUCTION	1425
WHY ARE WE HERE?	1425
WHAT DID WE LEARN?	1426
WHERE DO WE GO FROM HERE?	1428
WHAT ARE THE CHALLENGES?	1428
WHAT ARE THE RECOMMENDED RESPONSES FOR ADDRESSING THE MAJOR KNOWLEDGE GAPS?	1429

KEY RESEARCH ACTIVITIES AND DEVELOPMENT AREAS1430

PERFORM DETAILED AND INTEGRATED MEDIUM-SCALE FIELD EXPERIMENTS 1430

DEVELOP ENHANCED CHARACTERIZATION TECHNIQUES AND TECHNOLOGIES1432

ADDRESS ISSUES OF UNCERTAINTY IN VADOSE ZONE FLOW AND TRANSPORT MODELING 1433

DEVELOP IMPROVED VALIDATION AND PERFORMANCE MONITORING FOR VADOSE ZONE & MEDIATION ACTIVITIES1435

DEVELOP A BETTER TECHNICAL BASIS FOR TAKING ACTION AND SETTING GOALS AT CONTAMINATED SITES 1437

DEVELOP A BETTER UNDERSTANDING OF COMPLEX BIOLOGICAL AND CHEMICAL INFLUENCES ON MIGRATION . 1438

IMPROVE PROCESS SIMULATION CAPABILITIES FOR VADOSE ZONE CHEMICAL FATE, TRANSPORT, AND REMEDIATION . . . 1440

DEVELOP REMEDIATION METHODS FOR STRONGLY HETEROGENEOUS SYSTEMS, AND FOR COMPLEX MIXED WASTES 1441

SUMMARY1443

CASE STUDY

THE VADOSE ZONE RESOURCE ALLOCATION CHALLENGE 1444

APPENDIX: Additional Case Studies on Accompanying CD 1459

INDEX1465