Contents

Contributors xiii

Preface xi

Part I. Basics of the pump-and-treat and permeable reactive barrier systems 1

1. Groundwater remediation using active and passive processes 3
F.-G. Simon, T. Meggyes and T. Tünnermeier

1.1. Introduction 3
1.2. The basics of pump-and-treat systems 3
1.3. The basics of PRB systems 6
1.3.1. Organic pollutants 6
1.3.2. Heavy metals 10
1.4. Cost comparison between pump-and-treat and PRB systems 15
1.5. Engineering of permeable reactive barriers 16
1.5.1. Construction of cut-off walls 18
1.5.2. Construction of reactive barriers 21
1.6. Outlook 28
1.7. Acknowledgements 29
1.8. References 29

Part II. Groundwater remediation engineering 35

2. Remediation of chromium-contaminated groundwater in subsurface Fe^0 reactor systems 37
M. Schneider

2.1. Introduction 37
2.2. Characterization of the field site and hydrogeological setting 37
2.3. Groundwater remediation concept 38
2.4. Results and discussion 41
2.5. References 43

3. Current R&D needs and tailored projects for solving technical, economic, administrative and other issues concerning permeable reactive barrier implementation in Germany **45**
H. Burmeier, V. Birke and D. Rosenau

3.1. Introduction 45
3.2. Current status of PRB technologies worldwide 46
3.3. Development in Germany 47
3.4. Mission, goals and structure of RUBIN 48
3.5. Appendix 52
1. Bernau 52
2. Denkendorf 55
3. Dresden 56
4. Edenkoben 57
5. Nordhorn 61
6. Offenbach 62
7. Rheine 65
8. Wiesbaden 71
9. University of Applied Sciences of North-East Lower Saxony, Suderburg (general project) 71
10. Christian Albrechts University, Kiel (general project) 72
11. Eberhard Karls University, Tübingen (general project) 72
3.6. References 73

4. Engineering design of reactive treatment zones and potential monitoring problems **75**
S. Jefferis

4.1. Introduction 75
4.2. The location of the contamination 75
4.3. Natural RTZs 76
4.4. Reaction time 77
4.5. Reaction mechanisms 78
4.5.1. First-order reactions 78
4.5.2. Second-order reactions 78
4.6. Types of reactor 78
4.6.1. Batch reactors 78
4.6.2. Plug-flow reactors 79
4.6.3. Stirred-tank reactors 79
4.6.4. Reactor types used in RTZs 79
4.7. Degree of reaction in the reactor 79
4.8. Use of a reactor recycle (recycling) 80
4.9. Dispersion and diffusion 82
4.10. Short circuiting/by-passing 82
4.11. Monitoring 85
4.12. Conclusions 85
4.13. References 86

5. Performance monitoring of a permeable reactive barrier at the Somersworth Landfill Superfund Site **87**
T. Sivavec, T. Krug, K. Berry-Spark and R. Focht

5.1. Introduction 87
5.2. Site description and characteristics 88
5.3. PRB installation and development 89
5.4. Cored material testing 90
5.5. Groundwater wells and monitoring 92
5.6. Hydraulic testing 97
5.7. Acknowledgements 99
5.8. References 99

Part III. Sorptive removal and natural processes **101**

6. Metals loading on sorbents and their separation **103**
K. A. Matis, A. I. Zouboulis, G. P. Gallios and N. K. Lazaridis

6.1. Introduction 103
6.2. Flotation 105
6.3. Biosorption 106
6.3.1. Sorptive flotation 108
6.3.2. Electroflotation 110
6.4. Conclusion 112
6.5. References 112

7. Sorption mechanisms of heavy metal ions on inorganic solids **115**
M. Fedoroff

7.1. Introduction 115
7.2. Distribution coefficients 116
7.3. Sorption isotherms 117
7.4. Sorption models 118
7.4.1. Ion exchange model 119
7.4.2. Surface complexation models 120
7.5. Speciation in solution 123
7.6. Sorption kinetics 123
7.7. Sorption mechanisms 124
7.8. Influence of other factors 125
7.9. Conclusion 126
7.10. References 126

8. Experience with monitored natural attenuation at BTEX-contaminated sites **129**
W. Püttmann, P. Martus and R. Schmitt

8.1. Introduction 129

8.2. Analytical monitoring of natural attenuation 130
8.3. Biodegradation of saturated hydrocarbons under aerobic conditions 131
8.4. Biodegradation of saturated hydrocarbons under anaerobic conditions 132
8.5. Biodegradation of aromatic hydrocarbons under aerobic conditions 133
8.6. Biodegradation of aromatic hydrocarbons under anaerobic conditions 133
8.7. References 136

9. Heavy metal speciation and phytoextraction 141
D. Leštan

9.1. Introduction 141
9.2. Materials and methods 142
9.2.1. Soil samples and analysis 142
9.2.2. Sequential extraction 144
9.2.3. Column phytoextraction experiments – disturbed soil profile 144
9.2.4. Column phytoextraction experiments – undisturbed soil profile 144
9.2.5. HM analysis 144
9.2.6. Phospholipid analysis 145
9.3. Results and discussion 145
9.3.1. Sequential extractions 145
9.3.2. Chelate-induced phytoextraction of lead, zinc and cadmium 148
9.4. Conclusions 153
9.5. Acknowledgement 154
9.6. References 155
9.7. Further reading 156

Part IV. Enhancing the efficiency of remediation processes 157

10. Development of novel reactive barrier technologies at the SAFIRA test site, Bitterfeld 159
H. Weiss, M. Schirmer and P. Merkel

10.1. Introduction 159
10.2. The SAFIRA project 159
10.2.1. The structure of SAFIRA 160
10.3. The SAFIRA site 160
10.3.1. Geology and hydrogeology 160
10.3.2. Groundwater contamination 162
10.4. Pilot facility 163
10.5. Reactor technologies 165
10.5.1. Some preliminary results 165

10.6. Conclusions 170
10.7. Appendix 171
10.8. References 171

11. Electrokinetic techniques and new materials for reactive barriers 173
K. Czurda, P. Huttenloch, G. Gregolec and K. E. Roehl

11.1. Introduction 173
11.2. Electrokinetic techniques 173
11.2.1. Electrokinetic soil remediation 174
11.2.2. Fundamental transport processes 174
11.2.3. Electrode reactions 176
11.2.4. Application 177
11.3. Innovative sorbents for PRBs 180
11.3.1. Zeolites 180
11.3.2. Chlorosilane surface-modified natural minerals 185
11.4. References 190

Part V. Groundwater remediation following mining activities 193

12. Kinetics of uranium removal from water 195
B. J. Merkel

12.1. Sources of uranium 195
12.2. Toxicity of uranium 196
12.3. Water chemistry 197
12.4. Natural attenuation processes 198
12.5. Case study 200
12.5.1. Königstein 200
12.5.2. Experiments with zero-valent iron (ZVI) 205
12.6. Conclusions 206
12.7. Appendix 207
12.8. References 208

13. Flooding strategies for decommissioning of uranium mines – a systems approach 211
R. Gatzweiler, A. Jakubick, G. Kiessig, M. Paul and J. Schreyer

13.1. Introduction 211
13.2. Mine remediation and flooding 212
13.3. Pump and treat versus collect and treat 214
13.4. Flooding strategies at Wismut mines 214
13.5. Summary and conclusions 220
13.6. References 221

14. Investigation into calcium oxide-based reactive barriers to attenuate uranium migration **223**
M. Csővári, J. Csicsák and G. Földing

14.1. Introduction 223
14.2. Leaching of uranium and other heavy metals from the wastes 223
14.3. Results of laboratory experiments 224
14.3.1. Main steps of the process 225
14.3.2. Open-air experiments 225
14.3.3. Building reactive barriers in practice 234
14.4. Conclusions 235
14.5 References 235

Part VI. Groundwater flow modelling **237**

15. Observed and modelled hydraulic aquifer response to slurry wall installation at the former gasworks site, Portadown, Northern Ireland, UK **239**
R. Doherty, U. S. Ofterdinger, Y. Yang, K. Dickson and R. M. Kalin

15.1. Introduction 239
15.2. Geology and topographic setting 240
15.3. Installation phases 242
15.4. Hydrogeology 242
15.5. Numerical modelling 245
15.6. Discussion 246
15.7. Conclusion 249
15.8. Acknowledgements 249
15.9. References 249

16. A finite-volume model for the hydrodynamics of flow in combined groundwater zone and permeable reactive barriers **251**
D. B. Das and V. Nassehi

16.1. Introduction 251
16.1.1. Modelling approaches 252
16.1.2. The finite-volume method 253
16.2. Formulation of the mathematical model 254
16.3. Numerical results and discussion 256
16.4. Conclusions 262
16.5. Acknowledgement 262
16.6. References 262

Part VII. Active and passive methods – a comparison **265**

17. Technical and economic comparison between funnel-and-gate and pump-and-treat systems: an example for contaminant removal through sorption **267**
P. Bayer, C. Bürger, M. Finkel and G. Teutsch

17.1. Introduction and background 267
17.2. Design optimization framework 268
17.3. Case study 268
17.4. Hydraulic performance evaluation 270
17.4.1. Conventional pump-and-treat systems 270
17.4.2. Innovative pump-and-treat systems 270
17.4.3. Funnel-and-gate systems 271
17.5. Evaluation of remediation costs 272
17.5.1. Conceptual model of sorptive removal – assumptions and input parameters 272
17.5.2. Results for pump-and-treat systems 273
17.5.3. Results for funnel-and-gate systems 275
17.5.4. Comparison of the three remediation options 278
17.6. Summary and conclusions 281
17.7. Acknowledgement 281
17.8. References 281

18. Engineering and operation of groundwater treatment systems: pump and treat versus permeable reactive barriers **283**
E. Beitinger

18.1. Evaluation of best available techniques (BATs) 283
18.2. Selection criteria and evaluation process 284
18.3. Data gathering and data gaps 292
18.4. Conceptual design/dimensioning criteria 295
18.5. Treatability studies/final design 296
18.6. Operation/maintenance/monitoring/risks 300
18.7. Costs 300
18.8. References 302

19. Discussion: status, directions and R&D issues **303**
C. McDonald

19.1. Introduction 303
19.2. Setting the scene 304
19.2.1. Is there a level playing field? 304
19.2.2. Where do our findings come from? 304
19.2.3. Treating what with what? 305
19.2.4. Do they work and how do they compare? 306
19.2.5. How fundamental are the distinctions anyway? 307
19.3. Setting about remediation 309
19.3.1. What contaminants have we got here? 309
19.3.2. How should remediation approach be selected? 309

19.4. Combined approaches 311
19.4.1. How can technologies vary over place and time? 311
19.4.2. What other 'treatment trains' are there? 312
19.5. Targets and agents 313
19.5.1. How is the active agent selected or improved? 313
19.5.2. Are the chemical processes understood? 314
19.6. Outcomes 315
19.6.1. How well do the reactors work? 315
19.6.2. How well do the system hydraulics work? 316
19.7. Monitoring and durability 317
19.7.1. How are reactor systems monitored? 317
19.7.2. How often and for how long are they monitored? 318
19.7.3. For how long are the reactor systems effective? 318
19.7.4. Can contaminants be remobilized? 319
19.7.5. Can contaminants be recovered? 320
19.8. Comparative economics 320
19.8.1. Have the economics of the various systems been investigated? 320
19.8.2. How is a proper basis for comparison made? 321
19.8.3. How do their (modelled) costs compare? 321
19.9. Investment, risk and acceptability 322
19.9.1. How much remediation is affordable? 322
19.9.2. How can risk be reduced? 323
19.9.3. How can acceptance be gained for solutions? 324
19.10. Conclusion 324
19.11. References 325

Index **327**