SUSTAINABLE WELLS

Maintenance, Problem Prevention, and Rehabilitation

Stuart A. Smith
Allen E. Comeskey

CRC Press
Taylor & Francis Group
SUSTAINABLE WELLS

Maintenance, Problem Prevention, and Rehabilitation
Contents

List of Tables and Figures ................................................................. xiii
Disclaimer .......................................................................................... xxi
Preface ................................................................................................. xxiii
Authors ............................................................................................... xxvii
Acknowledgments ............................................................................... xxix

Chapter 1  A Brief Colorful History of Well Maintenance and Rehabilitation and Their Milestones .................................................... 1

1.1 Some History ............................................................................. 1
1.2 The Role of the “Environmental” Sector in Shaping Well Rehabilitation and Maintenance ................................... 5
1.3 The Impact of Biology on Hydrogeology and Ground-Water Technology .......................................................... 6
1.4 Economics, Human Skills, Personalities, Demographics, and Other Issues ................................................................. 8
1.5 A Word about Terminology ..................................................... 11

Chapter 2  Causes and Effects of Well Deterioration .......................................... 13

2.1 Summary: Causes of Poor Performance ........................................ 13
2.2 True Grit—Sand and Silt ............................................................. 13
2.3 Yield and Drawdown Problems ............................................... 17
2.4 Chemical Incrustation ............................................................. 20
2.5 Corrosion ................................................................................. 22
2.6 Plastic Deterioration ................................................................. 26
2.7 Biofouling—A Hitchhiker’s Guide to How Life Takes Over .......................................................... 26

2.7.1 Biofilm and Biofouling Basics................................................. 27
2.7.1.1 Biofilms and Microbial Survival ................................. 29
2.7.1.2 Biofilm Function and Ecological Function ..................... 30
2.7.1.3 Biofilms and Biofouling in Ground Water ...................... 30

2.7.2 Water Quality Degradation: Monitoring and Remediation Problems ..................................................... 33
2.7.3 Microbially Mediated Metallic Corrosion ......................... 37
2.7.4 Iron, Manganese, and Sulfur Biofouling ......................... 39
2.7.4.1 Fe, Mn, and S Biofouling: What’s Happening ............. 39
2.7.4.2 How Fe, Mn, and S Biofouling Occurs ......... 40
2.7.4.3 The Redox Fringe ....................................................... 42
2.7.5 Effects on Performance of Well Systems: A Summary .............................................................. 43
  2.7.5.1 Hydraulic Impacts .............................................. 46
  2.7.5.2 Sample Quality in Monitoring Wells ............ 47
  2.7.5.3 ASR Well Systems ........................................ 47
2.7.6 Health Concerns Relating to Biofouling .................. 48
  2.7.6.1 Pathogens ..................................................... 48
  2.7.6.2 Toxic Accumulation ...................................... 49
  2.7.6.3 Chlorination of Organic Chemicals ............... 49

2.8 Impacts on Treatment Plants ........................................ 49

2.9 Engineering and Construction Aggravation of Clogging and Corrosion ........................................ 50

2.10 Well Structural Deformation and Failure: Natural and Human Caused ........................................ 51
  2.10.1 Natural .......................................................... 51
    2.10.1.1 Earthquakes .............................................. 51
    2.10.1.2 Mass Wasting ......................................... 53
  2.10.2 Human Induced .................................................. 55
    2.10.2.1 Mining .................................................... 55
    2.10.2.2 Mine Blasting ........................................ 56
    2.10.2.3 Grouting .................................................. 57
    2.10.2.4 Casing Weight/Quality/Integrity/ Engineering Issues .............................................. 59
    2.10.2.5 Improper Rehabilitation and Development Methods, and Other Abuses of Wells .......... 61
    2.10.2.6 Electrochemical Corrosion from Stray Potentials ................................................ 62
    2.10.2.7 And Other Factors ........................................ 63

2.11 Disaster-Related Flooding ........................................ 64

2.12 Management and Operational Overview ...................... 65

Chapter 3 Economic Impacts of Well Deterioration .................. 67

3.1 Identifying Costs of Well Deterioration .............. 67
  3.1.1 Defining Economic Parameters .................... 67
  3.1.2 Types and Dimensions of Costs of Well Operation and Service ........................................ 69
3.2 Asset Management and Life Cycle Cost .................. 73
  3.2.1 Asset Management Features of Well Systems .... 74
  3.2.2 Life Cycle Costs .............................................. 75
3.3 Assigning Economic Value .................................. 76
  3.3.1 Water Supply EV ............................................... 77
  3.3.2 Other Environmental EV ................................. 77
  3.3.3 Government Accounting Valuation of Assets .... 78
3.4 A Costly Example ...................................................... 78
Chapter 4  Prevention Practices for Sustainable Wells ........................................ 81
  4.1 Prevention—Its Place in the Well Life Cycle ........................................ 81
  4.2 Interlude: Teeth and Motor Vehicles ............................................... 82
  4.3 Prevention: Design and Construction Considerations ......................... 84
    4.3.1 Planning Considerations ..................................................... 84
    4.3.2 Role of Well Purpose ....................................................... 86
    4.3.3 Well Design ...................................................................... 86
    4.3.4 Casing for Well Completion .............................................. 87
    4.3.5 Well Hydraulics and Efficiency—General Considerations ............... 89
    4.3.6 Well Screens and Intakes .................................................. 90
      4.3.6.1 Screen Design .......................................................... 91
      4.3.6.2 Screen and Filter Pack Material Selection .......................... 91
    4.3.7 Grouting and Well Sealing ............................................... 93
  4.4 Well Development ......................................................................... 94
    4.4.1 Reasons for Development .................................................. 94
    4.4.2 Development Method Descriptions ....................................... 95
      4.4.2.1 Overpumping ............................................................. 96
      4.4.2.2 Surging and Pumping or Bailing (Utilizing Surge Block) .......... 96
      4.4.2.3 Airlift Development .................................................... 99
      4.4.2.4 Jetting ........................................................................ 100
    4.4.3 “Conventional” Development Choices .................................... 102
    4.4.4 Fluid-Pulse Development ................................................... 104
    4.4.5 Other Care Issues in Development and Redevelopment .................. 105
  4.5 Preventing Contamination during Drilling, Well Construction, and Development .............................................. 105
  4.6 Preventative Pump Choices and Actions .......................................... 106
    4.6.1 Pump Selection .................................................................... 107
      4.6.1.1 Pumps in Water Supply and Other Extraction (or Abstraction) Wells ................. 107
      4.6.1.2 Pumps in Monitoring Wells .......................................... 108
    4.6.2 Pump Protection ................................................................. 110
  4.7 Design Aspects: The “Cliff Notes” Version ......................................... 113
  4.8 A Note about Well Houses .............................................................. 114
  4.9 Well Array Design Recommendations ............................................ 115
  4.10 A Developing World Note ............................................................... 116

Chapter 5  Maintenance Monitoring Programs for Wells .................................... 119
  5.1 Maintenance Monitoring: Rationale for Instituting a Monitoring Program ............................................................. 119
  5.2 Maintenance Procedures Overview .................................................... 122
5.3 Implementing a Maintenance Program—It’s Institutional, Not Personal ..................................................... 122
5.4 Maintenance Is Personal (and Personnel), Too ...................... 122
5.5 Maintenance Basics ............................................................... 123
  5.5.1 Well System Maintenance Records .......................... 123
  5.5.2 Maintenance Monitoring for Performance and Water Quality ....................................................... 124
  5.5.3 Maintenance Actions and Treatments ...................... 125
5.6 A Maintenance Monitoring Protocol for Wells .....................126
  5.6.1 Purposes of Maintenance Monitoring ...................... 127
  5.6.2 Background for Current Monitoring Recommendations .................................................... 127
  5.6.3 Deciding How to Monitor ........................................ 128
    5.6.3.1 Incorporating PM Data Collection into the Facility Data Collection Effort ........... 130
5.7 Recommended Testing and Information Monitoring Methods ................................................................. 130
  5.7.1 Visual and Other Sensory Examination ....................... 130
  5.7.2 Well and Pump Performance .................................... 131
    5.7.2.1 Benchmarking ........................................... 132
    5.7.2.2 Compare Apples with Apples ..................... 136
    5.7.2.3 Monitoring Pump and Pump Motor Performance ..................................................... 137
    5.7.2.4 Tracking Well Performance ...................... 137
    5.7.2.5 Water Level Measurement Recommendations ..................................................... 139
    5.7.2.6 Well Discharge Measurement ...................... 139
    5.7.2.7 Pressure Measurement .................................. 141
    5.7.2.8 Electrical (Power) ..................................... 141
  5.7.3 Water Sampling ........................................................ 142
  5.7.4 Physicochemical Analyses ....................................... 142
  5.7.5 Biological Monitoring: Decision Making ............. 143
    5.7.5.1 Whether to Monitor for Biofouling.............. 144
    5.7.5.2 Biofouling Monitoring: What Methods to Choose .................................................. 144
    5.7.5.3 A Note about the Current State of the Art in Well Maintenance Monitoring Methods ..................................................... 144
  5.7.6 Biofouling Monitoring Methods: Analysis ................ 145
    5.7.6.1 Microscopic Examination and Analysis.... 145
    5.7.6.2 Culturing Methods .................................... 146
    5.7.6.3 How Minimal Can Testing Be? ................... 149
  5.7.7 Biofouling Monitoring Methods: Sampling Methods ................................................................. 151
5.7.7.1 Pumped Sampling................................. 151
5.7.7.2 Surface Collection on Slides or Coupons .................................................... 152
5.7.7.3 Representativeness of Collection Sampling................................................... 153
5.7.8 Electrochemical In-line Sensors .................................................. 155

5.8 Summary of Recommendations for Maintenance Monitoring in Routine Practice .............................................. 156
5.8.1 Summary of Data Collection Requirements ........................... 156
5.8.2 Well Data File Features .......................................................... 156
5.8.3 Pumping Rates ........................................................................ 157
5.8.4 System Pressure........................................................................ 157
5.8.5 Water Level Data......................................................................... 157
5.8.6 Electrical (Power) Data ....................................................... 158
5.8.7 Video for Historical Comparison ........................................ 158
5.8.8 Hydrogeologic Information That Should Be on File ........................................................................ 158
5.8.8.1 Piezometric Data ......................................................... 158
5.8.8.2 Piezometric Maps ................................................................ 159
5.8.8.3 Geologic Regime ...................................................... 159
5.8.9 Development Data .................................................................. 159
5.8.10 Maintenance Logs for Individual Wells ................................... 161
5.8.10.1 Where Records Should Be Kept ...................................... 161
5.8.10.2 Downtime History .................................................. 161
5.8.10.3 File Records Purpose and Format Issues ........................................ 162

5.9 Schedule of Maintenance Monitoring Actions for Wells ..................................................... 163
5.9.1 Minimum Regular Schedule for First Year ........................................ 163
5.9.2 Schedule for Reducing Maintenance Monitoring after First Year ........................................ 163
5.9.3 Rationale and Commentary ....................................................... 165

5.10 Institutional and Funding Issues in Maintenance Planning, Analysis, and Execution ........................................ 165
5.10.1 Background and Barriers to Effective Maintenance Implementation ........................................ 165
5.10.2 Institutional Needs for Effective Implementations ........................................ 167
5.10.3 Quarterly Review of Facility Performance Data ........................................ 168
5.10.4 Baseline and Historical Data for Wells/Site ........................................ 168
5.10.5 Operator/Working Crew Leader Qualifications and Training ........................................ 169
5.10.6 Determination of Operational Maintenance Responsibilities ........................................ 170
Chapter 6  Preventive Treatments and Actions .................................................. 171

6.1 Sand/Sediment Pumping ................................................................. 171
6.2 What Do We Do if We Have Corrosion? ............................... 172
6.3 Biofouling (General) ................................................................. 174
6.4 Inorganic Encrustations (General) ........................................... 174
6.5 Preventive Chemical Treatments ........................................... 174
   6.5.1 General: Cost-Effectiveness, Professionalism ........ 174
      6.5.1.1 Cost-Effectiveness ................................................... 175
      6.5.1.2 Professionalism ..................................................... 176
   6.5.2 Chemical Classes and Properties .................................... 176
      6.5.2.1 Acids for Maintenance Treatment ..................... 176
      6.5.2.2 Biocides and Oxidizing Compounds .................... 176
      6.5.2.3 Penetrating, Sequestering, and Dispersing Agents .... 181
      6.5.2.4 Blended Method Treatments .............................. 181
   6.5.3 Use and Interpretation of MSDSs .................................... 182
   6.5.4 Compatibility with Well Cleaning Chemicals ............... 183
6.6 Mechanical Agitation and Augmentation .................................... 183
6.7 Chemical Emplacement ............................................................. 184
6.8 Chemical Removal and Recovery ............................................. 184
6.9 In Situ Maintenance Treatment Techniques .............................. 185
   6.9.1 Chemical Feeders in Wells .......................................... 185
   6.9.2 Radiation—That Gentle Glow ....................................... 185
   6.9.3 Application of Electromagnetically Charged Surfaces .......... 186
   6.9.4 CO₂ Well Environment Adjustment—Making the Environment Inhospitable for Biofouling ... 186
6.10 Further Procedural Requirements .............................................. 187
   6.10.1 Regulatory Aspects ..................................................... 187
   6.10.2 Biofouling Recurrence ............................................... 187
6.11 Health and Safety Concerns ...................................................... 187
   6.11.1 Health and Safety Plan .................................................. 187
   6.11.2 Level of Protection for Mixing and Well Application ............... 188
   6.11.3 Chemical Handling Hazards ......................................... 188
   6.11.4 Mixing Chemicals—Personal Safety Aspects ............... 188
6.12 Costs and Time of Routine Preventive Measurements ............. 189
   6.12.1 Maintenance Cost-Benefit Analysis .............................. 189
      6.12.1.1 Cost-Benefit Analysis: A Spreadsheet Approach......... 189
      6.12.1.2 The Heartbreak of Well Failure: An Overriding Weighting Factor .... 190
   6.12.2 Costs of Maintenance Activities ................................. 192
6.12.2.1 Maintenance Monitoring Costs— Typical ...................................................... 192
6.12.2.2 Preventive Treatment Costs ...................... 194
6.12.3 Improving Cost-Effectiveness in Maintenance ....... 194

Chapter 7 Rehabilitation and Reconstruction Planning............................................. 197

7.1 Decisions on Rehabilitation Methods: After Things Go Wrong ................................................................. 197
7.2 Management and Safety in Well Rehabilitation....................... 198
    7.2.1 Facility Management Considerations ................... 198
        7.2.1.1 Responsibility for the Work ................... 199
        7.2.1.2 Getting the Job Done ................................ 200
    7.2.2 Safety and Productivity in Well Rehabilitation Work ................................................................. 201
        7.2.2.1 Safety Assurance ................................... 201
        7.2.2.2 Facilitating Productivity ........................ 202
    7.2.3 Rehabilitation Contractor Considerations .......... 203
        7.2.3.1 Safety: What the Contractor Needs to Have and Know ........................................ 203
        7.2.3.2 Practical Stuff: Access and Response ...... 205
7.3 Contractors and Consultants: Avoiding Trouble in Working Together ......................................................... 208
    7.3.1 Mutual Respect in Rehabilitation Work .......... 208
    7.3.2 Specifications: Business and Bidding Considerations ................................................................. 208
        7.3.2.1 Specification Pitfalls ................................ 208
        7.3.2.2 Overcoming Pitfalls .............................. 209
    7.3.2.3 Effluent Waste Water Containment .............. 210
7.4 Well Rehabilitation: Decision Making on Methods .............. 210
    7.4.1 To Rehab or Not to Rehab? That Is the Question .... 210
    7.4.2 The Costs of Well Rehabilitation ...................... 213
        7.4.2.1 The Cost of Doing Nothing .................... 213
        7.4.2.2 Costs for Serious Rehabilitation Work .... 214
    7.4.3 Contractor Pricing of Rehabilitation Work ............ 215
    7.4.3.1 Choosing Rehabilitation Methods .................. 216
    7.4.4 Damage ...................................................... 217
    7.4.5 Issues in Rehabilitation Chemical Selection .......... 218
    7.4.6 Reconstruction .............................................. 220
7.5 Specifications for Rehabilitation ............................................. 221
    7.5.1 Specification Deficiencies ................................ 221
    7.5.2 What Well Rehabilitation Specifications Should Have ................................................................. 225
    7.5.3 Selecting Well Rehabilitation Bids ..................... 226
7.6 The Role of Consultant Specifier-Observer ........................... 227
Chapter 8  Rehabilitation Methods ................................................................. 229

Chapter Technical Descriptions .................................................................... 229

8.1 Physical Agitation ......................................................................................... 229
  8.1.1 Basic Principles ....................................................................................... 229
  8.1.2 “Conventional” Redevelopment ............................................................. 229
  8.1.3 Other or Advanced Physical Redevelopment Methods ............................ 231
    8.1.3.1 Cold CO₂ Treatment ....................................................................... 231
    8.1.3.2 Sonic/Vibratory Disruption—“Use the Force, Luke!” ....................... 233
    8.1.3.3 Fluid-Pulse Tools ........................................................................... 236

8.2 The Pharmacopoeia: Chemical Use in Rehabilitation ................................. 240
  8.2.1 Overview ............................................................................................... 240
  8.2.2 Acidizing ................................................................................................ 243
    8.2.2.1 Types of Acid Compounds .............................................................. 243
    8.2.2.2 Using Acidizing in Well Treatment ................................................ 245
  8.2.3 Sequestering and Other PSDD Functions ............................................. 247
  8.2.4 Antibacterial (Antimicrobial) Agents ................................................... 248
    8.2.4.1 Chlorination .................................................................................... 248
    8.2.4.2 Alternatives to Chlorine as Oxidants for Biofouling ......................... 252

8.3 Blended Method Treatments ......................................................................... 254
8.4 Application of Rehabilitation Methods Summary ...................................... 256
8.5 Posttreatment after Well Rehabilitation ................................................... 257
8.6 Some Follow-up “Truisms” .......................................................................... 257

Chapter 9  Learning and Going Forward .......................................................... 263

9.1 Learning from the Past ............................................................................... 263
9.2 Where Do We Go from Here? ..................................................................... 264
  9.2.1 Wish List ............................................................................................... 265
  9.2.2 Education, Communication, and Mutual Respect: Human Issues in Well Maintenance ........................................................................................................... 266

Recommended Reading List ............................................................................ 269
  Recommended Reading List ........................................................................... 269
  Selected References ....................................................................................... 272
  Selected Relevant Standards ........................................................................... 277
    ANSI/ASTM Standards (a selection) ............................................................. 278

Index .................................................................................................................. 279
List of Tables and Figures

LIST OF TABLES

TABLE 2.1 Categories of Well Problems and Related Causes .................. 14
TABLE 3.1 Costs of Pumping (Per Year and Per Unit Volume) ............... 71
TABLE 4.1 General Well Design and Placement Guidelines ................... 85
TABLE 4.2 Casing Types and Choices .................................................. 90
TABLE 4.3 Cathodic-Anodic Series of Metal Alloys ............................... 93
TABLE 5.1 Troubleshooting Summary Guide for Well Maintenance .......... 125
TABLE 5.2 Parameters Useful in Well Maintenance Monitoring ............. 126
TABLE 5.3 Features of Water Level Measurement Methods .................. 140
TABLE 5.4 Summary of Physicochemical Methods Relevant to Well
Maintenance .................................................................................. 143
TABLE 5.5 First-Year PM Monitoring Schedule .................................. 164
TABLE 5.6 Long-Term PM Monitoring Schedule .................................. 166
TABLE 6.1 Acid Effectiveness, Safety and Handling—Recommended
Compounds .................................................................................... 177
TABLE 6.2 Common Well Cleaning Chemicals in Use—Not
Recommended (USACE) ................................................................. 178
TABLE 6.3 Well Treatment Chemical Incompatibility ........................... 182

LIST OF FIGURES

FIGURE 1.1 Elephant digging for water in sand. (Tarangire National Park,
Tanzania) ....................................................................................... 2
FIGURE 1.2 Pump impellers clogged by oxidized iron deposition.
Extraction well, DOE Fernald Preserve (Ohio) .............................. 6
FIGURE 2.1 Impellers destroyed by pumping sand and gravel (Mexico) .... 15
FIGURE 2.2 Precleaning flow from a clogged well ............................. 17
FIGURE 2.3 Well screen clogged by iron biofouling (North Dakota State
University Extension, Scherer, 2005, Circular AE 97) ............... 18
| FIGURE 2.4 | Pumping well yield and drawdown components | 18 |
| FIGURE 2.5 | Oxidation and reduction and ecology changes around pumping wells | 19 |
| FIGURE 2.6 | Pipe clogged by iron mineral (U.S. Environmental Protection Agency) | 20 |
| FIGURE 2.7 | Schematic of well with gas pressure release | 21 |
| FIGURE 2.8 | Mineral-clogged drain—mostly calcite (photograph courtesy of Chuck Cooper, Bureau of Reclamation) | 22 |
| FIGURE 2.9 | Corroded submersible pump end (southern Colorado) | 23 |
| FIGURE 2.10 | Diagram of a corrosion tubercle in steel pipe | 24 |
| FIGURE 2.11 | Cross section of steel pipe corrosion tubercles (Lytle, Gerken, and Maynard, 2004, U.S. EPA) | 25 |
| FIGURE 2.12 | Mixed biofilm from water well samples (normal light photomicrograph) | 28 |
| FIGURE 2.13 | Examples of manifestations of biofouling | 29 |
| FIGURE 2.14 | Zebra mussel fouling in pipe (Gemma Grace, Ontario, Canada) | 29 |
| FIGURE 2.15 | Bacterial size, movement, and attachment in relation to pore size in aquifer materials (U.S. Geological Survey) | 31 |
| FIGURE 2.16 | Iron-related biofilm from well water samples (normal light photomicrograph) | 31 |
| FIGURE 2.17 | Soil-water-oil-biofilm interface | 32 |
| FIGURE 2.18 | Microbial ecology schematic of a remediation system | 33 |
| FIGURE 2.19 | Passage of a contaminant plume in an alluvial aquifer. This is a simulation based on observed phenomena, usually indications of microbial activity are detected months or years later in response to some observed problem | 34 |
| FIGURE 2.20 | Fe, Mn, and S transformations and mobility in aquifers—a schematic of typical occurrences in a biologically active mixed reducing-oxidizing aquifer system | 35 |
| FIGURE 2.21 | Fe transformation and plugging zone around an affected well—a schematic of the many activities and results of activity in the busy environment of a pumping well | 35 |
| FIGURE 2.22 | Microbial corrosion processes schematic—illustrating the range of bio-electrical activity around a corrosion tubercle on a steel surface (some features also apply to crevice corrosion of stainless steel alloys) | 37 |
FIGURE 2.23  Example of mild steel well pump discharge pipe tuberculation..................................................................................38

FIGURE 2.24  Microbially influenced corrosion of Type 316 stainless steel monitoring well casing. Section at left has begun anodic attack under biofilm associated with bentonite grout, while in the section on the right, corrosion is associated with metal fatigue. ...38

FIGURE 2.25  *Gallionella*-dominated water well biofilm (normal light photomicrograph). ..........................................................................40

FIGURE 2.26  Mixed filamentous biofilm featuring MnIV oxide mineralogy (normal light photomicrograph (PMG)). ........................................ 41

FIGURE 2.27  Filamentous Mn-precipitating bacteria reemerging when MnIV oxide particles (black) are rehydrated (Bureau of Reclamation–Stuart Smith PMG, annotated by SAS)—minutes after adding water ............................................................ 42

FIGURE 2.28  Sulfur oxidizing biofouling in well pump discharge pipe, South Africa (Courtesy of Hose Solutions Inc.) ......................... 42

FIGURE 2.29  *Thothrix*-dominated sulfur-oxidizing biofouling of geotechnical drains (Bureau of Reclamation–Stuart Smith photographs). .................................................................................. 43

FIGURE 2.30  White sulfur biomass associated with artesian spring (in actuality, an uncontrolled well) in western Ohio. ......................... 45

FIGURE 2.31  Schematic presentation of the initiation and development of a biofilm (P. Dirckx, Montana State University Center for Biofilm Engineering). ..................................................................... 45

FIGURE 2.32  Extensively tuberculated pipe interior (Argentina: photo by Miguel A. Gariboglio). ............................................................ 46

FIGURE 2.33  Some causes of well structural failure. ............................................. 52

FIGURE 2.34  Slope and rail line affected by soil creep (Courtesy U.S. Geological Survey). ................................................................. 53

FIGURE 2.35  Slope affected by slump (Courtesy U.S. Geological Survey).... 54

FIGURE 2.36  Shoreline erosion processes, Ashtabula County, Ohio........ 54

FIGURE 2.37  House foundation undermined by collapse of mining cavities (Pennsylvania Dept. of Environmental Protection photo). 55

FIGURE 2.38  Long-wall mining effects diagram (Pennsylvania Dept. of Environmental Protection). ...................................................... 55

FIGURE 2.39  PVC casing distorted by heat due to improper cement grouting (photo by Gary L. Hix). The casing is pushed in and cracked at the visible joint and the foreground surface is blistered. 58
FIGURE 2.40 Monitoring well casing bent due to vehicle collision.................62
FIGURE 2.41 PVC water well casing broken due to vehicle strike in parking lot. There was an attempt to fix it with a rubber boot coupling and protect it with a tire. This was a public water supply (bowling alley, now closed) in Ohio. ........................................62
FIGURE 2.42 Flooding in the St. Mary’s River watershed (Ohio) (NOAA photo). ........................................................................................................64
FIGURE 3.1 The meter is running.................................................................68
FIGURE 4.1 The well life cycle continuum..................................................82
FIGURE 4.2 Some types of connections used in well casing and pump discharge pipe. (a) bell-end PVC casing pipe and (b) spline-lock coupling (Certain Teed CertaLok™)..................................................88
FIGURE 4.3 The necessary in-and-out motion of proper well development.....96
FIGURE 4.4 Example surge blocks (both double surge block tools).............97
FIGURE 4.5 Example well cleaning brush (manufactured by Cote Chemical Corp., figure courtesy of Kevin McGuiness). .......................98
FIGURE 4.6 Schematic of airlift development and pumping apparatus (North Dakota State University, Scherer, 2005).................................99
FIGURE 4.7 Jetting system schematic (North Dakota State University Extension, Scherer, 2005).................................................................101
FIGURE 4.8 Jetting heads (North Dakota State University Extension, Scherer, 2005).....................................................................................101
FIGURE 4.9 Airlift testing and development, test drilling in carbonate aquifer (Ohio). The illustrated system is set up to permit periodic flow testing by measuring tank fill volume over a set period of time. .................................................................103
FIGURE 4.10 Testing for field parameters during test drilling. pH, conductivity, temperature, and several key chemical parameters were measured in nonfiltered and filtered samples... 103
FIGURE 4.11 Well pump electrical system protection (photo by Gary L. Hix)....110
FIGURE 4.12 Schematic of suction flow control device (Eucastream SFCD design, Kabelwerk Eupen AG product literature, Eufor S.A., Eupen, Belgium)...................................................................................111
FIGURE 4.13 Sand separator for submersible pump installation (illustration courtesy of LAKOS Separators and Filtration Systems)..............112
FIGURE 4.14 Blow-off hydrant examples (photos courtesy of Kupferle Foundry Company, illustration modified)..............................................115
FIGURE 4.15  Example easy-to-service well house. ............................................... 116
FIGURE 5.1  Well decision-making flowchart............................................................ 120
FIGURE 5.2  Some indications that you may have biocorrosion problems in the well (Ohio). Corrosion hole (middle section, top), above pump was losing several 100 gpm.................................................. 131
FIGURE 5.3  Down- and side-view borehole video camera system operated by Geoscope Inc., Mansfield, Ohio. ......................................................... 132
FIGURE 5.4  Example pump performance curve (Scherer, 1993, AE-1057, North Dakota State University Extension). Note: HP and head are per stage. ........................................................................ 133
FIGURE 5.5  A plot of step-drawdown test data...................................................... 134
FIGURE 5.6  Analysis of step-drawdown test using Hantush-Bierschenk straight-line method, B established by intercept and C from slope of plot. ........................................................................... 134
FIGURE 5.7  Graph of efficiency vs. pumping rate from analysis of step test plot, aquifer loss and well loss illustrated........................................ 135
FIGURE 5.8  Plot of percent well efficiency vs. pumping rate. Derived from analysis illustrated in Figures 5.5 and 5.6, with extrapolations to gpm above and below the tested flow rates (Figure 5.5)......... 136
FIGURE 5.9  BART method tube schematic. (Courtesy Droycon Bioconcepts Inc.) .............................................................................. 147
FIGURE 5.10  A selection of BART reactions from an alluvial aquifer well..... 148
FIGURE 5.11  Inoculated BRS-MAG tubes and syringe applicator. Sample is injected into vial................................................................. 149
FIGURE 5.12  Wellhead flow cell collector: (a) element and (b) as installed on a wellhead.............................................................................. 153
FIGURE 5.13  Electron micrographs (EMGs) of filamentous biofilms (Bureau of Reclamation project—scanning EMGs by L. Tuhela-Reuning, Ohio Wesleyan University). ........................................ 154
FIGURE 5.14  Field analysis of drive cores for physicochemical and biochemical parameters (Iowa). ................................................................. 155
FIGURE 6.1  Well maintenance decision tree.......................................................... 172
FIGURE 6.2  Projections of annual and cumulative costs over time using Sutherland et al. method. “Discounted annual costs” illustrates annual-cost profile, “Cumulative discounted costs” shows difference between “with” and “without” maintenance monitoring in this simulation. ...................................................... 191
FIGURE 7.1  Well rehabilitation work in motion. Cleaning carbonate aquifer wells in western Ohio................................................................. 198

FIGURE 7.2  Sometimes there are access challenges (photo courtesy of Ohio EPA Southeast District staff). ................................. 206

FIGURE 7.3  Good well site access is important. Note room for crane and service vehicles on pad within fence, personnel access at the crane side to the interior and access through the roof.................... 207

FIGURE 7.4  Wellhead in East Africa where site security is paramount. Well service will require removing a portion of the “castle” wall.. ........................................................................................................... 207

FIGURE 7.5  Lining a well, sealing off unsatisfactory zones using a Griffitts well packer (illustration courtesy Griffitts Drilling and Seals). ... 221

FIGURE 7.6  Setting a liner in place using an inflatable swaging system (illustration courtesy of Inflatable Packers International Pty Ltd). ........................................................................................................... 222

FIGURE 7.7  Wireline or “riserless” pump installation schematic (illustration courtesy of Inflatable Packers International Pty Ltd). A riserless pump uses the casing as the discharge line. ...... 223

FIGURE 7.8  SFCD retrofit in well changes hydraulic profile (EucaStream SFCD design, Kabelwerk Eupen AG product literature, Eufor S.A., Eupen, Belgium). ................................................................. 224

FIGURE 8.1  Setting a well shooting charge (eastern Ohio sandstone-shale well). ................................................................................ 234

FIGURE 8.2  Sonar-Jet treatment sequence (Michigan). (a) The string is assembled and connected, (b) the assembled 5-ft string to be lowered to the screen interval, (c) the returning string after firing, (d) seeing what has been retrieved in the basket. ............. 235

FIGURE 8.3  AirShock air impulse gun. (Courtesy ProWell Technolgoies, Ltd.) .............................................................................................. 237

FIGURE 8.4  Airburst AIG well assembly—bolt air gun mounted on bail (foreground), compressor and winches background.................. 238

FIGURE 8.5  Airburst treatment sequence (carbonate aquifer, northern Ohio). (a) Hooking up and deploying the tool, (b) checking water level, (c) inserting the tool, (d) visible results at the surface. ........................................................................................................... 240

FIGURE 8.6  pH influence on relative occurrence of hypochlorite ion species plotted from calculated data. Note that actual values may vary due to water quality and temperature variables. ........ 250
FIGURE 8.7 Illustration of features of flexible well pump discharge pipe. (a) Coil of 6-in. pipe with fittings, (b) top connection at flanged well head, (c) pump connection, same installation, (d) full installation view, (e) installation of Wellmaster in an angled well (UK). Note that the pumps illustrated are not small. (Photos (b) and (c) courtesy of Boreline (Hose Solutions Inc., www.allhoses.com). Photos (a), (d), and (e) courtesy of Angus Flexible Pipelines.)
Disclaimer

This work provides insight and understanding on the problems of wells and their prevention and cures and is presented as a reference work. It is not a detailed specification or substitute for experience. Any conclusions and recommendations provided are based on the informed professional opinion of the authors, and these are based on their experience and research. People just reading this or any combination of books and manuals should not consider themselves fully qualified to perform, specify, or supervise well maintenance and monitoring programs without the necessary knowledge base and experience with specific situations. Generally this knowledge and experience is concentrated in consultants and contractors, but there is no reason that it cannot be developed “in house” within a facility’s operations and maintenance staff.

This book is based on a body of knowledge. How you apply it is up to you. The construction of wells is so individual and the geological environment so variable that we cannot guarantee the applicability or outcome in your particular situation. Also keep in mind that some of the procedures and technology mentioned are protected by patent.

If you are a consumer of professional services in well rehabilitation, this book will help you to get the most from your professional help. A major point in this work is the need for operational data collection and maintenance. This is important. If you will not do this, we cannot help you with this book. If you are a provider, this book is a source of information intended to help you do your job better and more safely. With that in mind, and understanding that we all have a lot to learn, read on.

Stuart A. Smith, CGWP
Allen E. Comeskey, CPG
Preface

This book is intended to be a guide in keeping well systems operating to their best capacity. These include pumping water supply and plume control, pressure relief and dewatering wells, barrier and other recharge wells—horizontal, angled, and vertical. To a certain degree, the scope covers monitoring wells and drains, and even wells for hydrocarbon withdrawal and fluid injection. It is written for those people who have to wrestle with these problems: well and overall facility managers, their operators, consultants and regulators, and contractors who may perform well and pump repair and rehabilitation services.

The problems you may be experiencing with your wells are not new or unique. They may be more intense for some wells than others. Each category of wells has its particular issues, for example:

- Public water supply (PWS) and hydrocarbon wells are perhaps best covered by well maintenance and rehabilitation experience (since some are willing to spend money on it).
- Private or farm water supply, small facility PWS, and some irrigation wells are also similar to other PWS wells, but often smaller in dimension and rarely maintained properly.
- Monitoring and recovery wells are only specialized wells, but often installed where no reasonable person would put a water supply well unless they were desperate.
- Recovery and treatment systems are also nothing more than specialized ground-water-source water treatment systems. What sets them apart from a maintenance standpoint is that they are routinely exposed to harsh environments and operated in such a way that maximizes the potential for performance and water quality deterioration.
- Even where ground water is considered to be uncontaminated but monitored due to potential hazards, monitoring wells are subject to greater deterioration effects than active pumped water supply wells, since they sit for long periods, unused.
- Aquifer storage and recovery (ASR) wells are increasingly being installed and used as utilities and regions attempt to better manage water resources. These systems are basically injection wells that can then be reversed to pumping wells. Injection wells have known maintenance problems. Can such wells be relied upon in the long run?
- Increasing numbers of nontraditional nonvertical wells, like drains, have their own maintenance issues, exacerbated by the environments in which they are developed and by construction and development methods that leave them vulnerable to clogging mechanisms.
The process of operating any engineered system should include active maintenance. The alternative (in this case, the neglect of well and pump problems) leads to continued performance deficiencies, or even additional problems. For a variety of reasons, wells have traditionally not been maintained like the active, valuable facility assets they are. However, an attitude of maintenance is catching on in all sectors.

This current work is an update and expansion of the 1995 work, *Monitoring and Remediation Wells: Problem Prevention, Maintenance and Rehabilitation*, by Stuart Smith (CRC Press). That work was intended to accompany reports coauthored by Smith and published by the AWWA Research Foundation, *Methods for Monitoring Iron and Manganese Biofouling in Water Supply Wells* (1992) and *Evaluation and Restoration of Water Supply Wells* (1993), which were oriented toward water supply wells. These have now been out of print for several years (although they are still quite relevant). This present work reflects those changes and positive improvements in the state of the art that have occurred in the last decade or so. It builds upon and complements other titles in the *Sustainable Well Series* that have documented improvements in the last twenty years.

This book, rather than focusing on one sector of well use as the 1995 book did, is intended to serve as a comprehensive yet readable state-of-the-art summary of performance maintenance, problem prevention, and rehabilitation or restoration practice for wells for the purpose of sustaining optimal performance over the long term. The current understanding of processes that impair performance and shorten well component life, practices designed to sustain performance during operations, and feasible rehabilitation and restoration methods will be considered. It will address design features to maximize sustainability and issues of cost-effectiveness in planning sustainable well efforts. Emphasis will be on operational practicality. It is a guidebook to the causes of well deterioration, methods of well maintenance, and well restoration or well rehabilitation methods.

Like a useful travel guidebook, this work is not a one-stop encyclopedia, but, where useful, it points you to further sources of more information. In this case, the information for this work is built on the experience of the authors and numerous other people, and a good chunk of that information is published and should be on the bookshelf of—and read by—anyone responsible for well systems. We supply a recommended reading list.

You know, as soon as you stop and go to print with a book, that a good story will come your way or a new technology will emerge that may sweep the industry. So consider this book as a snapshot. By all means, keep up with new developments. Even with new technology, most of the principles expressed herein will apply.

Seek all the good advice you can find, and respect it when you get it. The coauthors offer a website for up-to-date information, and they link it to other good sources. We plan to offer a discussion blog or some such vehicle for those who purchase the book in order to update the reader on new findings and ideas and to access additional resources.
A COMMENT ON THE “VOICE” OF THIS BOOK

The authors have devoted much time in front of groups of operators, municipal boards, etc., informing them of the mysterious goings-on in their wells. We have found that a relaxed discussion results in more understanding than a formal lecture. While the material is intended to be entirely serious and authoritative, we have applied the same style to this book. We envision ourselves sitting on our stools, talking with you. As with instruction, we repeat ourselves at times for emphasis, in case your attention drifts.
Authors

Stuart A. Smith has been managing partner of Smith-Comeskey Ground Water Science LLC (Ground Water Science) since 1996. He is certified (CGWP) and licensed as a hydrogeologist and is a highly applied environmental microbiologist focusing on the biofouling and biocorrosion issues of wells and geotechnical drains. Prior to forming the predecessor of Ground Water Science in 1986, Mr. Smith served as a technical editor for Battelle Memorial Institute, as an adjunct associate professor in ground-water technology for Wright State University (Ohio), and as education program coordinator and research associate for the National Ground Water Association (NGWA, then known as the National Water Well Association), where he joined the staff in 1979 after a short stint as a secondary school teacher in Ohio. He also served as a lecturer in biology at Ohio Northern University in the 1990s. He holds BA and MS degrees from Wittenberg University (Ohio) and The Ohio State University, respectively.

He is the author or coauthor of numerous publications, such as *Methods for Monitoring Iron and Manganese Biofouling in Water Supply Wells and Evaluation and Restoration of Water Supply Wells* (AWWA Research Foundation), *Monitoring and Remediation Wells: Problem Prevention, Maintenance and Rehabilitation* (CRC Lewis Publishers), and *Operation and Maintenance of Extraction and Injection Wells at HTRW Sites* (U.S. Army Corps of Engineers), and the first manual on the subject in Spanish (with the late Dr. Miguel Gariboglio), *Corrosión e incrustación microbiológica en sistemas de captación y conducción de agua: aspectos teóricos y aplicados*. He is also a contributor to AWWA’s *Water Quality & Treatment*, 5th edition and ASCE’s upcoming *International Manual of Well Hydraulics* (ASCE). He is a coauthor of both the 1992 *Australian Drilling Manual* and its 1997 successor, *Drilling*, published by CRC Press, and principal author-editor of NGWA’s 2nd edition of the *Manual of Water Well Construction Processes*. Since 1980, he has contributed to the general understanding of causes and cures for well problems through talks and seminars across North America and in Argentina and Australia, and through industry publications, such as the *Water Well Journal* and *National Drillers Buyers Guide/National Driller*, and web content. He is active with the NGWA (including being active in the development of the new water well standard, ANSI/NGWA-01) and the AWWA’s Ohio Section. He is currently chair of the Standard Methods for the Examination of Water and Wastewater joint technical group for Section 9240 (iron and sulfur bacteria). He is also active locally with the Sandusky River (Ohio) Watershed Coalition and involved in some water supply development planning in East Africa.

Allen E. Comeskey has been a member and partner in Ground Water Science since 1996. He is a certified professional geologist (CPG) and registered geologist in several states. He has been involved in water supply hydrogeology and exploration since 1979. With Ground Water Science, he focuses on well construction planning and
execution, and the performance and analysis of logging and well hydraulic and aquifer tests. He is also an experienced ground-water modeler and hydrologic analyst with extensive experience in both fractured rock and glacial-alluvial hydrology. Prior to forming Ground Water Science, he worked for 10 years with the North Dakota State Water Commission, and also with Earth Data and LBG, Inc. on projects in Maryland, New York, Pennsylvania, and New England. While in North Dakota, he conducted community and county water resources exploration and delineations (often logging more than 50,000 ft of borehole each year), and worked with wetlands water budgets. While in the eastern United States, he worked on complex wellhead protection and contaminant delineation studies and continued detailed modeling, well testing, and well rehabilitation project work with Smith-Comeskey. He holds BS and MS degrees in geology from Bowling Green State University and the University of North Dakota, respectively, and has completed advanced study in fractured rock hydrology and modeling at the University of Wisconsin–Madison and GIS at BGSU.
Acknowledgments

Thanks to the past support of AWWARF (Water Research Foundation) at that crucial time in the early 1990s when good information was being compiled again. They can fund future needed research proposals we send if they want to. Thanks also to the U.S. Army Corps of Engineers (USACE), the U.S. Department of Interior’s Bureau of Reclamation (BOR), and the National Ground Water Association for past and present support and confidence. “Up north,” Canada Agriculture’s Prairie Farm Rehabilitation Administration (PFRA) and the private company Droycon Bioconcepts, Inc. have provided vision, leadership, and crucial support to the art, and those witty Canadians coined the catchy concept of a “sustainable well.” We also acknowledge other working experts and authors in the field, who help one another learn and improve “as iron sharpens iron” (even in those instances when we do not agree). The input of George Alford, Olli Tuovinen, Roy Cullimore, Bill Frazier, Gennady Carmi, Miguel Gariboglio, Jay Lehr, Ross Carruthers, Rob McLaughlan, Peter Howsam, John Schneiders, Denise Hosler, and many others over the years is particularly appreciated. We most gratefully thank our clients who had the problems that have served as our classroom and laboratory (we benefit from the troubles of others), as well as our working colleagues on the service side, who move the iron and the water. Nothing gets done without them. Karen Ward helped with art carried over from the 1995 predecessor to this work. We slavishly acknowledge the support of our wives, who mostly humor us as we pursue our star. Crack librarian Rebecca Quintus, who finds things we seek, also contributed materially to this work.
1 A Brief Colorful History of Well Maintenance and Rehabilitation and Their Milestones

1.1 SOME HISTORY

No one recorded when well digging started, but surely humans imitated elephants in digging holes in the sand to access cooler water that did not make the children sick so quickly (Figure 1.1). People dig such “wells” to this day.

Well construction is an ancient craft: Genesis, the book of the Judeo-Christian scriptures that provides an account of the primordial history of human interaction with God, recounts the exploits of Abraham, leader of a large and successful nomadic pastoral clan and claimed as patriarch by many, living about four thousand years ago. Operating in a semiarid country, Abraham’s company (like their neighbors) dug wells, a skill they learned from other people in the Levant who had already been constructing wells for several thousand years. Excavated wells in Europe, Syria, Israel (including a site now 10 m deep in the sea), and South Asia have been dated to before 6300 BCE. As for the subsea well, people presumably constructed wells on land to access fresh water, so the well was constructed before the sea level rebounded at the end of the last Pleistocene ice advance.

Since such wells were valuable (Genesis reports squabbling among the tribes over Abraham’s wells), there presumably has been well maintenance and rehabilitation since that time—and before—if you count all that sand, silt, and debris removal from all those countless wells in dry riverbeds back to the dawn of humanity. Maintenance must have been at least selectively successful. In Jesus’ encounter with a woman at a well in Samaria (early first century CE), she attributes the source of the well to the patriarch Abraham’s son Jacob (who lived over seventeen hundred years before). That’s some long well life.

Naturally, maintenance of dug wells was not always performed, or performed well. Excavated wells are excellent sources of archaeological information from old settlements such as colonial sites in Virginia, Jamestown or Williamsburg. Objects in wells mean that people were throwing undesirable objects into wells back then, just as they do today. One of us (Comeskey) observed in North Dakota in the early 1980s (a process since stopped) that wherever a platform over an old dug well rotted away, the hole was soon filled with pesticide jugs and oil cans. As we see everywhere, if there is a hole in the ground, someone throws something in it.
Likewise, spoiling wells is an ancient tactic in warfare that was applied as recently as the Balkan wars and Rwandan civil strife of the 1990s, when human remains were dumped in wells. With less intention, spoiled wells can change history. Black rat remains found in Roman wells in Britain suggest that Romans may have lost their grip on northern Europe due to bubonic plague.

When such wells required attention, there was no simple option to “move over and drill new,” especially in rock country. Establishing a new well would involve an incredible investment of labor, since the engine-powered drill would not appear until the nineteenth century. Cleaning the existing well would be the more cost-effective strategy in terms of time and labor, even if it were risky.
Georg Houben and Christoph Treskatis, in their excellent McGraw-Hill book (see the recommended reading list), recount examples of well maintenance and reconstruction dating back to Neolithic times. One notable example of premodern well maintenance comes from Germany. By the sixteenth century, regular well maintenance on two- or three-year intervals was established in the city of Duderstadt. This took the form of a “well-cleaning feast.” Sadly, they report that the practice was abolished by 1724 “because the amounts of beer (5 barrels) served—free of charge—during this festivity caused ‘… on the one hand much exuberance, fighting and desecration of the holy days, on the other hand also the ruin of citizens and neighbours…’.” Maybe this is why we have industrial safety regulations today, but it must have been more fun then.

Well maintenance and rehabilitation through the history of dug-masonry wells was largely limited to cleaning out debris and silt, cleaning off what we would now call biofouling, and necessary deepening and reconstruction. The use of chlorine (chlorinated lime) as a disinfectant began in the nineteenth century in response to disease outbreaks associated with wells. One widely reported account is that of Dr. John Snow’s attempt to disinfect the Broad Street Pump in London in 1850 during the cholera outbreak, which Snow pinned on that infamous well. That it would occur to anyone to disinfect a well, of course, required an understanding of germ theory, which also did not emerge until the nineteenth century, and the industrial extraction of chlorine, also an innovation of the 1800s.

The face of well construction changed dramatically in the nineteenth century in Europe and the Americas with the advent of the steam engine and engine-powered reciprocating drilling machines. Although Chinese drillers reportedly drilled 1,000 m salt wells four thousand years ago with spring pole drilling systems, these took generations to complete (as one can imagine) and were therefore rare and valuable.

The appearance of the steam engine attached to a drilling machine (dated to the 1830s in the United States) provided a reasonable means to drill deep wells into aquifers rarely tapped before. These were better protected from contamination and tapped water with more abundant reduced iron, manganese, and sulfur. Although more sanitary and easier to protect, their inefficient water intakes were more vulnerable to clogging by what we would come to know as iron, manganese, and sulfur biofouling.

Thus, we came to an approximation of the modern drilled (tube) well maintenance situation:

1. A productive and valuable well that was (to varying degrees) prone to performance, sanitation, and structural issues.
2. The well is now deep—often quite deep—but no longer accessible for direct action by masons or youth with brushes and buckets.
3. Yet on the other hand, it could be built using engineering, process, and chemical capabilities also unavailable in previous millennia. For example, it can be pumped using a wind- or engine-powered piston pump.

The early decades of the twentieth century brought these notable advances in water well science, engineering, and technology:
1. The emergence of the cable tool drilling machine and associated tools and methods in their modern form provided a viable, powerful, and versatile well construction and service system
2. Modern well screen designs and other inventions with familiar names attached to them, such as Johnson, Layne, Moss, and (not to be forgotten) Cook
3. Modern metallurgy, giving us high-strength and corrosion-resistant alloys, precision machining, welding, and other fabrication methods
4. Development of technical procedures such as well grouting and filter packing
5. Development and adoption of the vertical turbine pump
6. Electric line power (often of high quality) becomes widely available
7. Development of well testing and analytical methods that are still in use today

As such drilled wells accumulated some age, performance decline and a need for rehabilitation, and of course pump service, became inevitable. As long as there have been well development tools and procedures, mechanical redevelopment has been used to clean wells that had filled with sediment or declined in performance. For many purposes, redevelopment worked well. However, it was not long before people tried various means to enhance the experience.

While talking with a retired driller, Hubert Keith, in the early 1980s, he related to one of us (Smith) that Layne Mishiwaka crews in the 1930s pumped hot water and steam generated by their steam-powered cable tool rigs into wells to dislodge “iron bacteria” deposits. They would let the wells work and pass the time reforging drilling bits. This is the kind of patience (rarely expressed today) that Depression-era men, glad to have good jobs, possessed. Houben and Treskatis report that a Heinrich Böttcher filed a 1905 patent in Germany (no. 181,578) that dealt with the “cleaning of tube wells by means of hot steam.” So the concept had widespread application.

The post–World War II period brought more revolution. The first was the spread of the truck-mounted rotary drilling rig. While they were used before the war, especially in the petroleum field, they were slow to be adopted by the water well industry due to cost and their complicated nature. However, once they became economical to deploy (and there was a suburban housing market), rotaries became common. Wells could be installed very quickly and less expensively. There was much less investment in time and emotion compared to installing them with cable tool rigs or by digging. Consequently, wells became consumables, to be used and discarded. Why maintain something you are going to use up and replace? In 1955, we had cheap land, cheap drilling, and limited regulatory environment.

A second revolution was in the flowering of industrial chemistry, which made a wide range of cleaning and disinfecting compound chemicals available for use in well cleaning, and the ingenious experimented with a lot of them. Mineral acids such as hydrochloric acid were used for removing deposits. Chlorinated lime, chlorine gas, and liquid sodium hypochlorite were used for disinfection and odor removal. The use of chemicals became more prevalent after World War II, with the final passing of steam engines and the universal use of internal combustion engines to power drilling equipment.

The proliferation of designer organic chemicals after World War II brought us the age of detergents, beginning in the 1950s. Paging through water well industry
journals of the time, one finds wide-eyed articles and advertisements for compounds from familiar manufacturers. These phosphate-containing detergents were a major part of the well-cleaning toolkit for decades. Starting in the 1980s, more sophisticated chemistry that presented fewer side effect problems came into wider use.

The period since the early 1980s brought a modern flowering of research, conferences, and publications (especially since the early 1990s) on well rehabilitation and maintenance. There was much experimentation in types of processes. That same period brought some of the first systematic experimentation and training in what constitutes effective well cleaning and maintenance. It also brought the era of well cleaning mass marketing, in which companies (including some of the major suppliers in the ground-water industry) provide us with designer compounds intended to be better and safer than what we select a la carte off the chemical supplier’s dock. Many of these products have names with letters and numbers. The innovation, testing, and exuberant marketing continue to the present day.

1.2 THE ROLE OF THE “ENVIRONMENTAL” SECTOR IN SHAPING WELL REHABILITATION AND MAINTENANCE

Millions of wells have been constructed in the industrialized world, mostly since the early 1980s, for a purpose other than the traditional ones: ground-water supply, recharge, or dewatering. Among these other purposes are monitoring ground-water quality and pumping to control or clean up contaminated ground water—the other side of the effect of the industrial chemical era on the industry.

At the same time that construction of such environmental wells was accelerating, the environmental industry (consultants, government, drillers, and service users such as waste management firms), one challenge was to make remediation systems work in an environment far more challenging than that of a potable ground-water system.

The development of several important consensus standards, including ASTM standards for construction and development and maintenance of monitoring wells, helped the process. An entire training and continuing education industry sprang up to service the needs of professionals in the environmental industry so that monitoring and recovery systems could be competently designed and installed. Manuals on monitoring well construction and design were written. Improved methods, tools and equipment, and personnel skills were developed and became part of the maturing of the industry. The results are not uniform—poorly designed systems are not disappearing. Unfortunately, with the gutting of funding for ground-water clean up, much of the training and continuing education sector has withered, but the publications and concepts remain.

The remediation side of the business has been transformed since the mid-1990s with the phasing out of many pump-and-treat systems due to their high operational failure rate. It is not that such systems could not be maintained, but resources and plans to do so were rarely included in project plans. The entire budget went to design and construction. In their place, in situ remediation has been a more prevalent tactic. Of course, the whole pace of ground-water cleanup slowed in recent years with the loss of funding.
Sustainable Wells: Maintenance, Problem Prevention, and Rehabilitation

In recovery and pump-and-treat systems, the chief problems are reduced flow and increased drawdown in the well systems and clogging of downstream piping and treatment apparatus. Pumps are a particularly hard-hit component of the system (Figure 1.2). Environmental well problems are fundamentally the same as those that cause water supply wells to provide poor performance. Poor design and poor construction and development also can contribute. However, inherent environmental causes of deterioration may occur even if design, installation, and development are adequate.

**Note:** We use numerous technical terms such as *drawdown* throughout this work. We are assuming an audience generally familiar with wells and their processes. If you are entirely new to well construction, testing, etc., we suggest reviewing primers on the subject (and do not forget to read the disclaimer and other warnings in this text).

Monitoring wells may have less obvious performance symptoms since they are not always stressed by pumping. Symptoms of well deterioration experienced in monitoring wells are most likely to include changes in physicochemical water quality and increased turbidity. Such changes can interfere with the quality of samples from wells, as well as their performance, for example, interfering with the recovery of organic constituents of ground water such as trichlorethylene (TCE) results in erratic sample results over time. Results become more consistent after wells are rehabilitated.

Aquifer storage and recovery (ASR) wells represent a new development in terms of their being in mainstream use. Injection wells for management of coastal salt water intrusion and barrier wells are known to be prone to particulate and biological clogging (Chapter 2). Such wells and associated infrastructure are large investments based on rather meager research into longevity issues.

**1.3 THE IMPACT OF BIOLOGY ON HYDROGEOLOGY AND GROUND-WATER TECHNOLOGY**

Much to the bafflement and annoyance of many people with pure physical science and engineering backgrounds (not everyone certainly), the concept that biological
occurrence, activity, and functions have significant impact on or dominance over the behavior of water and water constituents in the subsurface and the performance and service life of our engineered structures in the subsurface has become more and more difficult to ignore.

Everything about planet Earth, from the stratosphere of the atmosphere down to the base of the crust, is affected by life, and has been profoundly transformed since life appeared on Earth. Microflora are ubiquitous. If there is a niche, they exploit it. If there is a pore space, they occupy it. If there is a surface, they coat it. The world as we know it is a product of the actions of living things.

This revolution in understanding is hardly new. A very good conceptual understanding of the role of microflora in what we now call *geomicrobiology* (a term coined by 1954, according to Ehrlich (see Ehrlich and Newman in our recommended reading list) developed in the late nineteenth century, but went quiet for several decades for historical-political reasons. “Geomicrobiology” pioneers were Russians, and the Soviet revolution came along in 1917. By the 1950s, a revival of interest was developing in some academic circles. H. L. Ehrlich’s first edition of *Geomicrobiology* appeared in the 1960s. The field gained traction by the 1970s in various research groups and at the U.S. Geological Survey. A lot of good work continued to be published in Russian (largely inaccessible to Americans). Finnish geochemists and environmental microbiologists (who read Russian and German and communicated well across the Iron Curtain) were among the leaders in the “breakout” in the 1970s and 1980s.

Diffusion of these concepts to the practical ground-water field was rather slow. One of us (Smith) was the only individual on the staff of what was then the National Water Well Association (now National Ground Water Association) with a biology degree in the early 1980s. So he fielded all the inquiries about biological things and started on his “life of slime.” He met a lot of resistance and doubt when speaking about microbial corrosion and clogging. By the publishing of this work’s predecessor, *Monitoring and Remediation Wells: Problem Prevention, Maintenance and Rehabilitation* (CRC Press) in 1995, the role of microbial activity in well problems and the remediation of contaminated ground water were well on their way to being accepted in ground-water development and environmental remediation circles. By then, the now well-known Biological Activity Reaction Test (BART) tests were in the market and tested, a lot of work had been done in cleaning biofouled wells, the U.S. Department of Energy supported landmark work in deep subsurface microbiology that was very revealing, and D. R. Cullimore’s first edition of *Practical Manual of Groundwater Microbiology* was published by CRC Press. This growth and development (and intellectual acceptance) of the role of life in the ground-water engineering world has continued.

Such a paradigm shift in thinking is consistent with the growing acceptance of the idea of an integrated, interactive universe and interdisciplinary study of phenomena.

Although geomicrobiology has been experiencing another academic revival due to interest in global climate change and the possibility of life on Mars, the academic activity is not translating well into applied practice. It seems like a lot of people still are not paying attention. Ground-water remediation systems, especially those for commercial properties, are designed as if biological clogging will not occur—even if the system is designed to foster bioremediation. Then folks are stunned
when clogging does occur, but they remain unwilling to take the necessary steps in response, expecting it to simply go away or to be treated cheaply.

A more subtle issue is that of the influence of developed biomass on well and aquifer hydrology. Actually, the physics and math are what they are. If a biomass clog is present, it lowers the hydraulic conductivity and alters flow paths, so the effects of biomass development can be analyzed and modeled with available tools. The weakness in hydrologic practice is the persistant assumption that the water level response of pumping and monitoring wells (regardless of age and condition) during tests transparently reflects the surrounding aquifer. Experience shows that is not the case. We even have math for that: analysis of “skin effect.”

The problem with taking well biomass development into consideration is that to do so requires an initial step of well reconnaissance to assess conditions and then factoring those conditions into the analysis in a meaningful way. This requires a budget for such work, and suddenly, everyone likes simplifying assumptions. Myths like “isotropic and of infinite areal extent” are popular in the effort to do ground-water protection modeling on the cheap, for example.

1.4 ECONOMICS, HUMAN SKILLS, PERSONALITIES, DEMOGRAPHICS, AND OTHER ISSUES

As will be discussed further in this work, the economics of energy, land availability, water, and scarcity are driving a renewed interest in the economic benefits of well cleaning and maintenance in the commercial and municipal sectors. Practice is beginning to catch up with ideals, theory and persistent preaching. More of the water well industry has embraced rehabilitation, along with drilling, especially as the economic attractiveness of service has become evident. There is a beginning of a sense of economic value for ground water that was lacking before. Also, there is a sense that sustainable choices must be made: we cannot just run down a wellfield through neglect, then move over and establish another. There may be no other place available.

Nontechnical human choices heavily influence the acceptance of ideas and technologies. The Enlightenment movement in Western thought led to a flowering of robust science, but the Enlightenment’s model of a mechanistic, clockwork universe results in resistance to ideas such as complex, literally organic interaction of formation materials, hydrology, biology, and operations. Interestingly enough, the “mechanic” side of the ground-water field, the water well contracting sector, embraced the biological clogging and corrosion model faster than their colleagues with academic and engineering credentials. This organic view of the situation fits their experience in life. Life is an integrated whole of earth, biology, machines, people, institutions, and various intangibles such as matters of faith.

The modern story of water well construction, maintenance, and rehabilitation is also a social history, and heavily influenced by personalities.

1. It is impossible to envision the development of modern (meaning nineteenth century to present) water well and environmental technology without (a) free enterprise, (b) the American view of patent and intellectual rights
(inventors should benefit from their work, and this is something to shoot for), and (c) the development of oil and gas. People had incentive to invent, try new methods, and take risks because they could benefit materially. Otherwise, we stay in the feudal system. The water well and rehabilitation fields are rich with invention. This continues today. Oil required invention to make serious progress and money. Oil and gas were the drivers for the cable tool rig’s development, the blowout preventer, and the tricone drilling bit, among so much more. Oil is valuable and people have strong incentive to invent and engineer to get it. Face it—people will get water from a creek. It required an economic incentive (irrigation, settling on prairie land, raising living standards) and social imperative (improve the lives of the poor and women) to drive improvement in water.

2. We have to make note of the “farm boy” phenomenon of North American society (which includes “farm girls” by the way). University engineering departments recognize that farm kids make the best mechanical engineers. Whether or not they have an engineering degree, people with this rural, machine-rich background know how to figure out how things work and how to do things like making field innovations and repairs. Are we losing this capacity-building ability in our society?

3. The story is full of colorful and interesting individuals. The 2007 movie There Will Be Blood, based loosely on Upton Sinclair’s 1927 novel Oil!, follows one such character, an inventive sociopath. That example is rather extreme. The pioneers and current drivers of the ground-water industry, especially the water well sector, are not likely to commit child abandonment and brutal acts of murder, but they tend to be individualistic, creative, technically focused inventors. They are not organization people. The drivers of recent improvements in well cleaning practice include the pioneers and visionaries typical of new or newly flowered technologies.

It is impossible for us to imagine the current state of well diagnosis, maintenance, and cleaning without several people who demonstrated laser-like focus on these subjects—personal mission, actually, that resembles some kind of apostolic calling more than personal choice. Two that come to mind are the late George Alford on the cleaning side and his collaborator, Roy Cullimore (and his longtime devoted staff of associates). Then there is the skill of tent preaching that brings the sinners to repentance and salvation: Where would we be without Dave Hanson in that regard (setting aside for the moment some details of doctrine)?

One person who labored in relative obscurity, and who should not be forgotten, is the late Miguel Gariboglio of Argentina. Since most of the publication in our field is done in North America and Europe, and much of it in English or its technical cousins German and French, this Spanish-speaking Argentine labored off on stage right. Besides, during the height of his work, Argentina was economically and politically isolated. Still, he and a number of his compatriot colleagues labored on developing and practicing practical biofouling and biocorrosion diagnosis in a very difficult situation, adding materially to our knowledge.
4. However, despite how we lift up and remember the colorful personalities and the pioneers, the full mainstreaming of well cleaning required the influence of our “mud” and “screen” company colleagues. These businesses put the “soap” in jugs on the shelf with the appropriate instructions and certification labels, print the literature, staff the booths, and generally have brought well cleaning to the back roads of North America. Likewise, our laboratory supply mass marketers, with their catalogs and websites, and using our relentlessly organized package transport system, put the new biological tests in the hands of the operators who need them. Together, these businesses generally brought the combination of mass marketing and relentlessly efficient distribution that has come to be known as “walmarting” to well maintenance and cleaning tasks.

5. The occurrence of a maintenance mindset: The worldview that it is virtuous and valuable to maintain valuable systems is one that is culturally dependent and somewhat dependent on economics and other intangibles. Indoctrination is important (as we will discuss). One also finds that the maintenance ethic is most evident in societies (and segments of those societies) that have the most experience with machines and complex engineered structures (e.g., agriculture). This ethic is magnified when one owns or has fiduciary responsibility for the object of maintenance.

Maintenance vision can be selective. This is well exemplified by the experience of water wells. People are most likely to maintain what they see or can otherwise readily detect. Operators will maintain a pump (especially a lineshaft turbine) but neglect the well structure.

A maintenance ethic is less evident in societies (such as in the developing world) where machines have been dropped in by outsiders rather recently without transition from a previous condition. A state of lack of maintenance is amplified when the local people do not own the asset. Then the donor gets the message, “Dear friend, YOUR [fill in the blank—tractor, well pump, etc.] is broken. Please send money.” When frustrated by such a situation, understand that experience and comfort with (even love of) machines and systems comes through generations of acclimation and familiarity. Remember that the current state of ground-water technology had evolved over close to two centuries by the time this work was written.

Such lapses of maintenance vision and planning occur in the United States. Here, funding for maintenance (as we discuss later) is not universally provided. Under some urban areas, subways were constructed, and in some cases, operated for some time but left to deteriorate due to lack of maintenance, and then abandoned. Highways and other infrastructure are often built, funded by grants, without maintenance funding and requirements. The political system can generate the will and momentum to build it, but no long-term commitment to maintain it.

The rise of the “asset management” culture from roughly the turn of the twenty-first century is an attempt to systematize asset maintenance and financial responsibility. This is a system and ethic that can be readily (and rightly) applied to the specific assets known as wells and associated systems.
6. The deep training, indoctrination, and knowledge needed to do these properly are yet to be mainstreamed. There is much evidence that many in charge of operating or advising operators of ground-water assets have paid no attention to the last twenty years’ progress. We (the authors) provide training where we can, as do some others. This book is one attempt to extend our reach. Fortunately, well cleaning methods now being lifted up (as described within) are relatively effective and much less hazardous than older methods, even if applied inefficiently.

Just when improved well cleaning technologies are being mainstreamed, we now are experiencing a relative shortage of the service personnel necessary to perform well service work. As in the water and wastewater operations sector, the skilled and available ground-water industry workforce in the United States is aging. It remains predominantly rural, white, and male, while the United States is increasingly urban and pluralistic. Language and (sometimes ridiculous) immigration barriers impede the recruitment of other willing, skilled workers, and many women with the right skills and temperament find better pay and working conditions in other sectors, such as medical trades. Many other good people for this work are also occupied with being in the military—indefinitely it seems. How this will work out will await future works.

1.5 A WORD ABOUT TERMINOLOGY

Our English language (the only one either of us uses with any confidence) allows for subtle subdivisions of meaning and easy word creation. In the current context, the process of cleaning and repairing a well to improve or restore performance has been referred to as rehabilitation, remediation, restoration, and simply as well cleaning. Each has merit. Remediation is a term often reserved for cleaning up contaminated ground water. That is how we will use the term here. Restoration was used in Evaluation and Restoration of Water Supply Wells, the 1993 manual that one of us (Smith) coauthored. That is a good term, but it may be too optimistic. Cleaning is a straightforward concept, and we use it herein for the process of clearing out debris, biofouling, and so forth. It implies, but does not promise, restoration. Roy Cullimore, in the new edition of Practical Manual of Groundwater Microbiology, favors regeneration for excellent reasons, including facility manager distaste for rehabilitation, which reminds them of the process of bringing injured workers back to health—an uncertain process with hidden costs and legal minefields, as he points out. We choose to stay with rehabilitation because it is a widely understood and used term for what we are discussing, and the process does have those features: risk, uncertainty, and hidden costs. Thus, we promote preventive maintenance as a lower-risk and more sure policy alternative. Besides, we would have to conduct a word search and change a lot of text, and we are acquiring age-related attention-deficit disorder as we look ahead to more important struggles in life than word choices.

As you read Cullimore’s work (and you should not fail to do so—order it now if you do not have it), you will find some other differences in terminology. We stay with biofilm and biofouling where we use them and use biomass less often, although
he is entirely correct in his choices. We tend to stay with a much simplified and mainstream choice of terminology. As you applaud our choice, remember that his terminology (consortia, biomass, no iron bacteria, etc.) pushes into mainstream literature and teaching, displacing the “mainstream.” It will continue to do so as long as he is writing and people pay attention to what he says, for he is the prophet of biology in the underground and we are apostles, applying and proclaiming what is revealed to us.

And finally, following decades of U.S. Geological Survey usage (through March 2009) and the preference of the National Ground Water Association, ground water is two words as a modified noun and hyphenated ground-water as an adjective. Either that or we go with surfacewater, drinkingwater, or potablewater in the German style.

Enough pontificating, on with the meat of the discussion …