

IHS CHEMICAL

PEP Report 295

Wastewater Treatment Technologies

December 2015

ihc.com

PEP Report 295

Wastewater Treatment
Technologies

Ron Smith
Sr. Principal Analyst



PEP Report 295

Wastewater Treatment Technologies

Ron Smith, Sr. Principal Analyst

Abstract

In an effort to help meet growing demands being placed on available water supplies, many communities throughout the United States and the world are turning to water reclamation and reuse. Water reclamation and reuse offers an effective means of conserving limited high-quality freshwater supplies while helping to meet ever-growing demands for water, with industrial waste management practices leading the way.

Industrial wastewater treatment technologies include physical, chemical, and biological processes such as oil-water separators, dissolved air flotation, clarification, filtration, and sludge handling technologies to name a few. Ultimately, the treated water can be utilized in internal reuse purposes or to meet the site discharge water quality requirements.

The chemical and energy process industries represent a very significant portion of water use in the private sector. But in general, most of these facilities use a large amount of water for a variety of purposes, including steam generation, cooling water, utility water, process water, etc. In addition, a significant amount of this water is returned to the environment in various water and wastewater streams, which are treated to meet environmental discharge standards. For overall water reclamation, wastewater treatment processes are employed either singly or in combination to achieve water quality goals.

PEP Report 288 reminds us that off-the-shelf industrial water management systems do not exist. Tailored strategies are needed for specific industries, applications, and sites. Water recycling based on recirculation of process water is normally only a viable option if contamination levels are low and water treatment is relatively inexpensive. Water recycling is less efficient for waste streams that are highly contaminated and/or contain substances that have a very diverse range of chemical and physical properties.

This report reviews over 80 wastewater treatment technologies to develop 32 wastewater treatment modules—16 for contaminant removal and 16 for solids handling, treatment, and disposal—to aid in the development of first-level capital and operating cost economics for use in determining wastewater treatment costs for chemical and industrial processes.

Contents

1 Introduction	23
Wastewater disposal	25
Water reuse—Surface disposal	25
Subsurface disposal	25
Disposal by dilution	25
Industrial water reuse	26
Cooling towers	26
Boiler makeup water	27
Process water	28
Water recycling	28
Recycled water use in refineries	28
Water recycling in coal-to-liquids (CTL) processing	29
Water reclamation and reuse	31
Water reclamation	31
Nitrification and denitrification	35
Risk factors for water consumers	36
Background	41
Wastewater reuse	42
Water reclamation and reuse	43
Advanced wastewater treatment	45
Ceramic membranes	45
Pretreatment technologies	46
Membrane distillation	47
Advanced membrane technologies	47
Electrochemical charge-driven separation processes	48
Osmotically driven membrane processes	49
Membrane treatment facilities	49
Wastewater overview	50
Solid waste abatement	52
Precipitation	53
Biological treatment processes	53
Solids disposal	54
Landfill	54
Land application	55
Landfarming	55
Chemical fixation	56
Deep welling	56
Thermal treatment and incineration	56
Report scope and content	57
Intelligen SuperPro Designer	68
2 Summary	72
Markets	72
Technology	76
Wastewater reclamation technology	78
Industrial applications	78
Advanced engineered treatment	79
Nutrient removal	79

Suspended solids removal	79
Removal of organic matter and trace organic chemicals	79
Nanofiltration or reverse osmosis	80
Activated carbon	80
Biological filtration	80
Chemical oxidation	80
UV irradiation	81
Removal of dissolved solids	81
Economics	81
3 Industry status	87
Introduction	87
Wastewater flows	88
Wastewater composition	88
Treatment objectives	89
Level of wastewater treatment	90
Pollution prevention and minimization	91
Technology selection	92
Primary treatment	94
Secondary treatment	94
Anaerobic treatment	96
Recommendations	98
Industrial water and wastewater treatment	99
Industrial water and wastewater treatment—Food and beverage	100
Industrial water and wastewater treatment—Mining	101
Industrial water treatment technologies—Innovation	107
China—New environmental regulations affecting the industrial wastewater treatment sector	108
4 Technology review	116
Overview	116
The conventional activated sludge (CAS) process	117
Nitrification/denitrification	119
Nonbackwashing submerged filters	125
Tertiary denitrification	125
Phosphorus removal	129
Membrane bioreactors	130
Refinery water and wastewater treatment	137
Refinery processes	141
Hydrocarbon waste disposal	147
Refinery sludge treatment	149
Residual hydrocarbon waste generation	149
Crude oil storage	152
Desalting	152
Distillation	152
Catalytic cracking	153
Primary hydrocarbon waste treatment options—API separator	153
Primary hydrocarbon waste treatment options—Hydroclones	153
Primary hydrocarbon waste treatment options—Induced air filtration	154
Primary hydrocarbon waste treatment options—Chemical coagulation and flocculation	154
Residual hydrocarbon waste composition	154
Hydrocarbon waste removal efficiencies from wastewater treatment units	157
General industrial wastewater sludge treatments	158
Lime stabilization	160
Pasteurization	161

Primary clarification	166
Sludge thickening	169
Use of primary clarifiers for thickening	172
Suspended solids sludge	177
Secondary wastewater treatment	177
Anaerobic digestion	182
Anaerobic digestion process chemistry	183
Anaerobic digesters	184
Conventional anaerobic wastewater treatment system	189
Trickling filters	196
Rotating biological contactors	200
Commercially available bioreactor configurations considered to be efficient	205
Dispersed media IFAS systems	207
Fixed media IFAS systems	208
IFAS economics	208
Sludge thickening	208
Sludge stabilization	210
Sludge digestion	210
Autothermal thermophilic aerobic digestion (ATAD) process	216
ATAD Fuchs design	217
ATAD Thieme design	218
ATAD process operations	219
Anaerobic digestors	222
Anaerobic digestion mixing systems	223
Digestate	229
Acidogenic anaerobic digestate	229
Wastewater	230
Forward osmosis	230
Cooling tower makeup supply	235
Use of forward osmosis in district cooling	236
Forward osmosis—Desalination	237
Landfill leachate treatment using FO	239
Sequencing batch reactors	239
Reject water treatment	242
Sludge dewatering	242
Natural dewatering	243
Mechanical dewatering	243
Sludge disposal—Composting	246
Sludge hygienization—Biological treatment	252
Sludge drying	258
Direct dryers	260
Natural sludge drying	260
Indirect sludge drying	261
Sludge incineration	263
Sludge disposal—Gasification	270
Commercial status for sludge gasification	276
Sludge disposal—Landfarming	279
Landfill sludge disposal	280
Organic contaminants	287
Water recycling	291
Industrial water reuse and wastewater minimization	292
Advanced engineered wastewater treatment	293

Suspended solids removal	293
Removal of organic matter and trace organic chemicals	294
Removal of dissolved solids	299
Engineered natural processes	299
Subsurface managed natural systems	299
Surface spreading or soil aquifer treatment (SAT)	300
Riverbank filtration	301
Surface managed natural systems	302
Treatment wetlands	302
Reservoirs	303
Conclusions	304
5 Technologies for contaminant removal from industrial wastewater	305
Aeration	305
Carbon adsorption	305
Nitrification/denitrification	306
Ion exchange	306
Air stripping	306
Filtration	307
Wastewater treatment systems	307
Wastewater recycling and reuse	307
Application	309
Process description	310
Estimate basis	311
Economics	311
Application	314
Process description	314
Estimate basis	315
Economics	315
Application	316
Process description	316
Estimate basis	317
Economics	317
Application	318
Process description	318
Estimate basis	319
Economics	319
Application	324
Process description	325
Estimate basis	325
Economics	325
Application	326
Process description	327
Estimate basis	327
Economics	328
Application	332
Process description	332
Estimate basis	333
Economics	333
Application	337
Process description	338
Estimate basis	339
Economics	339

Application	343
Process description	343
Estimate basis	344
Economics	344
Application	348
Process description	348
Estimate basis	348
Economics	349
Application	353
Process description	353
Estimate basis	353
Economics	354
Application	373
Process description	373
Estimate basis	373
Economics	374
Application	387
Process description	387
Estimate basis	388
Economics	388
Application	392
Process description	392
Estimate basis	392
Economics	393
Application	397
Process description	397
Estimate basis	398
Economics	398
Application	402
Process description	402
Estimate basis	402
Economics	402
Application	406
Process description	406
Estimate basis	407
Economics	407
6 Technologies for solids handling, treatment, disposal, and final waste treatment	415
Sludge conditioning	416
Dewatering	417
Sludge disposal	419
Solids removal from wastewater	421
Precipitation	421
Biological treatment processes	421
Solids disposal	422
Landfill	422
Land application	422
Chemical fixation	422
Deep welling	423
Thermal treatment and incineration	423
Application	424
Process description	424
Estimate basis	425

Economics	426
Application	430
Process description	430
Estimate basis	430
Economics	431
Application	435
Process description	435
Estimate basis	435
Economics	436
Application	440
Process description	440
Estimate basis	440
Economics	440
Application	446
Process description	447
Estimate basis	447
Economics	447
Application	450
Process description	451
Estimate basis	451
Economics	451
Application	455
Process description	455
Estimate basis	455
Economics	456
Application	466
Process description	466
Estimate basis	466
Economics	466
Application	476
Process description	477
Estimate basis	477
Economics	478
Application	484
Process description	485
Estimate basis	485
Economics	486
Application	490
Process description	490
Estimate basis	492
Economics	494
Application	498
Microfiltration	498
Ultrafiltration	498
Membrane geometry for MF and UF	499
Estimate basis	500
Economics	500
Application	504
Process description	504
Estimate basis	504
Economics	505
Application	509

Process description	509
Estimate basis	510
Economics	510
Application	514
Process description	514
Estimate basis	515
Economics	515
Applications	519
Process description	524
Estimate basis	527
Economics	527
Appendix A—Design and cost bases	531
Design conditions	531
Industrial wastewater characteristics	531
Raw water characteristics	533
Water quality standards	534
Emerging contaminants—Endocrine disruptor compounds	535
Pretreatment of industrial wastes	536
Sludge disposal regulations	537
Plant sizing and layout	538
Plant location	538
Cost bases	538
Capital investment	538
Plant operating and maintenance costs	540
Chemicals and waste costs	541
Coproducts and by-products	541
Effect of operating level on production costs	541
Transport, storage, and monitoring Design assumptions	542
Overall estimate confidence rating	542
Appendix B—Cited references	544

Tables

Table 1.1	Configurations for subbituminous CTL synthesis plants	31
Table 1.2	Water quality parameters used to determine quality of reclaimed water	44
Table 1.3	Core and supplemental water quality indicators	52
Table 2.1	Wastewater treatment module topics	83
Table 3.1	Major classes of wastewater significance and origin	89
Table 3.2	Typical treated effluent standards as a function of the intended use of the receiving waters	90
Table 3.3	Classification of common wastewater treatment processes according to their level of advancement	90
Table 3.4	Classification of secondary treatment technology	95
Table 3.5	Advantages and disadvantages of physicochemical treatment of domestic or municipal wastewater	96
Table 3.6	Typical features of stabilization ponds	97
Table 3.7	Global 2015 CAPEX spending on industrial water and wastewater treatment technologies by water treatment industry segment (\$billions)	105
Table 3.8	US water and wastewater infrastructure—Capital budget 2015 spending distribution	105

Table 3.9	US water and wastewater operations—Capital budget 2015 spending distribution	106
Table 3.10	China—New environmental regulations affecting industrial wastewater treatment sector	109
Table 3.11	Outsourced water/wastewater treatment current activity in Chinese industrial parks	112
Table 4.1	Sources for potential phosphorus recovery from wastewater treatment	129
Table 4.2	Membrane bioreactor effluent quality comparison	135
Table 4.3	Physical, chemical, and biological constituents found in refinery wastewaters	140
Table 4.4	Typical pollutant concentrations of refinery wastewaters	141
Table 4.5	Refinery process descriptions by process category	142
Table 4.6	Major refinery wastewater streams	142
Table 4.7	Wastewaters and hydrocarbon wastes generated by various refinery processes	152
Table 4.8	Physical characteristics of representative hydrocarbon waste streams	155
Table 4.9	Relative change in key properties of different waste forms	156
Table 4.10	Representative physical properties for TPH fractions	156
Table 4.11	Hydrocarbon waste removal efficiencies for wastewater treatment units	157
Table 4.12	General approaches to controlling pathogens and vector attraction in sewage sludge	160
Table 4.13	Industrial sludge constituents	163
Table 4.14	Typical pollutant concentrations of industrial wastewater	163
Table 4.15	Chemicals used in primary clarification	167
Table 4.16	Gravity thickening of sludge	172
Table 4.17	Gravity thickener sludge moisture contents (by sludge type)	173
Table 4.18	Typical polymer doses used in WAS thickening	176
Table 4.19	Typical composition of biogas	194
Table 4.20	Physical properties of trickling filter media	199
Table 4.21	Design features for low and high rate trickling	200
Table 4.22	RBC design/performance attributes	201
Table 4.23	Aerobic sludge digestion general design features	221
Table 4.24	Anaerobic process operating parameters	221
Table 4.25	Advantages/disadvantages of digester mixing systems	228
Table 4.26	Advantages/disadvantages of digester mixing systems	229
Table 4.27	Makeup water source characteristics	237
Table 4.28	Forward osmosis versus reverse osmosis	238
Table 4.29	Summary of reject water treatment methods	242
Table 4.30	Summary of mechanical sludge dewatering attributes	246
Table 4.31	Belt filtration process stages	250
Table 4.32	Performance of dewatering units for wastewater sludges	251
Table 4.33	Thermal and chemical hygienization sludge management practices	254
Table 4.34	Biological hygienization practices in sludge management	254
Table 4.35	Summary—Main commercial thermal drying methods	259
Table 4.36	Incinerator features	268
Table 4.37	Order of magnitude alternative sludge treatment/disposal costs/ton of dry solids	270
Table 4.38	Biosolids feedstock analysis	271
Table 4.39	Sludge gasifier type attributes	274
Table 4.40	Technology comparison between incineration and gasification	276
Table 4.41	Sludge gasification technologies	277
Table 4.42	Staged gasification/combustion developers	279
Table 4.43	Typical results from an MBR operation at a sanitary landfill	287
Table 5.1	Activated carbon for liquid stream	311
Table 5.2	Chemical waste precipitation system—Variable costs	320
Table 5.2	Chemical waste precipitation system—Operating cost (concluded)	321
Table 5.3	Dissolved air flotation—Variable costs	328
Table 5.3	Dissolved air flotation—Operating cost (concluded)	329
Table 5.4	Facultative lagoon—Variable costs	334
Table 5.4	Facultative lagoon—Operating cost (concluded)	335

Table 5.5	Flocculation and sedimentation—Variable costs	339
Table 5.5	Flocculation and sedimentation—Operating cost (concluded)	340
Table 5.6	Hazardous waste incineration by liquid injection process—Variable costs	345
Table 5.6	Hazardous waste incineration by liquid injection process—Operating cost (concluded)	345
Table 5.7	Hydrolysis (for 10 wt% hydrolyzable waste)—Variable costs	349
Table 5.7	Hydrolysis (for 10 wt% hydrolyzable waste)—Operating cost (concluded)	350
Table 5.8	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Variable costs	354
Table 5.8	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Operating cost (concluded)	355
Table 5.9	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Variable costs	357
Table 5.9	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Operating cost (concluded)	358
Table 5.10	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Variable costs	360
Table 5.10	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Operating cost (concluded)	361
Table 5.11	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Variable costs	363
Table 5.11	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Operating cost (concluded)	364
Table 5.12	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Variable costs	366
Table 5.12	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Operating cost (concluded)	367
Table 5.13	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Variable costs	369
Table 5.13	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Operating cost (concluded)	370
Table 5.14	Lime neutralizer (1 wt% equivalent sulfuric acid content in waste stream)—Variable costs	374
Table 5.14	Lime neutralizer (1 wt% equivalent sulfuric acid content in waste stream)—Operating cost (concluded)	375
Table 5.15	Lime neutralizer (5 wt% equivalent sulfuric acid content in waste stream)—Variable costs	377
Table 5.15	Lime neutralizer (5 wt% equivalent sulfuric acid content in waste stream)—Operating cost (concluded)	378
Table 5.16	Lime neutralizer (10 wt% equivalent sulfuric acid content in waste stream)—Variable costs	380
Table 5.16	Lime neutralizer (10 wt% equivalent sulfuric acid content in waste stream)—Operating cost (concluded)	381
Table 5.17	Lime neutralizer (20 wt% equivalent sulfuric acid content in waste stream)—Variable costs	383
Table 5.17	Lime neutralizer (20 wt% equivalent sulfuric acid content in waste stream)—Operating costs (concluded)	384
Table 5.18	Nitrification/denitrification (for removal of 150 mg/L of nitrogen compounds)—Variable costs	389
Table 5.18	Nitrification/denitrification (for removal of 150 mg/L of nitrogen compounds)—Operating costs (concluded)	389
Table 5.19	Sequencing batch reactor process with combined waste pretreatment (old)—Variable costs	394
Table 5.19	Sequencing batch reactor process with combined waste pretreatment (old)—Operating costs (concluded)	394
Table 5.20	Steam stripping of organics from wastewater—Variable costs	399

Table 5.20	Steam stripping of organics from wastewater—Operating cost (concluded)	399
Table 5.21	Treatment costs for phosphoric acid plant wastes—Variable costs	402
Table 5.21	Treatment costs for phosphoric acid plant wastes—Operating cost (concluded)	403
Table 5.22	Trickling filter (with recycle)—Variable costs	408
Table 5.22	Trickling filter (with recycle)—Operating cost (concluded)	409
Table 5.23	Trickling filter (with single pass)—Variable costs	411
Table 5.23	Trickling filter (with single pass)—Operating cost (concluded)	412
Table 6.1	Activated sludge—Variable cost	426
Table 6.1	Activated sludge—Operating cost (concluded)	427
Table 6.2	Activated sludge by Unox pure oxygen process—Variable cost	432
Table 6.2	Activated sludge by Unox pure oxygen process—Operating cost (concluded)	432
Table 6.3	Circulating bed combustion—Variable cost	437
Table 6.3	Circulating bed combustion—Operating cost (concluded)	437
Table 6.4	Coarse particle dewatering centrifuge (for solid feed of 0.125 inch)—Variable cost	441
Table 6.4	Coarse particle dewatering centrifuge (for solid feed of 0.125 inch)—Operating cost (concluded)	441
Table 6.5	Coarse particle dewatering centrifuge (for solid feed size of 0.25 inch)—Variable cost	443
Table 6.5	Coarse particle dewatering centrifuge (for solid feed size of 0.25 inch)—Operating cost (concluded)	444
Table 6.6	Fine particle dewatering centrifuge (automatic batch)—Variable cost	448
Table 6.6	Fine particle dewatering centrifuge (automatic batch)—Operating cost (concluded)	448
Table 6.7	Fine particle centrifuge; solid bowl scroll discharge—Variable cost	452
Table 6.7	Fine particle centrifuge; solid bowl scroll discharge—Operating cost (concluded)	452
Table 6.8	Fluidized bed incineration; hazardous waste—Variable cost	456
Table 6.8	Fluidized bed incineration; hazardous waste—Operating cost (concluded)	457
Table 6.9	Fluidized bed incineration; nontoxic and noncorrosive waste (with steam generation)—Variable cost	459
Table 6.9	Fluidized bed incineration; nontoxic and noncorrosive waste (with steam generation)—Processing cost (concluded)	460
Table 6.10	Fluidized bed incineration; nontoxic and noncorrosive waste (without steam generation)—Variable cost	462
Table 6.10	Fluidized bed incineration; nontoxic and noncorrosive waste (without steam generation)—Operating cost (concluded)	463
Table 6.11	Sludge drying; direct (rotary direct dryer) (for solid feed of 15 wt% moisture content)—Variable cost	467
Table 6.11	Sludge drying; direct (rotary direct dryer) (for solid feed of 15 wt% moisture content)—Operating cost (concluded)	468
Table 6.12	Sludge drying; direct (rotary direct dryer) (for solid feed of 25 wt% moisture content)—Variable cost	470
Table 6.12	Sludge drying; direct (rotary direct dryer) (for solid feed of 25 wt% moisture content)—Operating cost (concluded)	471
Table 6.13	Sludge drying; direct (rotary direct dryer) (for solid feed of 50 wt% moisture content)—Variable cost	473
Table 6.13	Sludge drying; direct (rotary direct dryer) (for solid feed of 50 wt% moisture content)—Operating cost (concluded)	474
Table 6.14	Air-activated sludge with trickling filter—Variable cost	479
Table 6.14	Air-activated sludge with trickling filter—Operating cost (concluded)	479
Table 6.15	Oxygen-activated sludge with trickling filter—Variable cost	481
Table 6.15	Oxygen-activated sludge with trickling filter—Operating cost (concluded)	482
Table 6.16	Rotary kiln incineration—Variable cost	486
Table 6.16	Rotary kiln incineration—Operating cost (concluded)	487
Table 6.17	General key design parameters for SBR	493
Table 6.18	General SBR sizes w.r.t. flow rates of wastewater	494
Table 6.19	Sequencing batch reactor—Variable cost	494

Table 6.19	Sequencing batch reactor—Operating cost (concluded)	495
Table 6.20	Characterizations of different types of filtration options	499
Table 6.21	Ultrafiltration—Variable cost	500
Table 6.21	Ultrafiltration—Operating cost (concluded)	501
Table 6.22	Ammonia stripper—Variable cost	505
Table 6.22	Ammonia stripper—Operating cost (concluded)	506
Table 6.23	Ultraviolet disinfection—Variable cost	510
Table 6.23	Ultraviolet disinfection—Operating cost (concluded)	511
Table 6.24	Ozonation system (30 ppm ozone usage)—Variable cost	516
Table 6.24	Ozonation system (30 ppm ozone usage)—Operating cost (concluded)	516
Table 6.25	Typical loading rates and performance ranges for different applications	520
Table 6.26	Comparison of D2 continuous sand filtration with microfiltration	523
Table 6.27	Continuous deep sand filtration—Variable cost	527
Table 6.27	Continuous deep sand filtration—Operating cost (concluded)	528
Table B-1	Conventional and nonconventional pollutant categories	531
Table B-2	EPA's priority pollutant list	532
Table B-3	Common analyses to characterize raw water	534
Table B-4	Secondary maximum contaminant levels	535
Table B-5	Additional reasonable water quality goals	535

Figures

Figure 1.1	Schematic of conventional activated sludge process (top) and external membrane bioreactor (bottom)	34
Figure 1.2	Alternative membrane bioreactors	40
Figure 1.3	Treated wastewater disposal—A reversal of priorities	64
Figure 1.4	Treatment processes commonly used in water reclamation	65
Figure 2.1	Global water equipment CAPEX forecast (2013–18)	74
Figure 2.2	Total forecast spending on industrial water systems (2013–18)	75
Figure 2.3	Engineered unit processes and operations	85
Figure 3.1	Projected global industrial water treatment—CAPEX spending by technology type (2013–20)	99
Figure 3.2	Global spending on water and wastewater treatment technologies by industry segment (2015)	100
Figure 3.3	Projected global biotreatment technologies—CAPEX spending by industry sector (2013–20)	101
Figure 3.4	Projected global dissolved solids removal—CAPEX spending by technology (2013–20)	102
Figure 3.5	Industrial water technologies—CAPEX spending by end-use treatment type	103
Figure 3.6	Industrial water use by industry sector	104
Figure 3.7	Projected global W&WWT technologies—CAPEX spending by industry segment (2015)	104
Figure 3.8	NRDC pipeline of upcoming water/wastewater PPP contracts in China	113
Figure 3.9	Wastewater treatment capacity versus wastewater produced in India	114
Figure 4.1	Conventional activated sludge process alternatives—Process flow schematics	118
Figure 4.2	Typical denitrification process block flow schematic	122
Figure 4.3	Upflow continuous filter	124

Figure 4.4	Upflow biologically active filter	125
Figure 4.5	Internally submerged membrane bioreactor	131
Figure 4.6	Membrane bioreactor with a membrane filtration unit sidestream	131
Figure 4.7	Moving bed membrane bioreactor	132
Figure 4.8	Fluidized bed biofilm reactor	133
Figure 4.9	Membrane bioreactor filtration factors	135
Figure 4.10	Sustainable water management systems for refineries	138
Figure 4.11	Desalter process flow schematic	144
Figure 4.12	Hydrocarbon waste generation during wastewater treatment	150
Figure 4.13	Communal biosolids generation, treatment, and disposal	158
Figure 4.14	Pasteurization vessels	162
Figure 4.15	Generalized sludge processing operations alternatives	164
Figure 4.16	Conventional sewage treatment process flow schematic	166
Figure 4.17	Schematic diagram of primary sedimentation of wastewater designed for induced flocculation	168
Figure 4.18	Generalized block flow diagram for sludge processing	169
Figure 4.19	Sludge thickening by gravity	171
Figure 4.20	DAF systems with and without recycle	173
Figure 4.21	Gravity belt sludge thickener	175
Figure 4.22	Rotary drum thickener process flow schematic	176
Figure 4.23	Secondary wastewater treatment—Activated sludge	179
Figure 4.24	Secondary wastewater treatment—Schematic diagram of a completely mixed activated sludge process	181
Figure 4.25	Conventional wastewater treatment with anaerobic sludge digestion	189
Figure 4.26	Anaerobic digestion process stages	190
Figure 4.27	Sludge digestion tank	190
Figure 4.28	Alternative configurations of anaerobic digesters	195
Figure 4.29	Configurations of sludge digesters in two-stage digestion systems	196
Figure 4.30	Secondary wastewater treatment—Trickling filter	197
Figure 4.31	Enclosed trickling filter system	198
Figure 4.32	Single-pass trickling filter–based wastewater	199
Figure 4.33	Schematic diagram of a rotating biological contactor treatment system	201
Figure 4.34	General bioreactor system selection criteria—Decision chart	204
Figure 4.35	Commercially available and viable bioreactor configurations	205
Figure 4.36	Integrated fixed-film activated sludge (IFAS) system	206
Figure 4.37	Anaerobic biological treatment	212
Figure 4.38	The Fuchs system	216
Figure 4.39	The Thieme system	217
Figure 4.40	The Limus system	217
Figure 4.41	Unconfined and confined gas injection mixing systems	225
Figure 4.42	Unconfined and confined gas injection mixing systems (second version)	226
Figure 4.43	Mechanical pumping mixing systems	226
Figure 4.44	Slow-speed mechanical stirring systems	227
Figure 4.45	Mechanical stirring with internal draft tubes	227
Figure 4.46	Forward versus reverse osmosis	231
Figure 4.47	Forward osmosis process flow schematic	232
Figure 4.48	Desalination using forward osmosis	234
Figure 4.49	Forward osmosis—Use of alternative draw solutions	235
Figure 4.50	Forward osmosis—Evaporative cooling water makeup supply	236
Figure 4.51	Use of forward osmosis for desalination	238
Figure 4.52	SBR process sequence	240
Figure 4.53	A typical three-tank SBR system	241
Figure 4.54	Composting process operations	247
Figure 4.55	Belt filter press	250

Figure 4.56	Composting with windrows	252
Figure 4.57	Tunnel composting process flow schematic	256
Figure 4.58	Tunnel composting process system	257
Figure 4.59	Direct two-tier biosolids/sludge dryer systems	260
Figure 4.60	Natural sludge drying—Conventional sand drying bed	261
Figure 4.61	Indirect rotating sludge dryer schematic	262
Figure 4.62	Grate-fired combustion in a multiple hearth furnace	265
Figure 4.63	Treatment zones in a multiple hearth furnace	265
Figure 4.64	Fluidized bed sludge incinerator	267
Figure 4.65	Fluidized bed sludge incinerator—Hot windbox design	268
Figure 4.66	Alternative sludge gasification configurations	271
Figure 4.67	Thermal energy gasification system—Simplified block flow diagram	272
Figure 4.68	Sludge gasification generic process flow diagram	273
Figure 4.69	Kopf gasification process	275
Figure 4.70	Modern landfill	281
Figure 4.71	Hazardous waste landfill leachate treatment process	285
Figure 5.1	Activated carbon adsorption for liquid stream (Module 5.1)	309
Figure 5.2	Activated carbon adsorber for liquid stream—Cost contributions	313
Figure 5.2	Activated carbon adsorber for liquid stream—Total processing cost (continued)	313
Figure 5.2	Activated carbon adsorber for liquid stream—Total fixed capital (concluded)	314
Figure 5.3	Aeration for drinking water (Module 5.2)	316
Figure 5.4	Chemical waste precipitation system (Module 5.3)	318
Figure 5.5	Chemical waste precipitation system (residence time two hours)—Cost contributions	322
Figure 5.5	Chemical waste precipitation system (residence time two hours)—Total processing cost (continued)	323
Figure 5.5	Chemical waste precipitation system (residence time two hours)—Total fixed capital (concluded)	323
Figure 5.6	Clarifier or thickener (Module 5.4)	324
Figure 5.7	Dissolved air flotation (Module 5.5)	326
Figure 5.8	Dissolved air flotation—Cost contributions	330
Figure 5.8	Dissolved air flotation—Total processing cost (continued)	330
Figure 5.8	Dissolved air flotation—Total fixed capital (concluded)	331
Figure 5.9	Facultative lagoon (Module 5.6)	331
Figure 5.10	Facultative lagoon—Cost contributions	336
Figure 5.10	Facultative lagoon—Total processing costs (continued)	336
Figure 5.10	Facultative lagoon—Total fixed capital (concluded)	337
Figure 5.11	Focculation and sedimentation (Module 5.7)	337
Figure 5.12	Focculation and sedimentation—Cost contribution	341
Figure 5.12	Focculation and sedimentation—Total processing cost (continued)	341
Figure 5.12	Focculation and sedimentation—Total fixed capital (concluded)	342
Figure 5.13	Hazardous waste incineration by liquid injection (Module 5.8)	342
Figure 5.14	Hazardous waste incineration by liquid injection process—Cost contributions	346
Figure 5.14	Hazardous waste incineration by liquid injection process—Total processing cost (continued)	346
Figure 5.14	Hazardous waste incineration by liquid injection process—Total fixed capital (concluded)	347
Figure 5.15	Hydrolysis (Module 5.9)	347
Figure 5.16	Hydrolysis (for 10 wt% hydrolyzable waste)—Cost contributions	351
Figure 5.16	Hydrolysis (for 10 wt% hydrolyzable waste)—Processing costs (continued)	351
Figure 5.16	Hydrolysis (for 10 wt% hydrolyzable waste)—Total fixed capital (concluded)	352
Figure 5.17	Ion exchange (Modules 5.10a-f)	352
Figure 5.18	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Cost contribution	356

Figure 5.18	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total processing cost (continued)	356
Figure 5.18	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total fixed capital (concluded)	357
Figure 5.19	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Cost contribution	359
Figure 5.19	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total processing cost (continued)	359
Figure 5.19	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total fixed capital (concluded)	360
Figure 5.20	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Cost contribution	362
Figure 5.20	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total processing cost (continued)	362
Figure 5.20	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 1 lb/1,000 lb flow)—Total fixed capital (concluded)	363
Figure 5.21	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Cost contributions	365
Figure 5.21	Ion exchange system for anion exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Total fixed capital (concluded)	366
Figure 5.22	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Cost contributions	368
Figure 5.22	Ion exchange system for hydrogen cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Total fixed capital (concluded)	369
Figure 5.23	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Cost contributions	371
Figure 5.23	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Total processing cost (continued)	371
Figure 5.23	Ion exchange system for sodium cation exchanger (for ion concentration equivalent CaCO_3 of 20 lb/1,000 lb flow)—Total fixed capital (concluded)	372
Figure 5.24	Lime neutralizer (Module 5.11 a-d)	372
Figure 5.25	Lime neutralizer (1 wt% equivalent sulfuric acid content in waste stream)—Cost contribution	376
Figure 5.25	Lime neutralizer (1 wt% equivalent sulfuric acid content in waste stream)—Total processing cost (continued)	376
Figure 5.25	Lime neutralizer (1 wt% equivalent sulfuric acid content in waste stream)—Total fixed capital (concluded)	377
Figure 5.26	Lime neutralizer (5 wt% equivalent sulfuric acid content in waste stream)—Cost contribution	379
Figure 5.26	Lime neutralizer (5 wt% equivalent sulfuric acid content in waste stream)—Total processing cost (continued)	379
Figure 5.26	Lime neutralizer (5 wt% equivalent sulfuric acid content in waste stream)—Total fixed capital (concluded)	380
Figure 5.27	Lime neutralizer (10 wt% equivalent sulfuric acid content in waste stream)—Cost contributions	382
Figure 5.27	Lime neutralizer (10 wt% equivalent sulfuric acid content in waste stream)—Total processing cost (continued)	382
Figure 5.27	Lime neutralizer (10 wt% equivalent sulfuric acid content in waste stream)—Total fixed capital (concluded)	383
Figure 5.28	Lime neutralizer (20 wt% equivalent sulfuric acid content in waste stream)—Cost contributions	385
Figure 5.28	Lime neutralizer (20 wt% equivalent sulfuric acid content in waste stream)—Total processing cost (continued)	385
Figure 5.28	Lime neutralizer (20 wt% equivalent sulfuric acid content in waste stream)—Total fixed capital (concluded)	386

Figure 5.29	Nitrification/denitrification (Module 5.12)	386
Figure 5.30	Nitrification/denitrification (for removal of 150 mg/L of nitrogen compounds)— Costs contributions	390
Figure 5.30	Nitrification/denitrification (for removal of 150 mg/L of nitrogen compounds)—Total processing cost (continued)	390
Figure 5.30	Nitrification/denitrification (for removal of 150 mg/L of nitrogen compounds)—Total fixed capital (concluded)	391
Figure 5.31	Sequencing batch reactor mixed waste process with pretreatment (Module 5.13)	391
Figure 5.32	Sequencing batch reactor process with combined waste pretreatment (old)—Costs contributions	395
Figure 5.32	Sequencing batch reactor process with combined waste pretreatment (old)—Total processing cost (continued)	395
Figure 5.32	Sequencing batch reactor process with combined waste pretreatment (old)—Total fixed capital (concluded)	396
Figure 5.33	Steam/flue gas stripping (Module 5.14)	396
Figure 5.34	Steam stripping of organics from wastewater—Costs contributions	400
Figure 5.34	Steam stripping of organics from wastewater—Total processing cost (continued)	400
Figure 5.34	Steam stripping of organics from wastewater—Total fixed capital (concluded)	401
Figure 5.35	Treatment of phosphoric acid plant wastes (Module 5.15)	401
Figure 5.36	Treatment costs for phosphoric acid plant wastes—Costs contributions	404
Figure 5.36	Treatment costs for phosphoric acid plant wastes—Total processing cost (continued)	404
Figure 5.36	Treatment costs for phosphoric acid plant wastes—Total fixed capital (concluded)	405
Figure 5.37	Trickling filter (Module 5.16a,b)	405
Figure 5.38	Trickling filter (with recycle)—Costs contributions	410
Figure 5.38	Trickling filter (with recycle)—Total processing cost (continued)	410
Figure 5.38	Trickling filter (with recycle)—Total fixed capital (concluded)	411
Figure 5.39	Trickling filter (with single pass)—Costs contributions	413
Figure 5.39	Trickling filter (with single pass)—Total processing cost (continued)	413
Figure 5.39	Trickling filter (with single pass)—Total fixed capital (concluded)	414
Figure 6.1	Anaerobic digestion—Anaerobic digestion takes place in an enclosed tank	415
Figure 6.2	Screw press—A recent development in sludge dewatering equipment, used primarily in the pulp and paper industry	418
Figure 6.3	Activated sludge (Module 6.1)	424
Figure 6.4	Activated sludge—Cost contributions	428
Figure 6.4	Activated sludge—Total processing cost (continued)	428
Figure 6.4	Activated sludge—Total fixed capital (concluded)	429
Figure 6.5	Pure oxygen-activated sludge (Module 6.2)	429
Figure 6.6	Activated sludge by Unox pure oxygen process—Cost contributions	433
Figure 6.6	Activated sludge by Unox pure oxygen process—Total processing cost (continued)	433
Figure 6.6	Activated sludge by Unox pure oxygen process—Total fixed capital (concluded)	434
Figure 6.7	Circulating bed combustion (Module 6.3)	434
Figure 6.8	Circulating bed combustion—Cost contributions	438
Figure 6.8	Circulating bed combustion—Processing cost (continued)	438
Figure 6.8	Circulating bed combustion—Total fixed capital (concluded)	439
Figure 6.9	Coarse particle dewatering centrifuge (Module 6.4a,b)	439
Figure 6.10	Coarse particle dewatering centrifuge (for solid feed of 0.125 inch)—Cost contributions	442
Figure 6.10	Coarse particle dewatering centrifuge (for solid feed of 0.125 inch)—Cost contributions (concluded)	443
Figure 6.11	Coarse particle dewatering centrifuge (for solid feed size of 0.25 inch)—Cost contributions	445
Figure 6.11	Coarse particle dewatering centrifuge (for solid feed size of 0.25 inch)— Processing cost (continued)	445

Figure 6.11	Coarse particle dewatering centrifuge (for solid feed size of 0.25 inch)—Total fixed capital (concluded)	446
Figure 6.12	Fine particle centrifuge (automatic batch—Module 6.5)	446
Figure 6.13	Fine particle dewatering centrifuge (automatic batch)—Cost contributions	449
Figure 6.13	Fine particle dewatering centrifuge (automatic batch)—Processing cost (continued)	449
Figure 6.13	Fine particle dewatering centrifuge (automatic batch)—Processing cost (concluded)	450
Figure 6.14	Fine particle centrifuge; solid bowl (scroll discharge—Module 6.6)	450
Figure 6.15	Fine particle centrifuge; solid bowl scroll discharge—Cost contributions	453
Figure 6.15	Fine particle centrifuge; solid bowl scroll discharge—Total processing cost (continued)	453
Figure 6.15	Fine particle centrifuge; solid bowl scroll discharge—Total fixed capital (concluded)	454
Figure 6.16	Fluidized bed incineration (Module 6.7a-c)	454
Figure 6.17	Fluidized bed incineration; hazardous waste—Cost contributions	458
Figure 6.17	Fluidized bed incineration; hazardous waste—Total processing cost (continued)	458
Figure 6.17	Fluidized bed incineration; hazardous waste—Total fixed capital (concluded)	459
Figure 6.18	Fluidized bed incineration; nontoxic and noncorrosive waste (with steam generation)—Cost contributions	461
Figure 6.18	Fluidized bed incineration; nontoxic and noncorrosive waste (with steam generation)—Total processing cost (continued)	461
Figure 6.18	Fluidized bed incineration; nontoxic and noncorrosive waste (with steam generation)—Total fixed capital (concluded)	462
Figure 6.19	Fluidized bed incineration; nontoxic and noncorrosive waste (without steam generation)—Cost contributions	464
Figure 6.19	Fluidized bed incineration; nontoxic and noncorrosive waste (without steam generation)—Operating cost (continued)	464
Figure 6.19	Fluidized bed incineration; nontoxic and noncorrosive waste (without steam generation)—Total fixed capital (concluded)	465
Figure 6.20	Sludge drying—Rotary direct dryer (Module 6.8a,c)	465
Figure 6.20	Sludge drying; direct (rotary direct dryer) (for solid feed of 15 wt% moisture content)—Cost contributions	469
Figure 6.20	Sludge drying; direct (rotary direct dryer) (for solid feed of 15 wt% moisture content)—Total processing cost (continued)	469
Figure 6.20	Sludge drying; direct (rotary direct dryer) (for solid feed of 15 wt% moisture content)—Total fixed capital (concluded)	470
Figure 6.21	Sludge drying; direct (rotary direct dryer) (for solid feed of 25 wt% moisture content)—Cost contributions	472
Figure 6.21	Sludge drying; direct (rotary direct dryer) (for solid feed of 25 wt% moisture content)—Total processing cost (continued)	472
Figure 6.21	Sludge drying; direct (rotary direct dryer) (for solid feed of 25 wt% moisture content)—Total fixed capital (concluded)	473
Figure 6.22	Sludge drying; direct (rotary direct dryer) (for solid feed of 50 wt% moisture content)—Cost contributions	475
Figure 6.22	Sludge drying; direct (rotary direct dryer) (for solid feed of 50 wt% moisture content)—Total processing cost (continued)	475
Figure 6.22	Sludge drying; direct (rotary direct dryer) (for solid feed of 50 wt% moisture content)—Total fixed capital (concluded)	476
Figure 6.23	Trickling filter-based biological oxidation (air-/oxygen-activated sludge—Module 6.9a,b)	476
Figure 6.24	Air-activated sludge with trickling filter—Cost contributions	480
Figure 6.24	Air-activated sludge with trickling filter—Total processing cost (continued)	480
Figure 6.24	Air-activated sludge with trickling filter—Total fixed capital (concluded)	481
Figure 6.25	Oxygen-activated sludge with trickling filter—Cost contributions	483
Figure 6.25	Air-activated sludge with trickling filter—Total processing cost (continued)	483

Figure 6.25	Oxygen-activated sludge with trickling filter—Total fixed capital (concluded)	484
Figure 6.26	Rotary kiln incineration (Module 6.10)	484
Figure 6.27	Rotary kiln incineration—Cost contributions	488
Figure 6.27	Rotary kiln incineration—Total processing cost (continued)	488
Figure 6.27	Rotary kiln incineration—Total fixed capital (concluded)	489
Figure 6.28	Sequencing batch reactor (Module 6.11)	489
Figure 6.29	General set up of SBR simulation in SuperPro 9.0	491
Figure 6.29	General set up of SBR simulation in SuperPro 9.0	492
Figure 6.30	SBR simulation in SuperPro 9.0	493
Figure 6.31	Sequencing batch reactor—Cost contributions	496
Figure 6.31	Sequencing batch reactor—Total processing cost (continued)	496
Figure 6.31	Sequencing batch reactor—Total fixed capital (concluded)	497
Figure 6.32	Microfiltration and ultrafiltration (Module 6.12)	497
Figure 6.33	Ultrafiltration—Cost contributions	502
Figure 6.33	Ultrafiltration—Total processing cost (continued)	502
Figure 6.33	Ultrafiltration—Total fixed capital (concluded)	503
Figure 6.34	Ammonia stripping (Module 6.13)	503
Figure 6.35	Ammonia stripper—Cost contributions	507
Figure 6.35	Ammonia stripper—Total processing cost (continued)	507
Figure 6.35	Ammonia stripper—Total fixed capital (concluded)	508
Figure 6.36	Ultraviolet disinfection (Module 6.14)	508
Figure 6.37	Ultraviolet disinfection—Cost contributions	512
Figure 6.37	Ultraviolet disinfection—Total processing cost (continued)	512
Figure 6.37	Ultraviolet disinfection—Total fixed capital (concluded)	513
Figure 6.38	Ozonation system (ozone disinfection (Module 6.15)	513
Figure 6.39	Ozonation system (30 ppm ozone usage)—Cost contributions	517
Figure 6.39	Ozonation system (30 ppm ozone usage)—Total processing cost (continued)	517
Figure 6.39	Ozonation system (30 ppm ozone usage)—Total fixed capital (concluded)	518
Figure 6.40	Continuous upflow deep sand filtration (Module 6.16)	518
Figure 6.41	Ozonation system (30 ppm ozone usage)—Cost contributions	529
Figure 6.41	Ozonation system (30 ppm ozone usage)—Total processing cost (continued)	529
Figure 6.41	Ozonation system (30 ppm ozone usage)—Total fixed capital (concluded)	530

IHS Customer Care:

Americas: +1 800 IHS CARE (+1 800 447 2273); CustomerCare@ihs.com

Europe, Middle East, and Africa: +44 (0) 1344 328 300; Customer.Support@ihs.com

Asia and the Pacific Rim: +604 291 3600; SupportAPAC@ihs.com

