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Municipal Wastewater Treatment Technology Matrices

USAID

U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

June 18, 1998

Dear Colleagues:

The United States Agency for International Development (USAID) and the Environmental Export Council (EEC) are pleased to present the enclosed document, *Municipal Wastewater Technology Matrices*, prepared by Concurrent Technologies Corporation. We believe that the manual will serve as a valuable tool for municipal decision-makers in the process of designing, implementing, and financing wastewater treatment systems. The matrices provide information related to operations, performance, technical requirements, and costs of various wastewater treatment options and should be useful in assisting with the selection of the most appropriate technology for individual municipal systems.

The document was prepared in response to needs identified by the Latin America Water Task Force (LAWTF), a group of experts who began convening in 1995 to examine issues surrounding privatization of water and wastewater treatment systems in the region, but particularly in Brazil. The LAWTF's technical, regulatory, and financial work is one product of the Latin America Initiative for Environmental Technology (LA-IET), a collaborative effort between EEC and USAID to increase awareness of, and investment in, clean environmental technologies and processes. Under the LA-IET, a number of partnerships and initiatives have been established to better coordinate public, private, and nongovernmental programs in support of these goals.

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APPENDICES

1.0 LATIN AMERICAN WATER TASK FORCE - LAWTF

To maximize the benefits from increasing globalization, economic growth, and heightened environmental awareness, the Environmental Export Council (EEC) is working in collaboration with the United States Agency for International Development (USAID) on a program called the Latin American Initiative for Environmental Technology (LA-IET). The LA-IET acts as an umbrella program for activities in several different regions of Latin America. The primary objective of all programs falling under the LA-IET is to increase the role of the private sector in environmentally sustainable development. This is achieved by raising private sector awareness of appropriate environmental technologies and by encouraging private sector investment in clean technologies and processes. Under the LA-IET, these goals are achieved by forming innovative partnerships which leverage the resources of government, the private sector, industry associations, and non-governmental organizations. The result is a coordinated effort between the public and private sectors toward the mutually beneficial objective of environmentally sustainable economic growth and development.

Over the past four years the EEC has initiated a number of programs specifically targeted at increasing the level of U.S. private investment in municipal wastewater treatment privatization and concessions in Brazil. To address this goal, the EEC established the *Latin American Water Task Force* (LAWTF). The LAWTF is a small group of select U.S. and Brazilian experts in the areas of project finance, wastewater treatment technology, and federal and contract law that collaborates with the EEC, USAID, and the Department of Commerce to overcome barriers to financing, implementing, and sustaining municipal wastewater treatment concessions and privatization in Latin America.

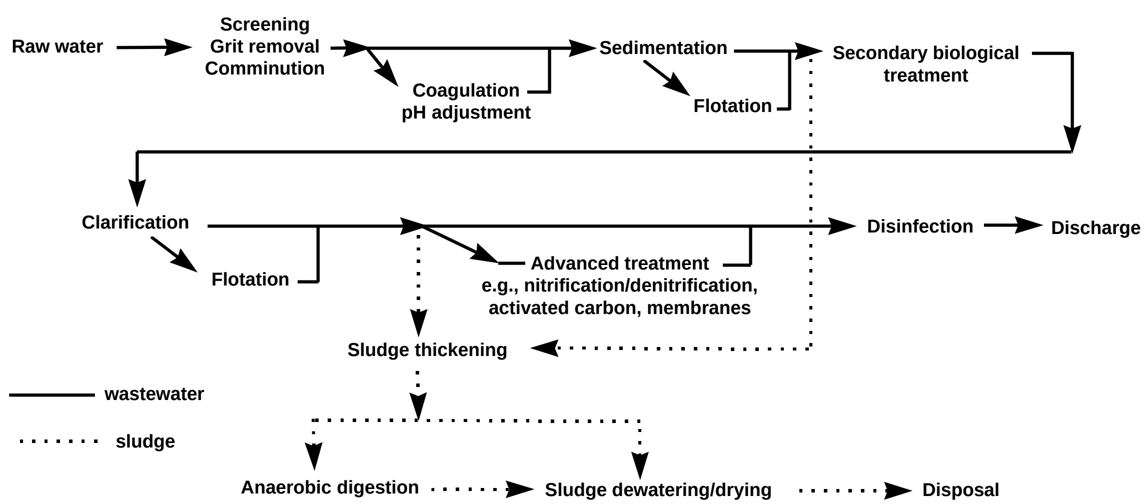
The purpose of the LAWTF is to create the necessary conditions for long-term private portfolio investment in municipal wastewater projects in Latin America. To this end, the EEC has recruited private and public sector professionals who have worked for years on a pro-bono basis, to develop regulatory, technical, and financial recommendations for implementing water and wastewater treatment privatization programs. Participants have included mayors of the states of São Paulo, Rio de Janeiro, Mato Grosso do Sul, and Minas Gerais, and representatives from BNDES (Brazil's national development bank), U.S. Export-Import Bank, Inter-American Development Bank, International Finance Corporation, Concurrent Technologies Corporation (CTC), CG/LA Infrastructure, and others.

The meetings of the LAWTF have also produced a series of documents focused on legal, technical, and financial issues for concessions designed to attract international capital to support the long term viability of projects. The EEC contracted CTC to produce the latest of these documents, a matrix presenting descriptions and comparisons of available municipal wastewater treatment technologies based on their performance, requirements and cost. This document is intended to support the work of the LAWTF and assist municipal officials and other decision makers as they consider various municipal wastewater treatment options according to their needs.

2.0 DEVELOPMENT OF MATRICES

This document is based on available literature and *CTC* expertise. Outside reviewer comments were also incorporated.

Analysis of municipal wastewater treatment plant designs indicates that treatment consists of a number of discrete operations that are widely if not universally employed in plants that serve medium to large sized urban communities (tens of thousands population and up) while meeting modern U.S. effluent standards. In addition, a variety of operations are frequently used or considered in addition to the basic steps. Figure 1 is a generic flow diagram for municipal wastewater treatment that notes these operations. The diagram is a simplification that does not show all steps or flows of materials (for instance, addition of treatment chemicals, aeration, return sludge, or methane recovery).



Note: The flow diagram is divided into branches to indicate alternative or optional steps.
Source: *CTC*

Figure 1. Generic Flow Diagram for Municipal Wastewater Treatment

A set of matrices was developed rather than a single matrix to compare wastewater treatment technologies. The reason for this is that some operations are not comparable; they are designed to perform different functions. For instance, disinfection technologies are not comparable to sedimentation technologies. The matrices feature comparable technologies and in some cases will be nested. For example, different aerobic biological treatment technologies can be compared and within particular approaches, say, the activated sludge process, several variations are comparable. Information on relative advantages and disadvantages of the technological options was obtained. The pertinent parameters to include in each matrix vary with the operation being described. In some cases quantitative data are available. In other cases, only semiquantitative or qualitative data are available. Often cost and performance will depend on individual site or design factors that may not be generalized.

Several assumptions define the parameters of the study. It is assumed that toxic or refractory wastewater containing metals, organic solvents, and other materials damaging to conventional municipal wastewater treatment works are adequately pretreated by the industries that generate them. Therefore, technologies for treating such effluents are not included. It is assumed that a wastewater conveyance infrastructure is in place and, furthermore, that storm drainage does not enter the sanitary sewer system. Thus, technologies for sewerage collection are not considered. It is assumed that municipalities with population levels in the tens of thousands or above will be the main users of the document. Small package wastewater treatment systems and septic tanks are not discussed. Finally, the study focused on available processes rather than technologies in the research and development phase.

3.0 MUNICIPAL WASTEWATER TREATMENT TECHNOLOGIES

Descriptions and matrix elements of municipal wastewater treatment technologies are presented in the following sections.

3.1 Physical Treatment Technologies

Physical treatment technologies are used at various stages of municipal wastewater treatment. Typically, screens, grit chambers, and comminution (grinding) are the first steps in wastewater treatment. Sedimentation, sometimes supplemented by flotation is used to remove suspended particles in primary treatment. Aeration may be integral to aerobic biological treatment. Sedimentation, filtration, flotation, or other physical approaches may also be used to clarify effluents from biological wastewater treatment. Several physical treatment technologies are used to thicken and dewater sludges (these are described in section 3.6.1). Finally, filtration or adsorption may be employed as advanced treatment to provide very high quality water for final discharge.

The paragraphs below describe each of the selected physical wastewater and sludge treatment technologies (in alphabetical order). The descriptions also note factors that may be important to consider in selecting and designing wastewater treatment facilities. Cost considerations are also provided where available.

Tables 2 through 5 provide more specific design and performance parameters of the selected technology types. Data on attributes describing wastewater flow, treatment, equipment and cost are provided. Each attribute is defined in Appendix E.

Table 2 provides detailed design information on screening and comminuting/grinding technologies. Tables 3, 4, and 5 provide data on grit removal, clarification/sedimentation, and flotation technologies, respectively. Subjective information is also provided for some parameters, where (+++) is most favorable, (++) is intermediate, and (+) is the least favorable grade for the particular attribute. Justification for subjective scores is included.

3.1.1 Adsorption

Adsorption is a common technique for removing organic chemicals by means of physical adhesion of chemicals to the surface of a solid. A common adsorbent is granular activated carbon (GAC) which is very porous. In a typical GAC system, contaminated water enters the top of a vessel partially filled with adsorbent. The water trickles through the GAC and is released at the bottom. The filter eventually becomes clogged with adsorbed contaminants and must be replaced or regenerated. Regeneration can be an expensive, energy-intensive process that is usually performed off-site. Carbon filters that cannot be regenerated due to their contaminant composition must be properly managed for disposal (Masters 1991, 253-254).

3.1.2 Aeration

Aeration can be an integral part of other treatment systems such as activated sludge biological treatment. In the activated sludge system, an aeration tank receives a combination of effluent and a mass of recycled biological organisms (activated sludge). Air or oxygen is pumped into the tank and the mixture is continually agitated. After about 6 to 8 hours of agitation, the wastewater flows into a secondary tank where the solids are allowed to settle. Careful control of oxygen demand--through system design, operations, and maintenance--is required for proper treatment. By using aeration, an activated sludge system takes up considerably less land than an alternative trickling filter system with the same results. The aerated activated sludge system also has certain cost, performance, and esthetic benefits relative to trickling filters. (See section 3.3 for discussion of biological treatment options). However, they require more energy for pumps and blowers, and have higher operating costs (Masters 1991, 245-247).

3.1.3 Clarification/Sedimentation

Clarification is the physical removal of suspended solids from water. Usually sedimentation (also called settling) is used to provide primary treatment of wastewater as well as to remove suspended solids after secondary (biological) treatment. It is possible to clarify water using multimedia filtration (see section 3.1.8) or, to obtain very high quality water, microfiltration (see section 3.1.7). Floculation (see section 3.1.6) and flotation (see section 3.1.5) may be employed to assist water clarification.

A clarifier (also referred to as a settling tank or sedimentation basin) is typically a large circular, square, or rectangular tank where flow speed is reduced sufficiently to allow most of the suspended solids to settle out by gravity. Typically, detention times range from 1 to 10 hours. A longer detention time improves performance but requires a bigger and more expensive tank. Detention times of 2 to 3 hours can remove 50 to 65 percent of suspended solids and 25 to 40 percent of the biological oxygen demand (BOD) in primary treatment while generating 2500 to 3500 liters of sludge per million liters of wastewater treated. Clarifiers may also be used to settle materials following secondary (biological) treatment. Plow-like scrapers move the settled solids to a sump or hopper to be sucked out of the bottom of the tank. Skimmers remove grease and scum that float to the top of the tank. In cases where only primary treatment is performed (that is, no secondary or biological treatment occurs), effluent from the clarifier is chlorinated to destroy bacteria and help control odors (Masters 1991, 243; Outwater 1994, 10).

Primary Clarifier Design Considerations: The amount and nature of suspended solids in the primary effluent can greatly affect the performance and solids yield from dual processes. Rock filter media tend to reduce the effects of high suspended solids in the primary effluent (Water Environment Federation and American Society of Civil Engineers, 1991).

Tank Geometry - Primary and Secondary Clarifiers: Circular tanks are commonly used for plants where land area is not restrictive; performance is good with relatively simple mechanical equipment. Square tanks with center mechanisms require corner sweeps on rake arms and more complex provisions for scum removal than circular tanks. Thus, square (and rectangular) tanks require more maintenance for acceptable performance. Using common-wall construction for square and rectangular tanks minimizes space needs and offers an opportunity to reduce construction costs. Hexagonal shapes are a possible compromise (Water Environment Federation and American Society of Civil Engineers, 1991).

Tank Geometry and Depth for Secondary Clarifiers: Common shapes include rectangular, square, and circular. At average to peak hydraulic loads, there is no observable difference in performance of secondary clarifiers of differing shapes. Increased depth, however, generally improves performance in total suspended solids removal and recycled activated sludge concentration. Construction cost increases with depth. Most U.S. consulting firms use depths of 4 to 5 m. An overflow rate correction of 0.17 m/h for each 0.3 m of depth less than the minimum tablated value has been suggested (Water Environment Federation and American Society of Civil Engineers, 1991).

3.1.4 Comminuting/Grinding

A comminuter is a device that is used to grind large items often collected on the screens. A comminuter can grind coarse materials into pieces small enough to be left in the wastewater flow (Masters 1991, 243).

Grinding is a method of treating collected scum because it often contains other flotables such as plastics (e.g., tampon applicators). Scum, and miscellaneous flotables, are usually sent to the digester to be coprocessed with sludge. Grinding the scum and sludge reduces the particle size to the point where flotables are unrecognizable. Grinding also facilitates mixing during the digestion process that can enhance grease destruction and gas production. A two-stage sludge grinding may be necessary because some flotables, such as tampon applicators, may be difficult to grind in a single stage due to their shape (Outwater 1994, 43, 46-49).

3.1.5 Flotation

The three most common flotation processes are described as follows:

1. Dissolved air flotation (DAF): This occurs when air is injected while the wastewater is under pressure. Fine bubbles are released when the pressure is reduced in the flotation tank.
2. Air flotation: This occurs by means of aeration, typically by diffuser, at atmospheric pressure
3. Vacuum flotation: This occurs when the wastewater is saturated with air before application of a vacuum (Corbitt 1989, 6.96).

DAF is the most common method used. In DAF the fine gas bubbles attach to suspended solids causing them to float to the surface for collection and removal. DAF occurs when air is injected while the wastewater is under pressure. Fine bubbles are released when the pressure is reduced in the flotation tank. DAF is effective for removing a wide range of solids, but flotation methods have higher operating costs for power (Corbitt 1989, 6.96). However, DAF may sometimes save costs because of compact size relative to conventional gravity settling. DAF can generate thicker and more active sludges than generated by gravity settling. Higher sludge consistency results in less sludge volume which reduces sludge handling and disposal costs. Thicker and more active return sludge from DAF use in secondary clarification may allow the biological treatment unit to be sized smaller. Thus system wide cost savings may accrue. Some DAF units may require more skilled operators than alternative gravity settling systems. But automated DAF units may require only modest operator attention.

3.1.6 Flocculation

Flocculation typically follows coagulation. The flocculation tank provides a gentle agitation for approximately one-half hour. During this time, the precipitating coagulant (e.g., alum, or other precipitates if $FeCl_3$, $FeSO_4$, etc., are used) attracts colloidal particles, forming a plainly visible floc.

Mixing in the flocculation tank must be done very carefully. It must be sufficient to encourage particles to make contact with each other, enabling the floc to grow in size, but not so vigorous that fragile floc particles break apart. Mixing also helps keep the floc from settling in the tank, rather than in the sedimentation tank that follows (Masters 1991, 230-231).

3.1.7 Microfiltration

Microfiltration uses membranes with pore sizes of one micrometer or less to separate fine particles from water. Microfiltration clarifies water and other fluids by catching suspended matter and microorganisms on the surface or inside a filter while passing dissolved substances and water (Pontius 1990, 711).

3.1.8 Multimedia Filtration

Filtration is used for 1) removing suspended solids as a pretreatment for low suspended solids wastewater, or 2) following coagulation in physical chemical treatment, or 3) as a tertiary treatment following a biological wastewater treatment process. Filtration efficiency is a function of 1) the concentration and characteristics of the solids in suspension, 2) the characteristics of the filter media, and 3) the method of filter operation. Media size is an important factor in filter design. In dual media filters, the size is selected to provide 75 to 90 percent suspended solids removal through 0.46 to 0.6 meters of media depth. Table 1 shows media options.

Table 1. Filter Media Types, Materials, Sizes and Depths

Type	Material	Size (mm)	Depth (cm)
Monomedia: a. Fine b. Coarse	 a. Sand b. Anthracite coal	 0.35 to 0.60 1.3 to 1.7	 25 to 50 91 to 152
Dual	Sand, anthracite coal	0.45 to 0.6 1.0 to 1.1	25 to 30 51 to 76
Multimedia	Garnet*, sand, anthracite coal	0.25 to 0.4 0.45 to 0.55 1.0 to 1.1	5 to 10 20 to 30 46 to 61

* other materials may be used

Coarse media filters generally enable longer filter runs and can respond well to plant upset conditions. Dual media and multimedia systems have traditionally been used in potable water applications and their use has carried over into tertiary wastewater treatment. The optimum filtration rate is achieved when the filtration rate results in the maximum volume of filtrate per unit filter area while achieving an acceptable effluent quality. Higher filtration rate allows solids to penetrate the coarse media and accumulate on the fine media causing premature blinding of the fine media. A low filtration rate is insufficient to achieve good solids penetration of the coarse media. Filtration rate will also influence effluent quality depending on the nature of the particles being removed.

Improved suspended solids removal is possible by adding coagulants to the wastewater prior to filtration. Use of alum also results in precipitation and removal of phosphorus through the filter. Flocculation is not needed since the filter serves as a flocculator. Effective mixing is required prior to filtration to disperse the chemicals for either process. Since suspended solids are removed by filtration rather than by sedimentation, 25 to 50 percent less chemicals are required in many cases. For most applications, a maximum feed concentration of 100 mg/l suspended solids is used (Eckenfelder 1989, 381-385.)

3.1.9 Screening

Screening removes large floating objects such as rags, sticks, and other objects that might damage pumps or clog small pipes. Screen designs vary, but typically consist of parallel steel bars spaced anywhere from 2 to 7 cm apart, perhaps followed by a wire mesh screen with smaller openings (Masters 1991, 243).

Screening sludge and scum can effectively remove most plastics from the waste stream. Screening separates particles as a function of the size of the opening of the screen. Smaller openings collect more material but require more cleaning. To effectively clean screens high temperature washings may be required. However, the elevated temperature may result in the release of volatile organic and inorganic compounds that have bad odor (Outwater 1994, 49).

Table 2. Screening and Comminuting/Grinding Technology Attributes

Attribute Category	Technology Category: / Attribute	Screening: Trash Rack	Screening: Mechanical	Screening: Continuous	Screening: Coarse/Bar	Screening: Microscreen/ Fine Screen	Comminuting/ Grinding
Flow	Approach Velocity (m/s)	> 0.38[33]	0.60-1.2[18]	0.60-1.2[18]	0.60-1.2[1]		
	Overflow Rate ($m^3/day/m^2$)	NA	NA	NA	NA	295-585[2]	
Influent Composition	Screen Width (mm)	38-150[18]	6-38[18]	6-38[18]	12-40[14]	1-6[27]	NA
	Cut Length (mm)	NA	NA	NA	NA	NA	6-19[28]
Treatment	BOD Removal Rate (%, average)	NA	NA[5]			15-30[27]	
	TSS Removal Rate (%, average)		5-20[5]			15-30[27]	
	By-Products	screenings	screenings	screenings	screenings	screenings	solid waste
Cost Estimate (assume plant size) of 37,854 m^3/day or 10 mgd)	Capital ($1000s or low, med., high)				100[9]	500-900[15,16,26]	60-90[15,16,17]
	O&M ($1000s/yr or low, med., high)		40[9]				
	Power [35] ($1000s/yr or low, med., high)				0.9[9]		

Notes: NA = Not Applicable
TSS = Total Suspended Solids
BOD = Biological Oxygen Demand
SS = Suspended Solids
O&M = Operation and Maintenance

Power Cost Assumptions (from reference 9 for all tables): electricity = $0.02/kWh
fuel oil = $0.37/gal
gasoline = $0.60/gal

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27. WEF and ASCE, pg. 498
28. WEF and ASCE, pg. 398
29. GLUMRB, pg. 60-1 to 60-2
30. GLUMRB, "separate stage nitrification," pg. 60-2
31. GLUMRB, "extended aeration," pg. 60-2
32. GLUMRB, "conventional, step aeration, contact stabilization, and carbonaceous stage of separate stage nitrification," pg. 60-2
33. GLUMRB, pg. 50-1
34. Rittman
35. Qasim, pg. 656
36. Information from a vendor of flotation systems.

Table 3. Grit Removal Technology Attributes

	Technology Category:	Grit Removal				Relative Grades and Justification							
						Gravity [25]		Vortex [25]		Horizontal [25]		Aerated [20]	
Attribute Category	**Attribute**	**Gravity Chamber**	**Vortex System**	**Horizontal Flow**	**Aerated Chamber**	**Grade**	**Justification**	**Grade**	**Justification**	**Grade**	**Justification**	**Grade**	**Justification**
Flow	Detention Time (min.)	1[3]	0.6-0.9[22]	0.25-1.5[24]	2-5[11]								
	Handles Variability		highly effective[20]	less effective[23]	highly effective [20]	+++	• flow control not required	+++	• effective over a wide flow variation	+	• difficult to maintain velocity over a wide range of flows	+++	• wide flow range
	Approach Velocity (m/s)	0.3[3]	0.6-0.9[22]	0.15-.4[24]	0.6[20]								
Treatment	BOD Removal Rate (%, average)	small[12]	small[12]	small[12]	small[12]								
	TSS Removal Rate (%, average)	small[12]	≤ 73 of fine SS[22]	small[12]	small[12]								
	By-Products	sludge	sludge	sludge	sludge								
Equipment	Ease of Operation		medium[22]	difficult[23]	medium[20]	++	• assumed simple, but some mech. parts	++	• proprietary design	+++	• assumed not to be complicated • good use history	++	• assumed based on familiarity with aeration systems
	Space Requirements	medium to high space[3]	low space[22]			+	• fairly large tanks	+++	• requires a minimum of space • 42” diameter	++	• max. depth of 1.5m x max. length of 25m	+	• max. depth of 5m x max. width 25 x max. length of 125m
	Reliability		medium reliability[22]	medium reliability[22]	medium reliability[22]	+++	• bearings and moving parts above the water line	+++	• no submerged bearing or parts that require maintenance	+	• excessive wear on submerged chain &other equipment	++	• some poor performance noted
	Robustness/ Efficiency		average robustness[22]	average to low robustness[2]		++	• area dependent • inlet baffles not able to adjust flow	++	• removes fine grit	+++	• flexibility to alter performance is possible	+++	• adapt to varying field conditions
Cost Estimate (assume plant size of 37,854 m^3/day or 10 mgd)	Capital ($1000s or low, med., high)		low to medium cost[22]	medium cost[23]	medium to high cost[20]	++	• assumed	+++	• small space and reduces construction costs	+++	• no unusual construction required	+ - ++	• reference 20
	O&M ($1000s/yr or low, med., high)		low cost[22]	high cost[23]	medium to high cost[20]	+++	• see reliability	+++	• see Reliability and Power	++	• grit removed manually	+ - ++	• additional labor required • reference 20
	Power [35] ($1000s/yr or low, med., high)		low to medium cost[22]		high cost[20]	++	• assumed there are some energy requirements for a sludge rake	+++	• energy efficient	+++	• no major equipment	+	• power consumption is higher • reference 20

Notes: NA = Not Applicable
TSS = Total Suspended Solids
BOD = Biological Oxygen Demand

Relative Grades: +++ is better than ++ which is better than +
O&M = Operation and Maintenance
SS = Suspended Solids

Table 4. Primary and Secondary Clarification/Sedimentation Technology and Design Attributes

	Technology Category:	**Primary or Secondary Sedimentation/Clarification**				**Subjective Grades and Justification by Design Geometry**					
						Rectangular/ Circular [19]		**Circular [19]**		**Stacked [19]**	
Attribute Category	**Attribute**	**Primary [A,13,21] (Class II Sed.)**	**Intermediate [B,13] (Class II Sed.)**	**Final [C,13] (Class II Sed.)**	**Final [D,13,21] (Class III Sed.)**	**Grade**	**Justification**	**Grade**	**Justification**	**Grade**	**Justification**
Flow	Detention Time (hours)	1.5-2.5[6]									
	Handles Variability					++	• flow variations are a significant problem • highly dependent on design	++	• flow variations are a significant problem • highly dependent on design	++	• flow variations are a significant problem • highly dependent on design
	Approach Velocity (m/s)	0.020-0.025[26]									
	Overflow Rate ($m^3/day/m^2$)	24-61[7,29]	24-61[7,29]	24-49[7,29]	8-33[7,30] 8-41[7,31] 8-49[7,32]						
Influent Composition	SS Loading Rate ($kg/m^2/h$)				1-5 (ext.) 3-6 (conv.)[34]						
Treatment	BOD Removal Rate (%, average)	25-40[6] 30-35[29]									
	TSS Removal Rate (%, average)	50-70[6]									
	By-Products	sludge	sludge	sludge	sludge						
Equipment	Ease of Operation					+++	• simple mechanical requirements	+++	• simple mechanical requirements	+++	• simple mechanical requirements
	Space Requirements					++	• length = 15-90m; width = 3-24m • common wall construction advantageous for small spaces	+	• diameter: 3-90m • used where land area is not restrictive	+++	• for areas where land space is limited
	Reliability	high reliability				++	• assumed	+++	• uses trouble-free sludge removal equipment	+++	• used successfully for 20 years in Japan
	Robustness					+++	• removal efficiency is better than circular design	++	• lower removal efficiency than rectangular design	++	• assumed
Cost Estimate (assume plant size of 37,854 m^3/day or 10 mgd)	Capital ($1000s or low, med., high)	520[10]				++ - +++	• if common wall construction used	+++	• thinner walls and less expensive than rectangular tanks	+++	• small space requirement • low construction cost
	O&M ($1000s/yr or low, med., high)	45[10]				+++	• few hidden submerged parts	++	• seals near bottom of clarifier require maintenance	+	• maintenance on underlying level is difficult • has confined spaces
	Power [35] ($1000s/yr or low, med., high)	2[10]									

Notes:
NA = Not Applicable
TSS = Total Suspended Solids
SS = Suspended Solids
BOD = Biological Oxygen Demand
O&M = Operation and Maintenance
Sed. = Sedimentation

Relative Grades: +++ is better than ++ which is better than +
assumed: where no information available, ++ grade assumed
ext. = preceded by extended activated sludge treatment
conv. = preceded by conventional activated sludge treatment

A = Settling basin receiving raw wastewater before biological treatment. Class II sedimentation is common to this influent

B = Settling tank between two fixed film biological processes (e.g., trickling filters), or between a fixed film process and subsequent biological aeration. Assumed Class II sedimentation.

C = Settling tank following a fixed film biological filter. Assumed Class II sedimentation

D = Settling tank following an activated sludge process. Class III sedimentation is characterized by high concentrations of SS.

Table 5. Physical Wastewater and Sludge Treatment Technologies Characteristics and Relative Grades – Flotation

	Technology Category:	Flotation		Subjective Grades and Justification			
				Dissolved Air		Vacuum	
Attribute Category	Attribute	Dissolved Air	Vacuum	Grade	Justification	Grade	Justification
Flow	Detention Time (min.)	0.5-3[8]					
	Overflow Rate ($m^3/day/m^2$)	20-325[8]	200-400[8]				
Influent Composition	SS Loading Rate ($kg/m^2/h$)	5[34]	5[34]				
Treatment	TSS Removal Rate (%, average)	> 97[34]	> 97[34]				
	BOD Removal Rate (%, range)	40-60[36]					
	By-Products	sludge	sludge				
Equipment	Ease of Operation			+++	• Quick and easy start-up and on/off operation[4]	+++	• Quick and easy start-up and on/off operation[4]
	Space Requirements			+++	• Compact process[4]	+++	• Compact process[4]
	Robustness			++	• Typically respond faster than clarifiers to changes in inlet water quality[4]	= - ++	• Less effective than DAF at removing wide range of SS[8]
Cost Estimate (assume plant size of 37,854 m^3/day or10 mgd)	Capital ($1000s or low, med., high)			+ - ++	• Lower cost than vacuum[8]	++	• High cost compared to DAF[8] but lower than rectangular and circular clarifiers[4]
	O&M ($1000s/yr or low, med., high)			+ - ++	• Lower O&M cost than vacuum, but higher than gravity settling[8]	+	• High O&M cost compared to DAF[8]; about the same cost as rect. and circular clarifiers[4]
	Power [35] ($1000s/yr or low, med., high)			+ - ++	• Lower power than vacuum, but higher than gravity settling[8]; however flotation may lower power required for sludge handling (see text sec. 4.1.5)	+	• All flotation systems have higher costs for power and chemicals than gravity setting system[8]; however flotation may lower power required for sludge handling (see text sec. 4.1.5)

Notes: NA = Not Applicable; TSS = Total Suspended Solids; BOD = Biological Oxygen Demand; O&M = Operation and Maintenance; Relative Grades: +++ is better than ++ which is better than +

References:

1. Corbitt, pg. 6.75
2. Corbitt, pg. 6.78
3. Corbitt, pg. 6.79
4. Pontius, pp. 446-448
5. Hicks, pg. 11.27
6. Tchobanoglous, pg. 473
7. Corbitt, pg. 6.89
8. Corbitt, pg. 6.97
9. Qasim, pg. 662
10. Qasim, pg. 664
11. Qasim, pg. 243
12. Qasim, pg. 257
13. Hammer, pp. 390, 393,394
14. Mays, pg. 20.21
15. Peters & Timmerhaus, pg. 163
16. Grogan/ENR, pg. 152
17. Huang, pg. 3-104
18. WEF and ASCE, pg. 391
19. WEF and ASCE, pg. 142, 450-454
20. WEF and ASCE, pg. 412-415
21. Corbitt, pp. 6.81, 6.83
22. WEF and ASCE, pg. 418
23. WEF and ASCE, pg. 421
24. WEF and ASCE, pg. 422
25. WEF and ASCE, pg. 418-422
26. WEF and ASCE, pg. 459
27. WEF and ASCE, pg. 498
28. WEF and ASCE, pg. 398
29. GLUMRB, pg. 60-1 to 60-2
30. GLUMRB, "separate stage nitrification," pg. 60-2
31. GLUMRB, "extended aeration," pg. 60-2
32. GLUMRB, "conventional, step aeration, contact stabilization, and carbonaceous stage of separate stage nitrification," pg. 60-2
33. GLUMRB, pg. 50-1
34. Rittman
35. Qasim, pg. 656
36. Information from a vendor of flotation systems.

3.2 Coagulation

Coagulating or flocculating chemicals are added to wastewater in order to increase the particle size and density of precipitated solids, therefore increasing the rate of settling. Selection of a coagulant depends on the particular precipitates to be settled. The most popular coagulant is aluminum sulfate (alum). Ferric salts are also commonly used but are more difficult to handle. Lime is also used to precipitate calcium carbonate and orthophosphate but is not considered a true coagulant. Dosage rates vary from 75 to 250 mg/l for Alum (pH 4.5 to 7.0), 35 to 200 mg/l for ferric salts (pH 4.0 to 7.0), and 150 to 500 mg/l for lime (pH 9.0 to 11.0). Table 6 presents the advantages and disadvantages of some common coagulants.

Table 6. Comparison of Coagulants

Chemical	Advantages	Disadvantages
Alum	Easy to handle and use; commonly used; less sludge than lime use	Adds dissolved solids to water; works in limited pH range, 6.8 to 7.5
Ferric chloride	Wide pH range, 4 to 11; assists sludge dewatering	Adds dissolved solids to water
Ferric sulfate	Works in two pH ranges, 4 to 6 and 8.8 to 9.2	Adds dissolved solids to water; may need to add alkalinity
Ferrous sulfate	Not as pH sensitive as lime	Adds dissolved solids to water; may need to add alkalinity
Lime	Widely used and effective; may not add dissolved solids; sludge is easily dewatered	Very pH dependent; produces large amounts of sludge; overdose can damage water quality
Polymer	Small dosage; easy to handle and use	Improper dosage may yield poor floc formation; high unit cost ($ per dry kg)

Source: Robert Corbitt, Standard Handbook of Environmental Engineering (New York: McGraw-Hill, 1989).

3.3 Biological Treatment

Biological wastewater treatment removes organic matter by biological metabolism or digestion. This may be accomplished anaerobically (without oxygen) or aerobically (with oxygen). A variety of approaches exist for both types of biological systems. Anaerobic digestion is typically used for reducing sludge volume or by industry to treat or pretreat high strength effluents. There are some systems that include elements of both aerobic and anaerobic treatment. Wastewater treatment plants typically employ aerobic biological systems to achieve what is generally called secondary treatment standards for removal of BOD and suspended solids. Some degree of nutrient removal may also occur.

3.3.1 Anaerobic Digestion

Anaerobic digestion--degradation by microorganisms without the presence of oxygen--is used to break down wastes containing high levels of fermentable organic components. Its major use in municipal wastewater treatment is to reduce the volume of excess sludge produced in primary settling and secondary biological treatment. Anaerobic digestion may also be employed prior to aerobic digestion in situations where wastewater remains high in organic and suspended solids content following primary settling.

Methane, which can be used as fuel to offset plant energy costs, is generated by anaerobic digestion. Hydrogen sulfide is produced in small amounts as are hydrogen and carbon monoxide.

Anaerobic digestors may either be *suspended growth* or *fixed film* systems. In a suspended growth system, microorganisms operate suspended in water. Fixed film systems rely on organisms attached to some sort of matrix. Major types are as follows:

1. Suspended Growth Systems
   a) Anaerobic lagoons
   b) Anaerobic contact process
   c) Anaerobic upflow blanket
2. Fixed-Growth Systems
   a) Anaerobic upflow filter (with packing)
   b) Anaerobic downflow filter (with packing)
   c) Anaerobic fluidized bed (with sand or beads as media)
3. Combination Suspended/Fixed Growth Systems.

Anaerobic digestion is a biodegradation process capable of handling high strength aqueous waste streams that would not be efficiently treated by aerobic biodegradation processes. Advantages of anaerobic systems over aerobic systems include:

1. Capability to break down some halogenated organic chemicals
2. Low production of biomass sludges that require further treatment and disposal
3. Low cost
4. Lower energy consumption
5. Generation of methane off-gas that can be recovered for energy.

However, because anaerobic bacteria have slower growth rates than aerobic bacteria, anaerobic systems may take longer than aerobic systems to recover from upset conditions. Disadvantages of anaerobic systems include:

1. Potential for shock loading of biomass and termination of biodegradation due to variations in waste stream characteristics.
2. Low throughput due to the slow biodegradation process (two processes are required)
3. Frequent requirement for further treatment of effluent prior to discharge off-site
4. Potential for odor generation with sulfur-containing wastes.

A matrix of characteristics of anaerobic, aerobic, and hybrid digestion technologies is presented in Tables 8 and 9.

3.3.2 Aerobic Biological Treatment and Hybrid Methods

Aerobic digestion is performed by microorganisms in the presence of oxygen. Usually this step will yield water meeting secondary treatment standards. Major aerobic digestion processes include activated sludge, aerobic pond and lagoon systems, tricking filters, and rotating biological contactors. These systems exist in a number of varieties. Also, there are hybrid systems, such as facultative ponds, that combine aerobic and anaerobic treatment. Along with anaerobic biological treatment technologies, aerobic and hybrid system characteristics are noted in Tables 8 and 9.

The *activated sludge* process is used primarily to remove soluble organic materials. This process--which exists in a number of varieties, some proprietary--occurs mainly in an aerated biological reactor. Continuous sludge inoculation is provided from the subsequent clarification step. This recycling extends the mean sludge residence time, giving the microorganisms present an opportunity to adapt to the available nutrients.

Activated sludge systems can only treat aqueous organic waste streams having less than 1 percent suspended solids content, and cannot tolerate shock loadings of concentrated organic materials. A proper pH (6 to 8) and sufficient dissolved oxygen (a minimum of 1 to 2 mg/l) must also be maintained in the aeration basin to support a healthy and active system. The optimum operating temperature is usually between 25 to 32°C.

Pure oxygenation is a variation of the activated-sludge process in which high purity oxygen is used instead of air for aerobic treatment. Oxygen can be supplied from on-site gas generators with liquid oxygen storage as back-up. The aeration tank is covered which helps to eliminate odors and maintain temperature in cold-weather periods.

Autothermal Thermophilic Aerobic Digestion (ATAD) systems are normally two-stage aerobic processes that operate under thermophilic temperature conditions (40° to 80°C) without supplemental heat. ATAD systems can be used in lieu of anaerobic processes for high strength effluents. Pre-stage systems also provide thermophilic digestion and are normally incorporated in the treatment process prior to conventional anaerobic digestion.

The ATAD has many benefits: a high disinfection capability, odor reduction, low space and tankage requirements, and high sludge treatment rate. It is a relatively simple technology that is easy to operate (automatic monitoring or control equipment and full-time staff are not required) and economical, particularly for small facilities. For autothermophilic conditions, waste strength must be greater than 30,000 mg chemical oxygen demand per liter (COD/l), the reactor must be insulated and covered, and a relatively efficient aeration system (transfer efficiency of approximately 12 percent) is required.

Deep shaft technology is a form of the activated sludge process. It consists of a vertical shaft about 40 to 150 m deep and 1 to 7 m diameter. Thus, the technology takes up comparatively less land than many alternatives. The pressure of water at lower depths provides higher dissolved oxygen concentrations, and, therefore, greater biological activity when influent BOD concentrations are relatively high.

Sequencing batch reactor (SBR) technology is similar to the more widely used activated sludge process. The main difference is that the five-step treatment cycle is carried out in one tank in batch mode. This provides powerful flexibility with inherent design, process, and operational advantages. SBR technology has been shown to handle greater flows and higher loads with better effluent quality than activated sludge facilities. Because only one tank is needed, capital and space requirements are less than for the activated sludge process.

Trickling or percolating biological filters are a popular alternative to the activated-sludge process. A film or slime of microorganisms lives on solid packing which loosely fills a vessel designed to permit air to enter the lower portion of the bed. Biological activity rather than physical filtration removes contaminants. Low-rate biological filters usually provide clearer, more highly nitrified effluents than activated-sludge treatment does. Also, experience has shown that filters are less sensitive to shock loads of toxic substances than activated sludge processes. However, activated-sludge units are in some respects superior to trickling biological filters. See Table 7.

Table 7. Comparisons of Trickling Filter and Activated Sludge Processes

Factor	Trickling Filter	Activated Sludge
Capital Costs	High	Low
Operating Costs	Low	High
Space Requirements	High	Low
Aeration Control	Partial	Complete
Temperature Control	Difficult	Complete
Feed Variation Sensitivity	Fairly insensitive	More sensitive
Upset Recovery	Slow	Quite rapid
Final Effluent Clarity	Good	Not as good
Fly and Odor Nuisance	High	Low

The *rotating biological contactor* (RBC) is a variation of a fixed-film aerobic reactor, such as the trickling filter. The fixed film in the case of the RBC is attached to a drum rotating at a speed of about 1 to 7 revolutions per minute through the wastewater flow. The RBC requires only 10 percent of the ground area that is needed for a trickling filter. The RBC has good resistance to sudden changes in operating conditions and offers several advantages over other types of biological treatment process. These include operational simplicity, low power requirement, and high treatment efficiency (although not as good as conventional activated sludge processes). RBC systems can be run in either batch or continuous-flow mode, and either aerobically or anerobically. Efficiency is affected by the hydraulic retention time and the rotation speed of the disks.

The *biological tower* is similar to the trickling filter, except that plastic media are used as a matrix for microbial growth. Height (up to 12 m) and high specific surface area of biological towers allow more efficient use of land. Compared to aerated lagoons, biological towers consume less energy and take up less surface area while more than doubling the mass transfer of oxygen in aerobic-treatment reactions. The towers handle COD concentrations between 1 and 12 g/l.

Facultative (aerobic-anaerobic) stabilization ponds stabilize wastes through a combination of aerobic, anaerobic, and facultative bacteria. The facultative pond is easy to operate and maintain. However, large land areas are required to maintain pond biochemical oxygen demand BOD_5 loadings in a suitable range. The facultative treatment capability of the pond for raw wastewater usually does not exceed secondary treatment. Due to the potential for odor generation, pond sites should be located away from residential sites or from any area likely to be developed for habitation (at a minimum distance of 0.4 km.) Consideration should be given to site specifics such as topography, prevailing winds, and land use.

Aerated lagoons are often modifications of overloaded facultative ponds that require aeration to supply additional oxygen for proper treatment performance.

Tertiary-maturation low-rate stabilization ponds are designed to provide polishing and seasonal nitrification of effluents from secondary treatment. The biological mechanisms involved are similar to other aerobic suspended-growth processes. A minimum detention time of 18 to 20 days is required to completely digest residual solids. Only low solids loadings can be accommodated.

In *aquatic systems*, wastewater is treated principally by bacterial metabolism and physical sedimentation as in conventional trickling filter systems. The aquatic plants themselves provide little treatment of the wastewater (although there are a few systems in which polluting chemicals may be taken up into the plant). Rather, they are a component of the aquatic environment that improves the wastewater treatment capability and/or reliability of that environment.

Aquatic plant systems can be designed and operated to accomplish a variety of wastewater treatment tasks, but design and operation are not always simple. Hyacinth systems are susceptible to cold weather and may be affected by biological methods introduced to control plant growth in the natural environment. Mosquitoes may be an important consideration in the design and operation of aquatic plant systems. Finally, although water hyacinth systems may be useful for nutrient removal, there are limits to the treatment capacity and dependability of meeting very low effluent values.

Table 8. Biological Wastewater Treatment Matrix

		Activated Sludge					Attached Biological Growth				Aerobic Ponds			Aquatic Plant Systems (Hyacinth)	
Category	**Attribute**	Conven-tional	Pure Oxygenation	Extended Aeration	Deep Shaft	Sequencing Batch Reactor	Low Rate Trickling	High Rate Trickling	Biological Tower	Rotating Bio-Contactor	Aerobic (Tertiary)	Facultative	Aerated	Non-Aerated	Aerated
Flow	Capacity (Detention time)	4-8 h[6]	2-4 h[6]	18-36 h[6] 18-24 h [10]	0.4-6.2 h [12]	2-4 h	1-4 $m^3/d/m^2$ [2 6]	8-41 $m^3/d/m^2$ [2 6]	28-122 $m^3/d/m^2$ [2 6]	0.03-0.08 $m^3/d/m^2$ [2 6]	5-20 d [6]	30-180 d [6] 20-180 d [10]	5-20 d [6] 3-20 d [10]	10-36 d [7]	4-8 d [7]
	Effect of variability	++	++	+++	+++	++++	+++	+++	++	+++	+++	+++	+++	+++	++
	Ease of expansion	++	++	++	+	++	++	++	++	+++	+++	+++	+++	+++	+++
Composition of Influent	Limits of influent (Kg BOD_5 per m^3-d)	0.4-0.8 [6]	0.8-2.4 [6]	0.15-0.25 [6]	0.1-2.0 [12]	Depends on Process	0.1-0.4 [6]	0.4-1.6 [6]	1.6-8 [6]	1.6-8 [6]	0.03-0.06 [6]	0.003-0.008 [6]	0.001-0.008 [6]	0.0006-0.001 [7]	0.002-0.004 [7]
	Effect of variability	++[3]	++	++	++	++++	+++	+++	+++	+++	+++	+++	+++	+++	+++
	Effect of characteristics	Aerobic microorganisms are affected by pH, dissolved oxygen, suspended solids, food/microorganism ratio, and temperature. [6]												Vagaries of Nature [7]	
Treatment	Soluble BOD_5 removal	80-95% [5] 85-95% [11]	80-95% [5]	80-95% [5] 90-98% [11]	86-98% [12]	80-95% [5]	80-90% [6] 70-90% [11]	65-85% [6] 75-95% [11]	40-70% [6]	80-90% [6]	80-95% [6]	75-95% [6]	80-85% [6] 80-95% [10]	56-97% [9]	85-92% [7]
	Nutrient removal											10-50%[10] P	10-20%[10] P		
	By-products produced	Waste Activated Sludge; 1000-5000 mg/L Mixed Liquor Suspended Solids (MLSS)				< 20 mg/L BOD	Waste Activated Sludge;				Effluent (continuous); Dredging (periodic)			Effluent; Dredging	
	Possibility of upgrade	++	++	++	++	+++	++	+++	++	++	+++	+++	+++	+++	+++
Equipment	Technical skill level	++++	+++++	+++	++++	+++	+++	+++	++++	++++	+	+	++	+	++
	Space requirements	++	++	+++	+	++	+++	+++	++	+++	++++	+++++	++++	+++++	++++
	Temperature requirements	Good temperature control [3]					Rate decline @<15 °C [6]; Difficult to control [3]			13-32 °C [6]	0-40 °C range; 20 °C optimum [6]			Rate decline @<10 °C [7]	
	Reliability	++++	+++	++++	++++	++++	+++	+++	+++	+++	+++++	+++++	++++	+++++	++++
	Robustness of technology	+++	+++	+++	+++	+++++	++++	++++	+++	++++	++	++	++	++	++
Cost (for 37.8 mld hydraulic load)	Capital: ($ million)	7.43		12.6				5.04				4.68	0.93		
	Operational & Maintenance (per yr)	4300 hours, $230,000						4400 hours, $80,000				0.05	0.135		
	Power (kWh per year)	2.75						see clarifier							

Note: + denotes a low value, +++++ denotes a high value

1 Metcalf and Eddy, Chapter 12
2 Metcalf and Eddy, Table 8-7
3 Noyes
4 Metcalf and Eddy, Chapter 8
5 Metcalf and Eddy, Chapter 5
6 Corbitt, Chapter 6
7 Metcalf and Eddy, Table 13-22
8 Metcalf and Eddy, Chapter 11
9 Gerheart
10 EPA/625/R-92/005
11 Ranking of Technology Options for Wastewater Treatment
12 Deep Shaft vendor literature, "Full Scale Deep Shaft Plants - Municipal"

Table 9. Biological Wastewater and Sludge Treatment Matrix

		Anaerobic Digestion		Autothermal Thermophilic
		Standard Rate (mesophilic)	High Rate (thermophilic)	Aerobic Digestion
Flow	Capacity (Detention time)	30-90 d[1]	10-20 d[1]	3/4 - 4 d[1]
	Effect of variability	Poor	Poor	Poor
	Ease of expansion	Fair	Fair	Fair
Composition	Limits of influent (BOD_5 loading)	0.5-1.6 Kg/m^3*d[1]	1.6-4.8 Kg/m^3*d[1]	1.6-4.8 Kg/m^3*d[1]
	Effect of variability	Poor[3]	Poor[3]	Poor[3]
	Effect of characteristics	pH 6.8-7.2; COD:N:P ratio @100:1:0.2; [6]		Aerobic limitations
Treatment	Limits of effluent	3-10% Solids[1]	3-10% Solids[1]	<70% Solids[1]
	Possibility of upgrade	Fair	Fair	Fair
	By-products produced	Digested Liquor, Gas (Methane)		
Equipment	Technical skill level	High	High	High
	Space requirements	Higher than high rate or ATAD	Medium	Medium
	Temperature requirements	30-38 ^oC	49-57 ^oC	45-65 ^oC
	Reliability	Good, Prone to Corrosion		
	Robustness of technology	Good	Good	Good
	Capital cost			
	Operational cost			
	Proven technology			

[1] Metcalf and Eddy, Chapter 12
[2] Metcalf and Eddy, Table 8-7
[3] Noyes, Robert, Unit Operations in Environmental Engineering
[4] Metcalf and Eddy, Chapter 8
[5] Metcalf and Eddy, Chapter 5
[6] Corbitt, Robert, Standard Handbook of Environmental Engineering, Chapter 6
[7] Metcalf and Eddy, Table 10-17
[8] Metcalf and Eddy, Chapter 11
[9] Gerheart, Robert A., Municipal Wastewater Treatment Technology, "Use of Constructed Wetlands to Treat Domestic Wastewater, City of Arcata, California", Noyes Data Corporation, Park Ridge, NJ, 1993
[10] EPA/625/R-92/005
[11] Ranking of Technology Options for Wastewater Treatment
[12] Deep Shaft vendor literature, "Full Scale Deep Shaft Plants - Municipal"

3.4 Advanced Treatment

Advanced treatment includes a variety of physical, chemical, and biological approaches for removing nutrients (e.g., nitrogen, phosphorus) and refractory (hard to digest) organic compounds. Advanced treatment, tertiary treatment, or polishing yields a high quality water as effluent.

Phosphorus and nitrogen are the main targets for nutrient removal. These nutrients are usually partially removed in typical wastewater treatment plants, but advanced methods may be required to effect very low nutrient levels in the final effluent.

The most common means of reducing the phosphorous concentration is by chemical precipitation in the existing wastewater treatment plant process. Various factors influence the effectiveness of the coagulation process such as the type of coagulant used, equipment characteristics, wastewater characteristics, quantity of coagulant added and point of addition. Chemicals used for enhancing phosphorus removal are listed in Table 10. The addition of coagulants to a specific process within the wastewater treatment plant will have advantages and disadvantages associated with it, these are presented in Table 11.

Table 10. Chemical Enhancement of Phosphorus Removal

Stage	**Chemical(s) Added**
Primary settler	Alum and polymer
	Ferric chloride and polymer
	Ferrous chloride and lime
	Lime
Flocculation basin	Alum and polymer
	Ferric chloride and polymer
	Ferrous chloride and lime
	Lime
Aeration basin	Alum
	Ferric chloride
	Sodium aluminate
Aeration and multimedia filtration	Alum
	Ferric chloride
	Sodium aluminate
Trickling filter	Alum
	Ferric chloride
Trickling filter and multemedia filtration	Alum
	Ferric chloride
Conventional secondary treatment (flocculation basin)	Alum
	Ferric Chloride
	Lime (one or two stage)

Modified from Standard Handbook of Environmental Engineering

Table 11. Chemical Addition for Phosphorus Removal at Various Treatment Steps

Level of treatment	Advantages	Disadvantages
Primary	Applicable to most plants; increased BOD and suspended-solids removal; lowest degree of metal leakage from the coagulant; lime recovery demonstrated.	Least efficient use of metal coagulant; polymer may be required for flocculation; sludge more difficult to dewater than primary sludge.
Secondary	Lowest cost; lower chemical dosage than primary; improved stability of activated sludge; polymer not required.	Overdose of metal may cause low pH toxicity; with low-alkalinity wastewaters, a pH control system may be necessary; cannot use lime because of excessive pH; inert solids added to activated-sludge mixed liquor, reducing the percentage of volatile solids.
Advanced	Lowest phosphorus effluent; most efficient metal use; lime recovery demonstrated.	Highest capital cost; highest metal leakage.

Source: Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy

Near complete removal of nutrients can only be efficiently done by combining physical, chemical, and biological processes. The level of phosphorus and nitrogen to be met in the effluent stream requires advanced treatment schemes that take advantage of all three types of processes. The approximate levels of nutrient removal for typical wastewater treatment processes are presented in Table 12. Alternatively, Table 13 notes technologies that have been specifically designed for nutrient removal and their effectiveness. Figure 2 identifies various nutrient removal processes available, most of which are described in Table 14.

Table 12. Nutrient Removal Operations

	% Nitrogen removal	% Phosphorus removal
Conventional primary treatment	5-10	10-20
Conventional secondary treatment	10-30	
Conventional activated sludge		10-25
Conventional trickling-filter		8-12
Conventional rotating biological contactors		8-12
Bacterial assimilation	30-70	
Denitrification	70-95	
Harvesting algae	50-80	
Nitrification	5-20	
Oxidation ponds	20-90	
Breakpoint chlorination	80-95	
Chemical coagulation	20-30	see metal salt and lime precip.
Carbon adsorption	20-30	10-30
Selective ion exchange	70-90	
Filtration	20-40	20-50
Flotation		50-85[1]
Air stripping	50-90	
Electrodialysis	40-50	
Reverse osmosis	80-90	90-100
Precipitation with metal salt	see chem. coagulation	70-90
Precipitation with lime	see chem. coagulation	70-90
Biological mainstream treatment		70-90
Biological sidestream treatment		70-90
Combined biological N & P removal		70-90

Modified from Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy; [1] Information from vendor of flotation systems.

Table 13. Nutrient Removal Process Efficiencies

Amount of nutrient removed	Nitrogen removal	Phosphorus removal	Nitrogen and Phosphorus removal
30% N 30% P	conventional activated sludge (10-30%)	Conventional activated sludge (10-25%)	Conventional activated sludge
80% N 80% P	MLE A2/O™ PhoStrip II™ Oxidation Ditch Biodenitro™ Simpre™ UCT and VIP	A/O™ PhoStrip™ Sequencing batch reactors (SBRs) OWASA	Modified Bardenpho™ A^2/O™ with denite filters PhoStrip II™ Biodenipho™ Operationally modified activated sludge UCT PhoStrip™
95% N 98% P	4-Stage Bardenpho™ Modified Wuhrman Dual sludge Postaeration anoxic tank with methanol Denitrification filters Fluidized bed reactors Phase isolation ditches	PhoStrip™ Chemical precipitation plus filter	Dual sludge Modified Bardenpho™ with chemicals A^2/O™ with denite filters and chemicals Three sludge with chemicals

Typical concentration of 40 mg/l nitrogen and 10 mg/l phosphorus taken as incoming wastewater
Modified from Design of Municipal Wastewater Treatment Plants , WEF/ASCE

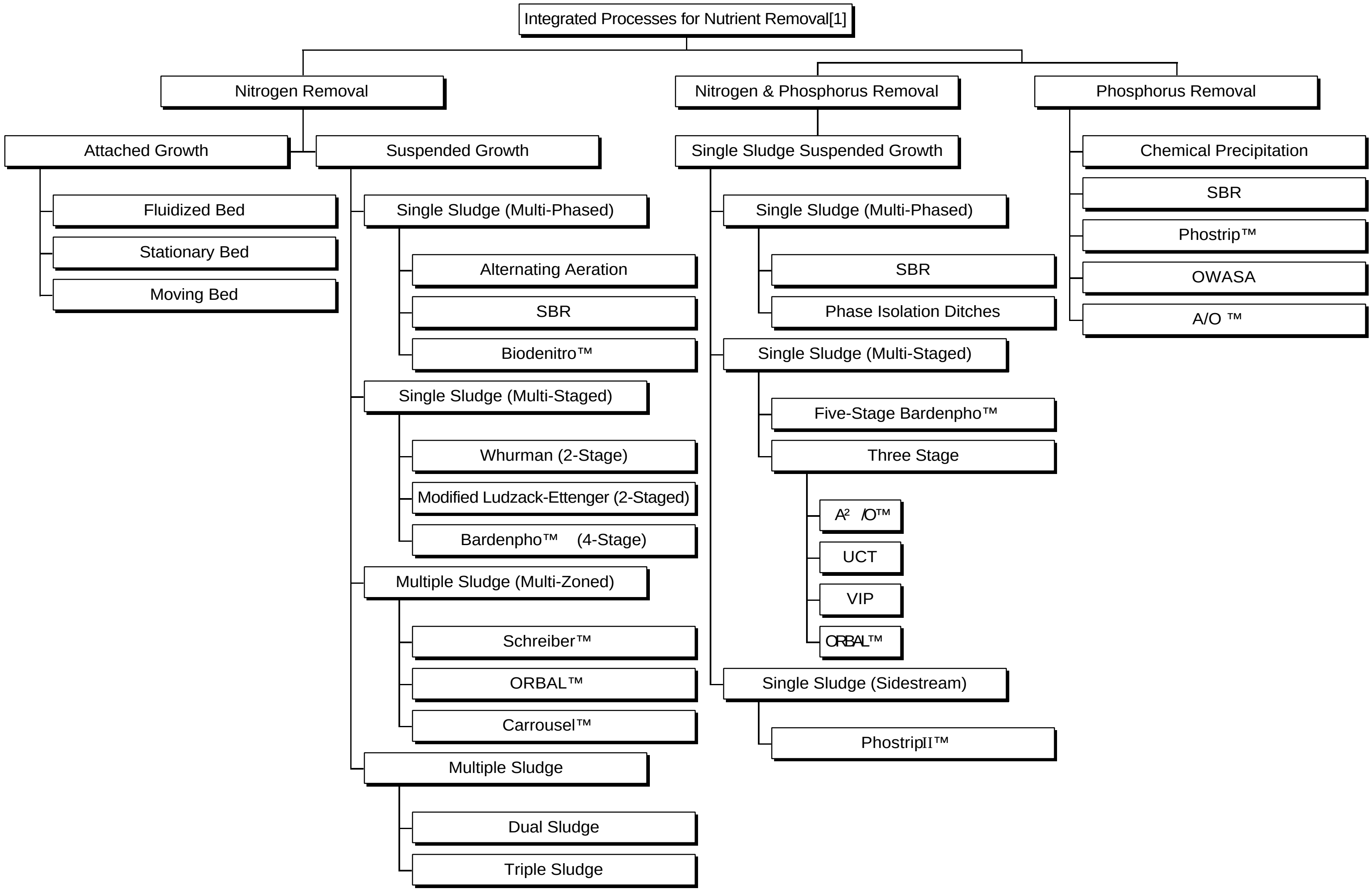

Figure 2. Nutrient Removal Processes

Source: Water Environment Federation and the American Society of Civil Engineers, Design of Municipal Wastewater Treatment Plants, p. 898, 1991.

Table 14. Nutrient Removal Processes

Process	Advantages	Disadvantages
Combined carbon oxidation nitrification suspended-growth	Combined treatment of carbon and ammonia in a single stage; low effluent ammonia is possible; inventory control of mixed-liquor stable due to high BOD_5/TKN ratio	No protection against toxicants; only moderate stability of operation; stability linked to operation of secondary clarifier for biomass return; large reactors required in cold weather
Combined carbon oxidation nitrification attached-growth	Combined treatment of carbon and ammonia in a single stage; stability not linked to secondary clarifier as organisms are attached to media	No protection against toxicants; only moderate stability of operation; effluent ammonia is normally 1-3 mg/L (except RBC); cold weather operation impractical in most cases
Separate-stage nitrification Suspended-growth	Good protection against most toxicants; stable operation; low effluent ammonia possible	Sludge inventory requires careful control when BOD_5/TKN ratio is low; effluent ammonia is normally 1-3 mg/L; greater number of unit processes required than for combined carbon oxidation nitrification
Separate-stage nitrification attached-growth	Good protection against most toxicants; stable operation; stability not linked to secondary clarifier as organisms are attached to media	Effluent ammonia normally 1-3 mg/L; greater number of unit processes required than for combined carbon oxidation nitrification
Combined carbon oxidation nitrification/denitrification in suspended-growth reactor using endogenous carbon source	No methanol required; lesser number of unit processes required; better control of filamentous organisms in activated-sludge process possible; single basin can be used; adaptable to sequencing batch reactor; process can be adapted to include biological phosphorus removal.	Denitrification occurs at very slow rates; longer detention time and much larger structures required than methanol-based system; stability of operation linked to clarifier for biomass return; difficult to optimize nitrification and denitrification separately; biomass requires sufficient dissolved-oxygen level for nitrification to occur; less nitrogen removal than methanol-based system.
Combined carbon oxidation nitrification/denitrification in suspended-growth reactor using waste-water carbon source	No methanol required; lesser number of unit processes required; better control of filamentous organisms in activated-sludge process possible; single basin can be used; adaptable to sequencing batch reactor; process can be adapted to include biological phosphorus removal.	Denitrification occurs at slow rates; longer detention time and larger structures required than methanol-based system; stability of operation linked to clarifier for biomass return; difficult to optimize nitrification and denitrification separately; biomass requires sufficient dissolved-oxygen level for nitrification to occur; less nitrogen removal than methanol-based system.

Process	Advantages	Disadvantages
Suspended-growth using methanol following a nitrification stage	Denitrification rapid; small structures required; demonstrated stability of operation; few limitations in treatment sequence options; excess methanol oxidation step can be easily incorporated; each process in system can be separately optimized; high degree of nitrogen removal possible.	Methanol required; stability of operation linked to clarifier for biomass return; greater number of unit processes required for nitrification/denitrification than in combined systems
Attached-growth (column) using methanol following a nitrification stage	Denitrification rapid; small structures required; demonstrated stability of operation; stability not linked to clarifier as organisms on media; few limitations in treatment sequence options; high degree of nitrogen removal possible; each process in the system can be separately optimized.	Methanol required; excess methanol oxidation process not easily incorporated; greater number of unit processes required for nitrification/denitrification than in combined systems.
A/O	Operation is relatively simple compared to other processes. Waste sludge has a relatively high phosphorus content (3-5%) and has fertilizer value. Relatively short hydraulic retention time. Where reduced levels of phosphorus removal efficiency are acceptable, process may achieve complete nitrification.	Is not capable of achieving high levels of nitrogen and phosphorus removal simultaneously. Performance under cold weather operating conditions uncertain. High BOD/P ratios are required. With reduced aerobic cell detention time, very high-rate oxygen-transfer devices may be necessary. Limited process control flexibility is available.
PhoStip	Can be incorporated easily into existing activated-sludge plants. Process is flexible; phosphorus removal process is not controlled by BOD/phosphorus ratio. Several installations in U.S. Significantly less chemical usage than mainstream chemical precipitation. Can achieve reliably effluent orthophosphate concentrations of less than 1.5 mg/L.	Requires lime addition for phosphorus precipitation. Requires higher mixed-liquor dissolved oxygen to prevent phosphorus release in final clarifier. Additional tankage required for stripping. Lime scaling may be a maintenance problem.
Sequencing batch reactor	Process is very flexible for combining nitrogen and phosphorus removal. Process is simple to operate. mixed-liquor solids cannot be washed out by hydraulic surges.	Suitable only for smaller flows. Redundant units are required. Effluent quality depends upon reliable decanting facility. Limited design data available.
A^2/O	Waste sludge has a relatively high phosphorus content (3-5%) and has fertilizer value. Provides better denitrification capability than A/O.	Performance under cold weather operating conditions uncertain. More complex than A/O.

Process	**Advantages**	**Disadvantages**
Bardenpho	Produces least sludge of all biological phosphorus removal systems. Waste sludge has relatively high phosphorus content and has fertilizer value. Total nitrogen is reduced to levels lower than most processes. Alkalinity is returned to the system, thereby reducing or eliminating the need for chemical addition. Has been widely used in South Africa and considerable data are available.	Large internal cycle increases pumping energy and maintenance requirements. Limited experience in U.S. Requires more reactor volume than A^2/O process. Primary setting reduces ability of process to remove nitrogen and phosphorus. High BOD/P ratios are required. Temperature effects on process performance are not well-known.
UCT	Recycle to anoxic zone eliminates nitrate recycle and provides better phosphorus removal environment in the anaerobic zone. Has slightly less reactor volume than Bardenpho process.	No installations in U.S. Large internal cycle increases pumping energy and maintenance requirements. Requirements for chemical addition uncertain. High BOD/P ratios are required. Temperature effects on process performance are not well-known.
VIP	Recycle of nitrate to anoxic zone reduces oxygen requirements and alkalinity consumption. Recycle of anoxic zone effluent to anaerobic zone reduces nitrate loading on aerobic zone. Adaptable to year-round phosphorus removal and seasonal nitrogen removal.	Large internal recycle increases pumping energy and maintenance requirements. Few operating installations in U.S. Low temperatures reduce nitrogen removal capabilities.
Air stripping	Process can be controlled for selected ammonia removals. Most applicable if required seasonally in combination with lime system for phosphorus removal. Process may be able to meet total nitrogen standards. Not sensitive to toxic substances.	Process is temperature sensitive. Ammonia solubility increases with lower temperatures. Air requirements also vary. Fogging and icing occur in cold weather. Ammonia reaction with sulfur dioxide may cause air pollution problems. Carbonate scaling of packing and piping. Potential noise and aesthetic problems.
Breakpoint chlorination	With proper control, all ammonia nitrogen can be oxidized. Process can be used following other nitrogen removal processes for fine-tuning of nitrogen removal. Concurrent effluent disinfection. Limited space requirements. Not sensitive to toxic substances and temperature. Low capital costs. Adaptable to existing facility.	May produce high chlorine residuals that are toxic to aquatic organisms. Wastewater contains a variety of chlorine demanding substances which increase cost of treatment. Process is sensitive to pH, which affects dosage requirements. High operating cost due to chemical requirements. Trihalomethane formation may impact quality of water supplies. Addition of chlorine raises effluent TDS. Process may not be able to meet total nitrogen standards. Requires careful control of pH to avoid formation of nitrogen trichloride gas. Requires highly skilled operator.

Process	**Advantages**	**Disadvantages**
Ion exchange	Can be used where climatic conditions inhibit biological nitrification and where stringent effluent standards are required. Produces a relatively low TDS effluent. Produces a reclaimable product (aqueous ammonia). Process may be able to meet total nitrogen standards. Ease of product quality control.	Organic matter in effluent from biological treatment can cause resin blinding. Pretreatment by filtration is usually required to prevent the buildup of excessive headloss due to suspended-solids accumulation. High concentrations of other cautions will reduce ammonia removal capability. Regeneration recovery may require the addition of another unit progress (e.g., gas stripping). High capital and operating costs. Regeneration products must be disposed of. Requires highly skilled operator.

Source: Metcalf & Eddy, Wastewater Engineering, Treatment, Disposal, and Reuse

3.5 Disinfection

Disinfection destroys pathogenic microorganisms. Chlorination is most widely used although other agents are available. Concerns about chlorine byproducts led to increased attention to dechlorination of disinfected water prior to discharge as well as increased application of ultraviolet light for disinfection. Table 15 lists attributes of different disinfection agents.

Case study: Use of ultraviolet lamps for wastewater disinfection

The Carters Creek (College Station, Texas) wastewater treatment plant increased its capacity from 8.9 mgd (33.4 million l/d) to 9.5 mgd (35.7 million l/d) and implemented new technologies, including autothermal thermophilic aerobic digestion and ultraviolet (UV) disinfection.

The plant had previously used chlorine for disinfection. However, there were several concerns about continued use of chlorine. Chlorine disinfection generates potentially hazardous byproducts. Disinfected effluent must be dechlorinated carefully to avoid reducing dissolved oxygen below required standards. Larger contact basins would need to be constructed to assure adequate chlorine contact time, and the city was worried about the cost of a scrubber system to control air emissions from the new basins. Furthermore, staff was concerned about the safety of storing and handling chlorine and dechlorination chemicals.

Upon the recommendation of an engineering firm, the city decided to install a UV disinfection system. The UV system requires less space than the chlorine disinfection system. Detention time is only 12 seconds for UV, in contrast with 20 minutes for chlorine. The UV basin has two channels so that one channel can operate while the other is maintained. Each channel has 15 modules in a 3-foot-wide (0.92 m) by 5-foot-wide (1.54 m) array. Each module has 40 UV bulbs. The system was completed in August 1995 at a cost of $800,000. It is estimated that the facility will pay for itself over a 10-year period relative to the cost of maintaining and upgrading the chlorine disinfection system. The city of College Station is expected to save over $1 million through use of UV disinfection.

Source: Wastewater Plant Turns to UV Disinfection, *WasteWater*, Vol. 13, No. 7 (July/August 1997) p. 46.

Table 15. Wastewater Disinfection Agent Attributes

	Ozone	Chlorine	Chlorine Dioxide	Hypochlorite	Ultraviolet Light
Plant size	medium to large[3]	all sizes[3]	small to medium[3]	all sizes[4]	all sizes[4]
Limits	not for high strength, complex, high concentration streams, affected by temperature	affected by temperature		affected by temperature[4]	limited by turbidity[1]
pH dependent	Slight[9]	Yes[9]	No[9]	Yes[4]	No[9]
Effluent	no hazardous end products, may increase BOD in reaction with refractory organics[3]	may create toxic residuals, may require dechlorination before discharge	moderate residuals; does not create chloramines, trihalomethanes[3]	may create toxic residuals; may require dechlorination before discharge[4]	no residuals[1]
Increases dissolved solids	No[9]	Yes[9]	Yes[9]	Yes	No[9]
Health/safety	storage and handling hazards, but is generated on-site[3]	chlorine storage and handling hazard	some safety concerns[3]	may generate chlorine gas	minimal concerns[3], UV needs proper shielding[4]
Toxicity	toxic[7]	highly toxic[7]	toxic[7]	toxic[7]	toxic[7]
Operation & Maintenance costs	very energy intensive, far more expensive than chlorine	low cost[7]	moderately low cost[7]	moderately low cost[7]	energy intensive[4], moderately high cost[7]
Technology issues	technology relatively complex[3], few full-scale systems in operation[6]	simple feeding, well proven[1], most frequently used[4],low to moderate complexity[3]	moderately complex[3], no known use in US municipal plants[5]	simple feeding, well proven, low to moderate complexity[4]	simple to moderate to operate, used in hundreds of wwt plants, use growing[5]
Bactericidal	good[3]	good[3]	good[3]	good[6]	good[3]
Virucidal	good[3]	moderate[3]	good[3]	moderate[6]	good[3]

Wastewater Disinfection Agent Attributes (Continued)

	Ozone	Chlorine	Chlorine Dioxide	Hypochlorite	Ultraviolet Light
Additional equipment	on-site ozone generation needed; enhanced by UV and ultrasonic[1]		on-site generation needed[6]		
Solubility	high[7]	slight[7]	high[7]	high[7]	N/A[7]
Stability	unstable[7]	stable[7]	unstable[7]	slightly unstable[7]	N/A[7]
Contact time	short[3]	medium[3]	medium[3]	medium[4]	short[3]
Interaction with extraneous material	oxidizes organic matter [7]	oxidizes organic matter [7]	high[7]	active oxidizer[7]	slight[7]
Penetration	high[7]	high[7]	high[7]	high[7]	moderate[7]
Corrosivity	highly corrosive[7]	highly corrosive[7]	highly corrosive[7]	corrosive[7]	N/A[7]
Deodorizing ability	high[7]	high[7]	high[7]	moderate[7]	none[7]
Form[8]	gas	liquid/gas	gas	solution, powder or pellets	N/A
Chemical formula[8]	O_3	Cl_2	ClO_2	$NaOCl$ or $Ca(OCl)_2$	N/A
Reliability	fair to good[3]	good[3]	good[3]	good[4]	fair to good[3]
Flexibility	good[9]	good[9]	good[9]		good[9]
Studies	medium[9]	maximal[9]	minimal[9]		medium[9]

[1] Unit Operations in Environmental Engineering, R. Noyes, 1993
[2] Industrial Water Pollution Control, Eckenfelder, 1989
[3] Water Quality and Treatment, AWWA, 1990
[4] Personal communication, Dean Hertert, Sept. 24, 1996
[5] Design of Municipal Wastewater Treatment Plants, WEF/ASCE, 1992
[6] Standard Handbook of Environmental Engineering, R.A. Corbitt, 1989
[7] Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy, 1991
[8] Wastewater treatment plants, Planning, Design, and Operation, S. R. Qasim, 1994
[9] Design Manual: Municipal Wastewater Disinfection, EPA 625/1-86-021, 1986

3.6 Sludge Treatment

Sources of waste sludge in a municipal wastewater treatment plant are the primary sedimentation basin and the secondary clarifiers. Some additional sources of sludge may include the chemical precipitation step, nitrification-denitrification process, screening, grinding, and filtration. Depending on the process design, some sludge streams may be recycled to a previous step. The sludge produced contains organic and inorganic materials brought by the raw wastewater, the chemicals added, and the biological solids produced during treatment.

Excess sludge must be disposed of. However, transport and disposal of raw sludge is very costly because of its high water content. Wastewater treatment plants employ a number of approaches to reduce sludge volume and moisture content. Anaerobic digestion (described in 3.3.1) reduces sludge volume and mass. Thickening and dewatering of sludge is accomplished by centrifugation, filtration, and/or drying, with a number of technological variations of each. Chemicals may also be used to help thicken and dewater sludge. These processes have enormous effect the amount of sludge requiring final disposal; raising the solids concentration of sludge from 2 percent to 20 percent reduces sludge volume by 90 percent.

Table 16 lists processes available for treating waste sludge. Some of these processes have already been described in previous sections (e.g. anaerobic digestion). The remainder of this section will focus on these sludge processing technologies.

Table 16. Sludge Handling Processes

Preliminary operations	Thickening	Stabilization	Conditioning	Disinfection	Dewatering	Drying	Thermal Reduction	Disposal
• Sludge grinding • Sludge blending • Sludge storage • Sludge degritting	• Rotary drum thickening • Gravity thickening • Float thickening • Centrifugatio n • Gravity belt thickening	• Chlorine oxidation • Lime stabilization • Heat treatment • Anaerobic digestion • Aerobic digestion • Composting	• Chemical conditioning • Elutriation • Heat treatment	• Pasteurization • Long term storage	• Vacuum filter • Pressure filter • Horizontal belt filter • Centrifuge • Drying bed • Lagoon	• Multiple effect evaporater • Flas drying • Spray drying • Rotary drying • Multiple hearth dryer	• Multiple hearth incineration • Fluidized bed incineration • Flash combustion • Co-incineration with solid wastes • vertical deep well reactor • wet air oxidation	• Landfill • Land application • Reclamation • Reuse • Composting • Recalcination

Sources: Wastewater Treatment Plants, Planning, Design, and Operation, S. R. Qasim
Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy

3.6.1 Sludge Thickening

Waste sludge is over 90 percent water. Thickening of the sludge is required in order to reduce the overall volume and concentrate the solids. The thickening process reduces the load on further treatment therefore reducing the chemical usage and equipment size requirements. Methods for thickening include gravity, dissolved air flotation, and centrifugation. These methods and their characteristics are presented in Tables 17 and 18.

3.6.2 Sludge Dewatering

The dewatering of the waste sludge is necessary in order to reduce the remaining moisture content for disposal or transportation of the sludge. The resulting sludge can contain up to 30 percent solids, further concentration of the sludge can be carried out by a drying step. The equipment typically used for dewatering are centrifuges, drying beds, lagoons, filter presses, horizontal belt filters, and vacuum filters. These methods and their characteristics are described below and summarized in Tables 19 and 20. Other dewatering techniques include freezing (which is assumed impractical for the Brazilian climate) and *Phragmites* reed beds (which are considered unsuitable for large treatment plants that generate over 19 million liters of sludge per year due to piping and drainage problems). These additional options are not discussed further.

<u>Sand Drying Beds</u>: Sand Beds are generally used for small- to moderate-scale municipal wastewater treatment plants. Space requirements are very large and time to dry may be lengthy (Outwater 1994, 82).

<u>Wedgewater Drying Beds</u>: Wedgewater drying beds use a fine wire screen mesh made of stainless steel (longer life, higher cost) or a high-density polyurethane medium (shorter life, lower cost). The stainless steel mesh is about one meter wide by any length, and laid over concrete floors on structural supports. The polyurethane mesh is made out of interlocking and self-supporting pieces measuring 30.5 cm by 30.5 cm and they are 5 cm high. These systems can drain water by capillary action with a loading capacity of almost 10 kg of dry solids per square meter which is twice the capacity of a sand drying bed. Under favorable conditions sludge solids content can reach 15 to 20% in 3 or 4 days (versus about 4 weeks on a sand drying bed that requires about 16 times more surface area). Some skill is required to operate these systems successfully. Beds are cleaned with a tractor (Outwater 1994, 83-85).

Lagoon Dewatering: This is a simple, low-cost alternative in a hot and dry climate where land is inexpensive, and where there are no neighbors nearby. Lagoons require relatively large land areas. Odor is difficult to control; some sludges need to be stabilized to reduce odors prior to lagooning. Lagoons are sensitive to weather conditions. Rain slows sludge thickening and lagoons are less efficient in colder climates. Sludge can also leach into the groundwater. Drying lagoons need to be periodically emptied of sludge. If the sludge layer is 36 cm or less, it will dewater in 3 to 5 months (Outwater 1994, 84-85).

Vacuum Filter Dewatering: The typical continuous vacuum filter consists of a horizontal drum rotating partially submerged in a reservoir of wet, unfiltered sludge. A filter medium made of various types of material overlays the face of the drum and supports the layer of dewatering sludge. The drum is divided into sectors spanning the length of the drum, each of which is placed under vacuum by automatic valving. As a sector revolves through the reservoir a vacuum is applied, resulting in the formation of a layer of sludge on the filter medium. The vacuum is maintained on the sector as it emerges from the reservoir, resulting in the continuous drainage of moisture from the sludge layer. Drainage continues until just prior to the sector reentering the reservoir, at which point, the sludge cake is automatically scraped off the filter medium. One of the major disadvantages of the drum-type filter is the frequency with which the operation must be shut down to wash the medium (Outwater 1994, 90-91).

Belt Filter Presses: Sludge is processed in three stages: conditioning/flocculation, gravity drainage, and compression shear. In the first stage, a polymer is added and mixed into the sludge. Sludge is then pumped onto a moving porous belt where water released during sludge conditioning drains by gravity, leaving behind a slurry of flocculated sludge solids. Plows agitate the sludge to improve release of water. Gravity drainage after initial sludge conditioning accounts for 50 to 75 percent of the water extracted in the mechanical dewatering process and is an essential step before the sludge is squeezed between the two belts.

In the compression stage, partially dewatered sludge is squeezed between two fiber belts. The belts are passed over a series of rollers that provide shearing action. At the end of the belt section the dewatered cake is scraped from the belt surface onto a conveyor for further processing or disposal (Outwater 1994, 91-93).

Centrifuge Dewatering: Centrifuge dewatering uses the centrifugal force developed by spinning a bowl or basket to separate heavier sludge solids from the liquids. Three types of centrifuges are commonly used: solid bowl decanter, basket type, and disk type. The solid bowl centrifuge, or decanter, is the most common type used. Sludge is pumped through a central pipe into a rotating bowl, where the solids are pressed to the inside walls and the lighter liquids pool near the center of the bowl. A scroll or screw conveyer moves the sludge cake out the open end. Centrate is evacuated through holes on either end of the bowl (Outwater 1994, 93-94).

3.6.3 Sludge Residual Disposal

The end product of the waste sludge treatment process must be disposed of in a manner that is both safe and cost effective. The disposal of the sludge can be handled in many ways and is dependent on severable variables such as cost of transportation, land availability, sludge toxicity, volume of sludge produced, and contaminants.

The most common disposal methods are landfilling, land application, chemical fixation, deep-well injection, and incineration. Other methods may also be used depending on the characteristics of both the sludge and the treatment plant: composting, pyrolysis, wet oxidation, and recalcination. Recalcination could allow recycling of lime from the sludge stream if the contamination level and economic factors are acceptable. Characteristics of several sludge disposal options are described in Table 21.

Table 17. Sludge Thickening Methods

	Advantages	Disvadvantages	Type of sludge	Use and success level
Gravity Settling	Provides sludge storage capacity	Large amount of space required	Primary	Increasing, excellent results
	Requires low operational skills	Can produce odors Produces low % solids[1]	Digested primary	Infrequent now, but feasible
	Provides low operation and maintenance costs[1]		Primary and waste activated	Decreasing, poor to marginal results
			Air waste activated	Essentially never used, poor results
Gravity (elutriation)			Digested primary and waste activated mixture	Many plant built, requires flocculants
Dissolved air flotation	Works best with ligther sludges Higher solids than gravity[1]		Primary and waste activated	Increasing, good results if primary sludge is gravity thickened separately
Solid bowl conveyor type			Waste activated	Some limited use, solid capture problem
Disk-type centrifuge	Low space requirements[1]	High costs[1]	Waste activated	Some limited use, data being gathered

Modified from the Standard Handbook of Environmental Engineering, R. Corbitt

[1] Sludge Management and Disposal, P.N. Cheremisinoff

Table 18. Sludge Thickening Characteristics

	Land requirements	Handling of flow variation	Handling of influent quality variation	Reliability	Ease of operation and maintenance
Gravity	Moderate	Fair	Good	Good	Good
Dissolved air flotation	Moderate	Fair	Good	Good	Fair
Centrifuge	Minimal	Good	Good	Good	Fair

Modified from Wastewater Treatment Plants: Planning, Design, and Operation, S. R. Qasim

Table 19. Sludge Dewatering Methods

	Dewatered cake use				**Characteristics**		
	Landfill	Land spread	Heat drying	Incine-ration	Plant size	Advantages[1]	Disadvantages[1]
Centrifuge (solid bowl)	Yes	Yes	Yes	Yes		Clean appearance, minimal odor problems, fast startup and shutdown capabilities. Easy to install. Produces relatively dry sludge cake. Low capital cost-to-capacity ratio.	Scroll wear potentially a high-maintenance problem. Requires grit removal and possibly a sludge grinder in the feed stream. Skilled maintenance personnel required. Moderately high suspended-solids content in centrate.
Centrifuge (basket)	No	Yes	No	No		Same machines can be used for both thickening and dewatering. Chemical conditioning may not be required. Clean appearance, minimal odor problems, fast startup and shutdown capabilities. Very flexible in meeting process requirements. Not flexible in meeting process requirements. Not affected by grit. Excellent results for difficult sludges.	Limed size capacity. Except for vacuum filters, consumes more energy per unit of sludge dewatered. Skimming stream may produce significant recycle load. For easily dewatered sludges, has highest capital cost-to-capacity ratio. For most sludges, produces lowest cake solids concentration. Vibration.
Drying beds	Yes	Yes	No	No	Small	Lowest capital cost method where land is readily available. Small amount of operator attention and skill required. Low energy consumption. Low to no chemical consumption. Less sensitive to sludge variability. Higher solids content than mechanical methods.	Requires large area of land. Requires stabilized sludge. Design requires consideration of climatic effects. Sludge removal is labor intensive.

Table 19. Sludge Dewatering Methods (cont.)

Dewatered cake use					Characteristics		
Lagoons	Yes	Yes	No	No	Small	Low energy consumption. No chemical consumption. Organic matter is further stabilized. Insensitive to sludge variability. Low capital cost where land is available. Least amount of skill required for operation.	Potential for odor and vector problems. Potential for groundwater pollution. More land intensive than mechanical methods. Appearance may be unsightly. Rain slows dewatering; best in hot and dry climate.
Filter press	Yes	Variable	No usually	Yes		Highest cake solids concentration. Low suspended solids in filtrate.	Batch operation. High equipment cost. High labor cost. Special support structure requirements. Large floor area required for equipment. Skilled maintenance personnel required. Additional solids due to large chemical addition require disposal.
Horizontal belt filters	Yes	Yes	Yes	Yes		Low energy requirements. Relatively low capital and operating costs. Less complex mechanically and easier to maintain. High-pressure mechanically and easier to maintain. High-pressure machines are capable of producing very dry cake. Minimal effort required for system shutdown.	Hydraulically limited in throughput. Requires sludge grinder in feed stream. Very sensitive to incoming sludge feed characteristics. Short media life as compared to other devices using cloth media. Automatic operation generally not advised.
Rotary vacuum filter	Yes	Yes	Yes	Yes		Skilled personnel not required Maintenance requirements are low for continuously operating equipment	Highest energy consumer per unit of sludge dewatered. Continuous operator attention required. Vacuum pumps are noisy. Filtrate may have high suspended solids content, depending on filter medium.

Modified from the Standard Handbook of Environmental Engineering, R. Corbitt

[1] Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy

Table 20. Sludge Dewatering Characteristics

	Land requirements	**Handling of flow variation**	**Handling of influent quality variation**	**Reliability**	**Ease of operation and maintenance**
Centrifuge	Lower	Fair	Fair	Good	Good
Filtration	Moderate	Fair	Fair	Good	Good
Drying bed	Higher	Good	Good	Fair	Very good

Modified from Wastewater Treatment Plants: Planning, Design, and Operation, S. R. Qasim

Table 201. Sludge Residual Disposal

	Land requirements	**Handling of flow variation**	**Handling of influent quality variation**	**Reliability**	**Ease of operation and maintenance**	**Issues**
Sanitary land-fill	Higher[2]	Good[2]	Good[2]	Very Good[2]	Good[2]	Leachates/runoffs to be controlled, regulations are established[1]
Land application	Higher[2]	Good[2]	Good[2]	Fair[2]	Good[2]	Low cost, regulations are established, crop consumption regulated, runoffs to be controlled[1]
Chemical fixation						For sludge containing hazardous wastes, high costs[1]
Deep-well injection						Groundwater contamination concerns[1]
Incineration	Lower[2]	Fair[2]	Good[2]	Very Good[2]	Fair[2]	Landfilling of ashes[2]

Source: [1] Standard Handbook of Environmental Engineering, R. Corbitt
[2] Wastewater Treatment Plants: Planning, Design, and Operation, S. R. Qasim

Case study: Use of biosolids as nutrient on farmland

The Landis Sewerage Authority in southern New Jersey upgraded its wastewater facility to an 8.2 mgd capacity. In order to meet established conservation goals, the authority purchased 380 acres of woodland close to the facility. A portion of that land will be used to grow hay and corn using the stabilized biosolids as sole source of nutrient. Benefits include revenues created by the sale of hay and corn and control of biosolids hauling and disposal costs. The application is limited to warmer months since regulations prohibit application on frozen or snow-covered soils.

Source: Palmer, D.W., and Shimp, C. G., New Jersey Wastewater Authority Buys Farmland for Biosolids Disposal, *Water Engineering & Management*, July 1995 p.37

3.7 Land Treatment of Wastewater

If land is available and the wastewater flow rate is within a specified range, the land treatment systems may provide a feasible wastewater treatment alternative. The systems use the plants, land surface, and soil matrix to treat the wastewater. Various physical, chemical, and biological processes are involved. Most land treatment systems require that the wastewater goes through at least a primary sedimentation step before being treated. Table 22 presents characteristics and requirements of these systems.

Table 22. Land Treatment Systems

	Slow Rate	Overland Flow	Rapid infiltration	Wetland Application	Floating Aquatic Plants
Treatment goals	Secondary or advanced wastewater treatment	Secondary, nitrogen removal	Secondary or advanced wastewater treatment	Secondary wastewater treatment[2]	
Vegetation	Various crop	Water-tolerant grasses	No	Required[1]	Required[1]
Climate restrictions	Storage often needed for cold weather	Storage often needed for cold weather	If properly designed, no storage is needed	Storage often needed for cold weather[1]	Storage often needed for cold weather[1]
Hydraulic loading	0.5-6 m/y	3-20 m/y	6-100 m/y	6-20 m/y[1]	6-20 m/y[1]
Area needed	0.0603-0.5920 km^2/(Million l/d) [1]	0.0065-0.0484 km^2/(Million l/d) [1]	0.0040-0.0603 km^2/(Million l/d) [1]	0.0194-0.0667 km^2/(Million l/d) [1]	0.0194-0.0667 km^2/(Million l/d) [1]
Design Guidelines	Can be used for primary treatment if in isolated location, restricted public access and no human consumed crops. Fecal under 1000 MPN/100ml is acceptable except for crops eaten raw. Fecal under 200 for public access areas	Screening or communition acceptable if in isolated location and restricted public access. Aeration required (odor control) if in urban environment	Can be used for primary treatment if in isolated location and restricted public access		
Soil depth requirements	>0.6 m	>0.3 m	>1.5 m		
Soil permeability	Slow to moderately rapid 1.5-500 mm/h	Very slow to moderately slow <5.0 mm/h	Rapid >50 mm/h	Slow to moderate[1]	Slow to moderate[1]
Depth to ground water	0.6-1 m	Not Critical	1 m	Not critical[1]	Not critical[1]
Slope %	<20% if cultivated <40% if non cultivated	0-15%	<10%	<5%[1]	<5%[1]
Max loading (BOD)	500 kg/ha*d	100 kg/ha*d	670 kg/ha*d		
Average effluent quality	<2 mg/l BOD <1 mg/l S.S. 3 mg/l Total N <0.1 mg/l Total P[1]	10 mg/l BOD 15mg/l S.S. 5 mg/l Total N 4 mg/l Total P[1]	2 mg/l BOD 2 mg/l S.S. 10 mg/l Total N 1 mg/l Total P[1]		

Modified from "Design of Municipal Wastewater Treatment Plants" Volume II WEF/ASCE
[1] Wastewater Engineering, Treatment, Disposal, and Reuse, Metcalf & Eddy
[2] Wastewater treatment plants, Planning, Design, and Operation, S. R. Qasim

3.8 Cost Analysis

Although equipment purchase, construction, and operating costs depend on various factors, some average cost figures available. Table 23 lists some of these. The values are for comparison only since the design phase yields the required information for more accurate cost estimation. Also, an appropriate factor such as the EPA Treatment Plant and Sewer Construction cost index should be used to account for inflation from the time the data in the table was originally derived. Additionally, differences in factor costs and exchange rates in different countries should be considered.

Table 23. Costs of specific wastewater treatment processes

	Construction cost Million $	Operation & Maintenance Million $ / year
Preliminary treatment	0.2-0.3	0.03-0.04
Primary clarifier	0.5	0.045
Conventional activated sludge	1.8	0.1
Final clarifier	0.8	0.065
High rate trickling filter	1.0	0.035
Clarifier for high rate trickling filter	0.9	0.085
Chlorination	0.3	0.065
Gravity thickener	0.1	0.006
Aerobic digester	0.6	0.068
Two stage anaerobic disgesters	0.6	0.035
Sludge drying beds	0.4	0.068
Filter press	0.7	0.063
Landfilling	0.075	0.04

Costs are indexed to September 1976, use appropriate cost indexes (e.g., EPA Treatment Plant and Sewer Construction cost index, Water Environment Federation). The above figures where taken from cost curves in Wastewater Treatment Plants, Planning, Design, and Operation, S. R. Qasim. The costs are for a specified flow of 10 million gallons per day.

4.0 SUMMARY

A description of major steps and technologies for municipal wastewater treatment is presented. Technologies are compared with regard to features such as performance, operation, and cost. A series of tables, matrices, and text comparisons are also provided.

The document can be used by municipal officials and other public and private sector decision makers to examine available options for municipal wastewater treatment. Such officials can screen these technologies to determine those appropriate for further consideration.

APPENDIX A REFERENCES

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APPENDIX B ASSOCIATIONS AND ORGANIZATIONS

American Consulting Engineers Council
Howard M. Messner, Executive Vice President
Suite 802
1015 15th Street, NW
Washington, DC 20005
tel. 202-347-7474
fax 202-898-0068

ACEC is an association of American consulting engineering firms including those involved in the design, construction, operation, and management of water supply and wastewater treatment infrastructure. ACEC publishes a membership list and *International Engineering Directory* that are useful resources for identifying experienced American consulting engineering firms.

American Society of Civil Engineers
James E. Davis, Executive Director
Suite 600
1015 15th Street, NW
Washington, DC 20005
tel 202-789-2200

ASCE is the professional society for American civil engineers. The society sponsors technical and professional activities in the area of water and wastewater engineering.

American Water Works Association
John B. Mannion, Executive Director
6666 West Quincy Avenue
Denver, CO 80235
tel. 303-794-7711
fax 303-795-1440
Web address: http://www.awwa.org/

AWWA is an association of U.S. and Canadian water utilities that supports research, standards development, and information services on design, construction, operations, and maintenance of water supply systems.

Environmental Business Council of New England
Merna Hurd, President
150 Federal Street, 23rd Floor
Boston, MA 02110-1726
tel. 617-737-0060
fax 617-951-8736

The EBC of New England is an association of environmental goods and services providers.

Environmental Export Council
John Mizroch, Executive Director
P.O. Box 77287
Washington, DC 20013
tel. 202-466-6933
fax 202-789-1623

The EEC is an association of U.S. environmental equipment and service providers. The council works closely with industry, government, and other entities to promote international trade and exchange of environmental technologies. The EEC and its Latin America Water Task Force work closely with Brazilian authorities and the U.S. Agency for International Development in promoting U.S. private sector participation in Brazil's developing water and wastewater infrastructure.

International Water Conference
Engineers' Society of Western Pennsylvania
The Pittsburgh Engineers' Building
337 Fourth Avenue
Pittsburgh, PA 15222
tel. 412-261-0710,

The International Water Conference is a technical water treatment conference. Emphasis is on end-user experts in the areas of industrial, utility, and wastewater technology. The 57th Annual International Water Conference was held in October, 1996 in Pittsburgh, Pennsylvania.

NACE International (formerly the National Association of Corrosion Engineers)
G.M. Shenkel, Director
P.O. Box 218340
Houston, TX 77218
tel. 713-492-0535
fax 713-492-8254

NACE is the professional association of corrosion engineers. Corrosion is a major concern of water and wastewater infrastructure.

Purdue Waste Conference
Attn.: Dr. Jim E. Alleman
Purdue University
School of Civil Engineering
West Lafayette, IN 47907-1284
tel. 317-494-7705
fax 317-496-1107

The Purdue Waste Conference is a major technical conference on industrial and hazardous waste treatment including industrial wastewater. The 51st Annual Industrial Water Conference was held in May, 1996.

U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460
Office of Water: tel. 202-260-5700
Office of International Activities: tel. 202-260-4870
EPA's water page web address: http://www.epa.gov/OWOW/

EPA is the U.S. agency responsible for most federal environmental regulations. The agency also supports research, development, technical assistance, and information dissemination. EPA's Office of Water has jurisdiction over water quality including drinking water and effluent discharge. The Office of International Activities is responsible for international environmental cooperation and technical assistance.

Water and Wastewater Equipment Manufacturers Association
Dawn C. Kristof, President
P.O. Box 17402
Dulles International Airport
Washington, DC 20041

tel. 703-444-1777
fax 703-444-1779

WWEMA is an association of manufacturers of equipment for waterworks, wastewater treatment, and industrial waste control. The association's *Membership Directory and Product Guide* is a useful resource for identifying American providers of water and wastewater related equipment. WWEMA is active in promoting international trade in environmental goods and services.

Water Environment Federation
Dr. Quincalee Brown, Executive Director
601 Wythe Street
Alexandria, VA 22314-1994
tel. 703-684-2400
fax 703-684-2492
Web address: http://www.wef.org

WEF is a technical society of scientists, engineers, municipal officials, plant operators, equipment manufacturers, students, and others interested in water quality issues. WEF supports research and education. It provides training courses, publications, videos, and conferences on water quality issues including design, operations, and maintenance of water and wastewater facilities.

APPENDIX C BUYERS GUIDES AND SUPPLIER INDEXES

A variety of industry magazines, professional journals, and associations publish annual buyers guides and supplier indexes relevant to identifying water and wastewater related products, vendors, and service providers. The Thomas Register is an extensive guide of U.S. firms in all manufacturing sectors (not just water and wastewater related).

"Buyer's Guide & Yearbook," Water Environment Federation, 601 Wythe Street, Alexandria, VA 22314. Telephone 703-684-2400. Web address: http://www.wef.org

"Chemical Engineering", McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020. Telephone: 212-512-2000 (ISSN 0009-2460). Web address: http://www.che.com

"Environmental Solutions", Advanstar Communications, Inc., 201 E. Sandpointe Ave., Suite 600, Santa Ana, CA 92707. Telephone: 714-513-8400 (ISSN 0898-5685).

"Environmental Engineers Selection Guide," American Academy of Environmental Engineers, 130 Holiday Court, No. 100, Annapolis, MD 21401. Telephone 410-266-3311.

"Environmental Science & Technology", The American Chemical Society, 1155 16th Street, N.W., Washington, DC 20036. Telephone: 202-872-6316 (ISSN 0013-936X).

"International Engineering Directory" and "Membership Directory," American Consulting Engineers Council, Suite 802, 1015 15th Street, NW, Washington, DC 20005. Telephone 202-347-0068.

"Membership Directory and Product Guide," Water and Wastewater Equipment Manufacturers Association, P.O. Box 17402, Dulles International Airport, Washington, DC 20041. Telephone 202-444-1777.

"Pollution Engineering", Cahners Publishing Company, 8773 S. Ridgeline Blvd., Highlands Ranch, CO 80126. Telephone: 303-470-4445 (ISSN 0032-3640).

"Pollution Equipment News", Rimbach Publishing Inc., 8650 Babcock Boulevard, Pittsburgh, PA 15237. Telephone: 412-364-5366.

"Power", McGraw-Hill Companies, Inc., 11 West 19th Street, New York, NY 10011. Telephone: 609-426-5667 (ISSN 0032-5929).

Thomas Register, Thomas Publishing Company, Five Penn Plaza, New York, NY 10001. Telephone: 212-695-0500. Web address: http://www.thomasregister.com

"Water & Wastes Digest", Scranton Gillette Communications, Inc., 380 E. Northwest Highway, Des Plaines, IL 60016. Telephone: 847-298-6622 (ISSN 0043-1141). Web address: http://WWDigest.com

"WaterWorld", PennWell Publishing Company, 1421 S. Sheridan Road, Tulsa, OK 74112. Telephone: 918-831-9862 (ISSN 1068-5839). Web address: http://www.waterworld.com

APPENDIX D WEB SITES

Organization	Contents	Site
American Water Works Assn.	Water supply association	http://www.awwa.org/
Chemical Engineering Magazine	Periodical publishing	http://www.che.com
Chemical Marketing Reporter	Chemical trade (current pricing)	http://www.chemexpo.com
Electric Power Research Institute	Electrotechnologies for wastewater	http://www.epri.com/96plan/csg/iats/iats2.html
Environment & Municipal Online	Environmental industry information and links	http://www.environmentonline.com
EPA	EPA's water page	http://www.epa.gov/OWOW/
EPA Office of Water	Point Source Information Exchange	http://pipes.ehsg.saic.com/pipes.htm
Instituto Brasileiro de Geografia e Estatistica	Statistics on Brazil	http://www.ibge.gov.br/english/e-home.htm
PennWall Publishing	Periodical publishing	http://www.penwall.com
Pollution Online	Environmental industry information and links	http://www.pollutiononline.com
Public Works Online	Public works information and links	http://www.publicworks.com
Remco	Water treatment company	http://remco.com/~remcobob/home.htm
Thomas Register	Vendor and supplier listings	http://www.thomasregister.com
University of California at LA	Industrial wastewater pretreatment	http://cct.seas.ucla.edu/cct.ww.html
University of Cracow	Water technology links	http://www.uci.agh.edu.pl/polconn/water.htm
Utility Plant Directory	Case studies	http://www.caeconsultants.com/plant.htm#wastewater
Virtual Library	Wastewater engineering	http://www.halcyon.com/cleanh2o/ww/commerce.html
Virtual Library	Water treatment plant studies	http://www.halcyon.com/cleanh2o/ww/muniwater.html
Virtual Library	Reference book list	http://www.halcyon.com/cleanh2o/ww/book1.html
Virtual Library	Waste treatment approaches	http://www.halcyon.com/cleanh2o/ww/wwt1.html
Water & Wastes Digest	Equipment suppliers	http://WWDigest.com
Water Engineering & Management	Water publication	http://WaterEM.com
Water Engineering Management	Water publication	http://waterem.com/waterem.html
Water Environment Federation	Water and wastewater professional association	http://www.wef.org
Water Online	Water business links	http://www.wateronline.com
Water Web	Information on water technology	http://www.waterweb.com
Water World Magazine	Water related technical data	http://www.waterworld.com

APPENDIX E ATTRIBUTES INDEX AND EXPLANATIONS

Category	Attribute	Explanation of Attribute
Flow:	Detention Time (min.):	A measure of the time the waste stream remains/must stay in the particular technology application for treatment.
	Handles Variability:	A relative description of how well the technology performs under variable flow conditions. "Highly effective" implies that the technology is very effective and handling variable rates of flow. "Moderate Effectiveness" and "Less Effective" are the other descriptive terms used for this attribute.
	Approach Velocity (m/s):	A measure of the speed at which the waste stream approaches the particular technology application for treatment
	Overflow Rate ($m^3/day/m^2$):	A measure of the volume and rate at which the waste stream leaves the particular technology application for treatment
Composition of Influent	Screen Width (mm):	A measure of the distance between the screening elements used in screening technologies
	Cut Length (mm):	A measure of the length into which solids in the waste stream are cut by comminuters or grinders
	SS Loading Rate ($kg/m^2/h$):	A measure of the rate at which suspended solids approach settling/ clarification/ sedimentation
Treatment	BOD Removal Rate (%, average):	The average percentage of Biological Oxygen Demand (BOD) removed from the waste stream
	TSS Removal Rate (%, average):	The average percentage of Total Suspended Solids (TSS) removed from the waste stream by a particular technology
	By-Products:	Materials generated by the use/operation of a technology that require additional handling or attention. Materials include the following: screenings, sludge, and solid waste
Equipment	Ease of Operation:	A relative description of the ease by which a particular technology is used. Factors considered in assigning the ratings of easy, medium, or difficult include the amount of training and education required, the number of operators needed, and the degree of difficulty in operating or maintaining a particular technology
	Space Requirements:	A relative description of space required by a piece of equipment: high, medium, or low
	Reliability:	A relative description of the reliability of a technology: high, medium, or low. One factor considered in assigning ratings was the relative number of moving parts
	Robustness:	A relative description of the robustness of a technology: high, medium, or low. Factors considered in assigning ratings include the ability to withstand unusual events (i.e., high flow rate, high concentration event, etc.), the ease with which the process may be shut down and restarted, and its capacity to accept changed operating conditions
Cost Estimate	Capital:	An estimate of the initial capital required to construct/install the technology. Data is given in US dollars ($1000s), or in relative terms: more expensive, medium cost, or less expensive.
	Operational & Maintenance/yr:	The approximate annual cost incurred to operate and maintain (labor and materials) the particular technology. Data is given in US dollars ($1000s), or in relative terms: more expensive, medium cost, or less expensive.
	Power/yr:	The approximate annual cost incurred to supply power for the particular technology in US dollars. Data is given in US dollars ($1000s), or in relative terms: more expensive, medium cost, or less expensive.