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Wastewater Engineering

Treatment and Reuse

(Fourth Edition)

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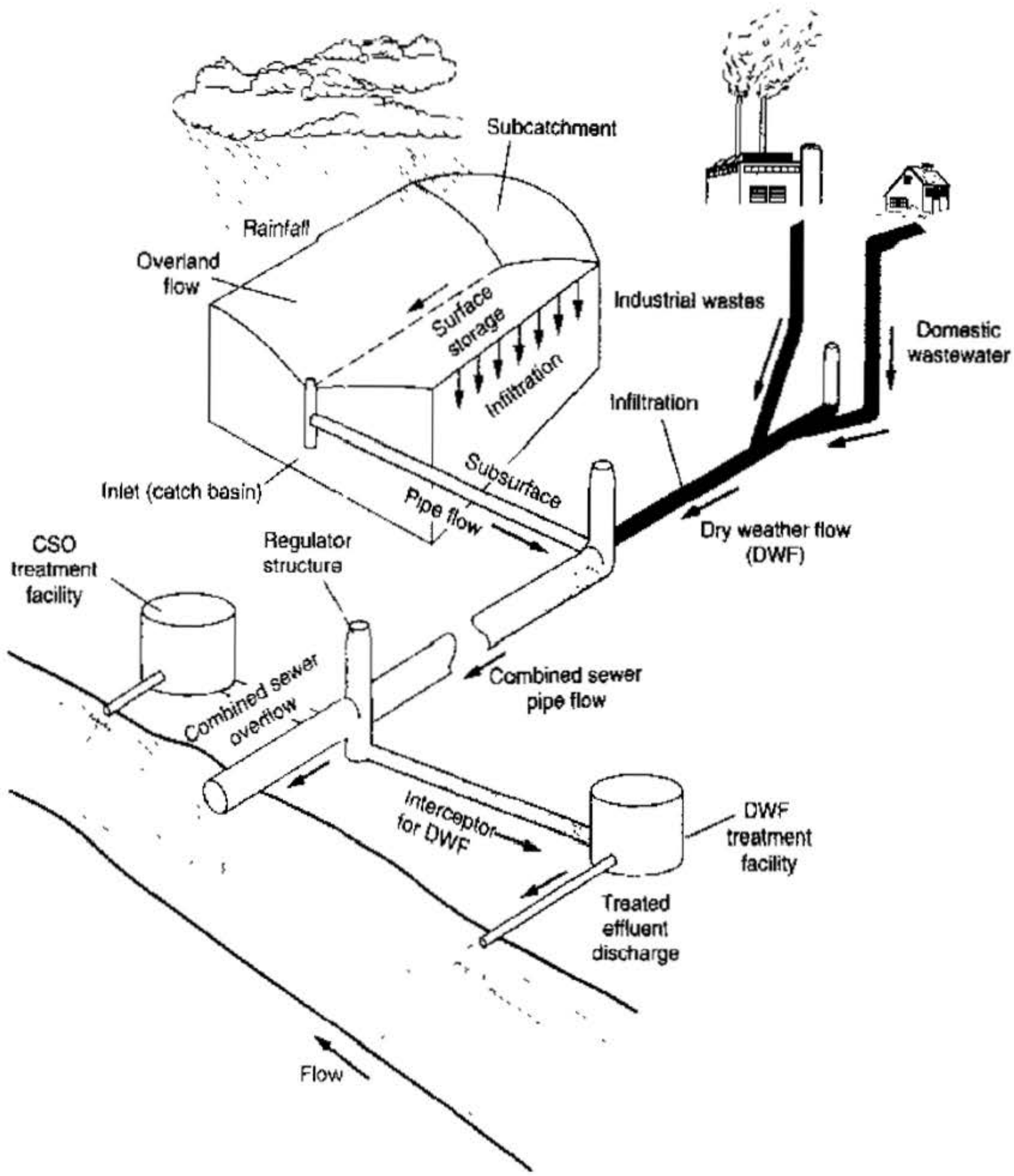
1 Wastewater Engineering: An Overview

Every community produces both liquid and solid wastes and air emissions. The liquid waste—wastewater—is essentially the water supply of the community after it has been used in a variety of applications (see Fig. 1–1). From the standpoint of sources of generation, wastewater may be defined as a combination of the liquid or water-carried wastes removed from residences, institutions, and commercial and industrial establishments, together with such groundwater, surface water, and stormwater as may be present.

When untreated wastewater accumulates and is allowed to go septic, the decomposition of the organic matter it contains will lead to nuisance conditions including the production of malodorous gases. In addition, untreated wastewater contains numerous

Figure 1-1

Schematic diagram of a wastewater management infrastructure.



pathogenic microorganisms that dwell in the human intestinal tract. Wastewater also contains nutrients, which can stimulate the growth of aquatic plants, and may contain toxic compounds or compounds that potentially may be mutagenic or carcinogenic. For these reasons, the immediate and nuisance-free removal of wastewater from its sources of generation, followed by treatment, reuse, or dispersal into the environment is necessary to protect public health and the environment.

Wastewater engineering is that branch of environmental engineering in which the basic principles of science and engineering are applied to solving the issues associated with the treatment and reuse of wastewater. The ultimate goal of wastewater engineering is the protection of public health in a manner commensurate with environmental, economic, social, and political concerns. To protect public health and the environment, it is necessary to have knowledge of (1) constituents of concern in wastewater, (2) impacts of these constituents when wastewater is dispersed into the environment, (3) the transformation and long-term fate of these constituents in treatment processes, (4) treatment methods that can be used to remove or modify the constituents found in wastewater, and (5) methods for beneficial use or disposal of solids generated by the treatment systems.

To provide an initial perspective on the field of wastewater engineering, common terminology is first defined followed by (1) a discussion of the issues that need to be addressed in the planning and design of wastewater management systems and (2) the current status and new directions in wastewater engineering.

1–1 TERMINOLOGY

In the literature, and in governmental regulations, a variety of terms have been used for individual constituents of concern in wastewater. The terminology used commonly for key concepts and terms in the field of wastewater management is summarized in Table 1–1. In some cases, confusion and undue negative perceptions arise with the use of the terms *contaminants, impurities,* and *pollutants,* which are often used interchangeably. To avoid confusion, the term *constituent* is used in this text in place of these terms to refer to an individual compound or element, such as ammonia nitrogen. The term *characteristic* is used to refer to a group of constituents, such as physical or biological characteristics.

The term "sludge" has been used for many years to signify the residuals produced in wastewater treatment. In 1994, the Water Environment Federation adopted a policy defining "biosolids" as a primarily organic, solid wastewater treatment product that can be recycled beneficially. In this policy, "solids" are defined as the residuals that are derived from the treatment of wastewater. Solids that have been treated to the point at which they are suitable for beneficial use are termed "biosolids." In this text, the terms of solids and biosolids are used extensively, but "sludge" continues to be used, especially in cases where untreated solid material and chemical residuals are referenced.

1–2 IMPACT OF REGULATIONS ON WASTEWATER ENGINEERING

From about 1900 to the early 1970s, treatment objectives were concerned primarily with (1) the removal of colloidal, suspended, and floatable material, (2) the treatment of biodegradable organics, and (3) the elimination of pathogenic organisms. Implementation in the United States of the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500), also known as the Clean Water Act (CWA), stimulated substantial changes in wastewater treatment to achieve the objectives of "fishable and swimmable" waters. Unfortunately, these objectives were not uniformly met.

From the early 1970s to about 1980, wastewater treatment objectives were based primarily on aesthetic and environmental concerns. The earlier objectives involving the reduction of biological oxygen demand (BOD), total suspended solids (TSS), and pathogenic organisms continued but at higher levels. Removal of nutrients, such as nitrogen and phosphorus, also began to be addressed, particularly in some of the inland streams and lakes, and estuaries and bays such as Chesapeake Bay and Long Island Sound. Major programs were undertaken by both state and federal agencies to achieve more effective and widespread treatment of wastewater to improve the quality of the surface waters. These programs were based, in part, on (1) an increased understanding of the environmental effects caused by wastewater discharges; (2) a greater appreciation of the adverse long-term effects caused by the discharge of some of the specific constituents

Table 1-1
Terminology commonly used in the field of wastewater engineering[a]

Term	Definition
Biosolids	Primarily an organic, semisolid wastewater product that remains after solids are stabilized biologically or chemically and are suitable for beneficial use
Class A biosolids[b]	Biosolids in which the pathogens (including enteric viruses, pathogenic bacteria, and viable helminth ova) are reduced below current detectable levels
Class B biosolids[b]	Biosolids in which the pathogens are reduced to levels that are unlikely to pose a threat to public health and the environment under specific use conditions. Class B biosolids cannot be sold or given away in bags or other containers or applied on lawns or home gardens
Characteristics (wastewater)	General classes of wastewater constituents such as physical, chemical, biological, and biochemical
Composition	The makeup of wastewater, including the physical, chemical, and biological constituents
Constituents[c]	Individual components, elements, or biological entities such as suspended solids or ammonia nitrogen
Contaminants	Constituents added to the water supply through use
Disinfection	Reduction of disease-causing microorganisms by physical or chemical means
Effluent	The liquid discharged from a processing step
Impurities	Constituents added to the water supply through use
Nonpoint sources	Sources of pollution that originate from multiple sources over a relatively large area
Nutrient	An element that is essential for the growth of plants and animals. Nutrients in wastewater, usually nitrogen and phosphorus, may cause unwanted algal and plant growths in lakes and streams
Parameter	A measurable factor such as temperature
Point sources	Pollutional loads discharged at a specific location from pipes, outfalls, and conveyance methods from either municipal wastewater treatment plants or industrial waste treatment facilities
Pollutants	Constituents added to the water supply through use
Reclamation	Treatment of wastewater for subsequent reuse application or the act of reusing treated wastewater
Recycling	The reuse of treated wastewater and biosolids for beneficial purposes
Repurification	Treatment of wastewater to a level suitable for a variety of applications including indirect or direct potable reuse
Reuse	Beneficial use of reclaimed or repurified wastewater or stabilized biosolids
Sludge	Solids removed from wastewater during treatment. Solids that are treated further are termed biosolids
Solids	Material removed from wastewater by gravity separation (by clarifiers, thickeners, and lagoons) and is the solid residue from dewatering operations

[a] Adapted, in part, from Crites and Tchobanoglous (1998)
[b] U.S. EPA (1997*b*).
[c] To avoid confusion, the term "constituents" is used in this text in place of contaminants, impurities, and pollutants.

found in wastewater; and (3) the development of national concern for the protection of the environment. As a result of these programs, significant improvements have been made in the quality of the surface waters.

Since 1980, the water-quality improvement objectives of the 1970s have continued, but the emphasis has shifted to the definition and removal of constituents that may cause long-term health effects and environmental impacts. Health and environmental concerns are discussed in more detail in the following section. Consequently, while the early treatment objectives remain valid today, the required degree of treatment has increased significantly, and additional treatment objectives and goals have been added. Therefore, treatment objectives must go hand in hand with the water quality objectives or standards established by the federal, state, and regional regulatory authorities. Important federal regulations that have brought about changes in the planning and design of wastewater treatment facilities in the United States are summarized in Table 1–2. It is interesting to note that the clean air acts of 1970 and 1990 have had a significant impact on industrial and municipal wastewater programs, primarily through the implementation of treatment facilities for the control of emissions.

Table 1–2
Summary of significant U.S. federal regulations that affect wastewater management

Regulation	Description
Clean Water Act (CWA) (Federal Water Pollution Control Act Amendments of 1972)	Establishes the National Pollution Discharge Elimination System (NPDES), a permitting program based on uniform technological minimum standards for each discharger
Water Quality Act of 1987 (WQA) (Amendment of the CWA)	Strengthens federal water quality regulations by providing changes in permitting and adds substantial penalties for permit violations. Amends solids control program by emphasizing identification and regulation of toxic pollutants in sewage sludge
40 CFR Part 503 (1993) (Sewage Sludge Regulations)	Regulates the use and disposal of biosolids from wastewater treatment plants. Limitations are established for items such as contaminants (mainly metals), pathogen content, and vector attraction
National Combined Sewer Overflow (CSO) Policy (1994)	Coordinates planning, selection, design, and implementation of CSO management practices and controls to meet requirements of CWA. Nine minimum controls and development of long-term CSO control plans are required to be implemented immediately
Clean Air Act of 1970 and 1990 Amendments	Establishes limitations for specific air pollutants and institutes prevention of significant deterioration in air quality. Maximum achievable control technology is required for any of 189 listed chemicals from "major sources," i.e., plants emitting at least 60 kg/d
40 CFR Part 60	Establishes air emission limits for sludge incinerators with capacities larger than 1000 kg/d (2200 lb/d) dry basis
Total maximum daily load (TDML) (2000) Section 303(d) of the CWA	Requires states to develop prioritized lists of polluted or threatened water bodies and to establish the maximum amount of pollutant (TMDL) that a water body can receive and still meet water quality standards

Pursuant to Section 304(d) of Public Law 92-500 (see Table 1-2), the U.S. Environmental Protection Agency (U.S. EPA) published its definition of minimum standards for secondary treatment. This definition, originally issued in 1973, was amended in 1985 to allow additional flexibility in applying the percent removal requirements of pollutants to treatment facilities serving separate sewer systems. The definition of secondary treatment is reported in Table 1-3 and includes three major effluent parameters, 5-day BOD, TSS, and pH. The substitution of 5-day carbonaceous BOD ($CBOD_5$) for BOD_5 may be made at the option of the permitting authority. These standards provided the basis for the design and operation of most treatment plants. Special interpretations of the definition of secondary treatment are permitted for publicly owned treatment works (1) served by combined sewer systems, (2) using waste stabilization ponds and trickling filters, (3) receiving industrial flows, or (4) receiving less concentrated influent wastewater from separate sewers. The secondary treatment regulations were amended further in 1989 to clarify the percent removal requirements during dry periods for treatment facilities served by combined sewers.

In 1987, Congress enacted the Water Quality Act of 1987 (WQA), the first major revision of the Clean Water Act. Important provisions of the WQA were: (1) strengthening federal water quality regulations by providing changes in permitting and adding substantial penalties for permit violations, (2) significantly amending the CWA's formal sludge control program by emphasizing the identification and regulation of toxic pollutants in sludge, (3) providing funding for state and U.S. EPA studies for defining nonpoint and toxic sources of pollution, (4) establishing new deadlines for compliance including priorities and permit requirements for stormwater, and (5) a phase-out of the construction grants program as a method of financing publicly owned treatment works (POTW).

Table 1-3
Minimum national standards for secondary treatment[a, b]

Characteristic of discharge	Unit of measurement	Average 30-day concentration[c]	Average 7-day concentration[c]
BOD_5	mg/L	30[d]	45
Total suspended solids	mg/L	30[d]	45
Hydrogen-ion concentration	pH units	Within the range of 6.0 to 9.0 at all times[e]	
$CBOD_5$[f]	mg/L	25	40

[a] *Federal Register* (1988, 1989).

[b] Present standards allow stabilization ponds and trickling filters to have higher 30-day average concentrations (45 mg/L) and 7-day average concentrations (65 mg/L) of BOD/suspended solids performance levels as long as the water quality of the receiving water is not adversely affected. Exceptions are also permitted for combined sewers, certain industrial categories, and less concentrated wastewater from separate sewers. For precise requirements of exceptions, *Federal Register* (1988) should be consulted.

[c] Not to be exceeded

[d] Average removal shall not be less than 85 percent.

[e] Only enforced if caused by industrial wastewater or by in-plant inorganic chemical addition.

[f] May be substituted for BOD_5 at the option of the permitting authority.

Recent regulations that affect wastewater facilities design include those for the treatment, disposal, and beneficial use of biosolids (40 CFR Part 503). In the biosolids regulation promulgated in 1993, national standards were set for pathogen and heavy metal content and for the safe handling and use of biosolids. The standards are designed to protect human health and the environment where biosolids are applied beneficially to land. The rule also promotes the development of a "clean sludge" (U.S. EPA, 1999).

The total maximum daily load (TMDL) program was promulgated in 2000 but is not scheduled to be in effect until 2002. The TMDL rule is designed to protect ambient water quality. A TMDL represents the maximum amount of a pollutant that a water body can receive and still meet water quality standards. A TMDL is the sum of (1) the individual waste-load allocations for point sources, (2) load allocations for nonpoint sources, (3) natural background levels, and (4) a margin of safety (U.S. EPA, 2000). To implement the rule, a comprehensive watershed-based water quality management program must be undertaken to find and control nonpoint sources in addition to conventional point source discharges. With implementation of the TMDL rule, the focus on water quality shifts from technology-based controls to preservation of ambient water quality. The end result is an integrated planning approach that transcends jurisdictional boundaries and forces different sectors, such as agriculture, water and wastewater utilities, and urban runoff managers to cooperate. Implementation of the TMDL rule will vary depending on the specific water quality objectives established for each watershed and, in some cases, will require the installation of advanced levels of treatment.

1–3 HEALTH AND ENVIRONMENTAL CONCERNS IN WASTEWATER MANAGEMENT

As research into the characteristics of wastewater has become more extensive, and as the techniques for analyzing specific constituents and their potential health and environmental effects have become more comprehensive, the body of scientific knowledge has expanded significantly. Many of the new treatment methods being developed are designed to deal with health and environmental concerns associated with findings of recent research. However, the advancement in treatment technology effectiveness has not kept pace with the enhanced constituent detection capability. Pollutants can be detected at lower concentrations than can be attained by available treatment technology. Therefore, careful assessment of health and environment effects and community concerns about these effects becomes increasingly important in wastewater management. The need to establish a dialogue with the community is important to assure that health and environmental issues are being addressed.

Water quality issues arise when increasing amounts of treated wastewater are discharged to water bodies that are eventually used as water supplies. The waters of the Mississippi River and many rivers in the eastern United States are used for municipal and industrial water supplies and as repositories for the resulting treated wastewater. In southern California, a semiarid region, increasing amounts of reclaimed wastewater are being used or are planned to be used for groundwater recharge to augment existing potable water supplies. Significant questions remain about the testing and levels of treatment necessary to protect human health where the commingling of highly treated wastewater with drinking water sources results in indirect potable reuse. Some professionals object in principle to the indirect reuse of treated wastewater for potable purposes; others express concern that current techniques are inadequate for detecting all microbial and chemical contaminants of health significance (Crook et al., 1999). Among the latter concerns are (1) the lack of sufficient information regarding the health risks posed by some microbial pathogens and chemical constituents in wastewater, (2) the nature of unknown or unidentified chemical constituents and potential pathogens, and (3) the effectiveness of treatment processes for their removal. Defining risks to public health based on sound science is an ongoing challenge.

Because new and more sensitive methods for detecting chemicals are available and methods have been developed that better determine biological effects, constituents that were undetected previously are now of concern (see Fig. 1–2). Examples of such chemical constituents found in both surface and groundwaters include: *n*-nitrosodimethylamine (NDMA), a principal ingredient in rocket fuel, methyl tertiary butyl ether (MTBE), a highly soluble gasoline additive, medically active substances including endocrine disruptors, pesticides, industrial chemicals, and phenolic compounds commonly found in nonionic surfactants. Endocrine-disrupting chemicals are a special health concern as they can mimic hormones produced in vertebrate animals by causing an exaggerated response, or they can block the effects of a hormone on the body (Trussell, 2000). These chemicals can cause problems with development, behavior, and reproduction in a variety of species. Increases in testicular, prostate, and breast cancers have been blamed on endocrine-disruptive chemicals (Roefer et al., 2000). Although treatment of these chemicals is not currently a mission of municipal wastewater treatment, wastewater treatment facilities may have to be designed to deal with these chemicals in the future.

Other health concerns relate to: (1) the release of volatile organic compounds (VOCs) and toxic air contaminants (TACs) from collection and treatment facilities, (2) chlorine disinfection, and (3) disinfection byproducts (DBPs). Odors are one of the most serious environmental concerns to the public. New techniques for odor measurement are used to quantify the development and movement of odors that may emanate from wastewater facilities, and special efforts are being made to design facilities that minimize the development of odors, contain them effectively, and provide proper treatment for their destruction (see Fig. 1–3).

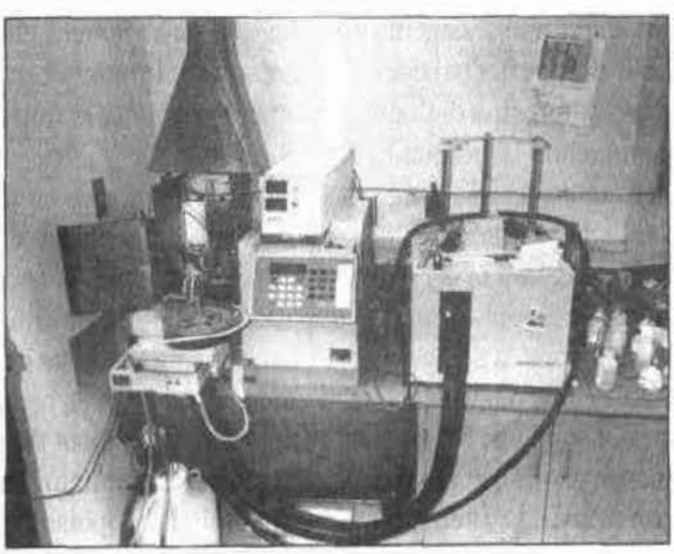


Figure 1–2

Atomic adsorption spectrometer used for the detection of metals. Photo was taken in wastewater treatment plant laboratory. The use of such analytical instruments is now commonplace at wastewater treatment plants.

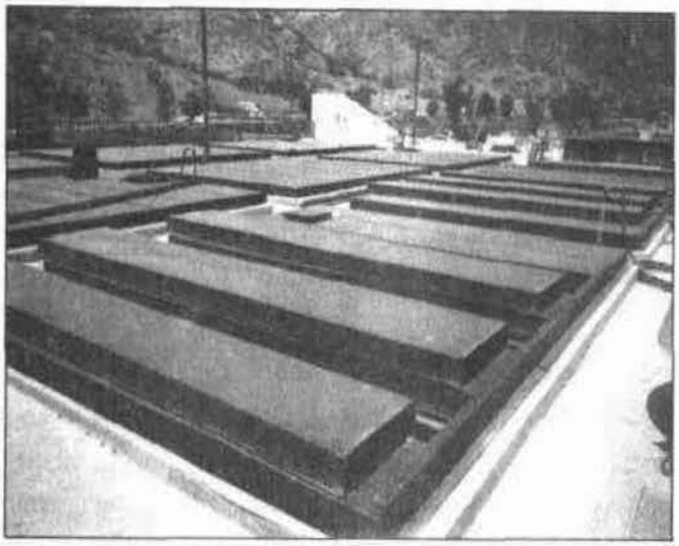


Figure 1-3

Covered treatment plant facilities for the control of odor emissions.

Many industrial wastes contain VOCs that may be flammable, toxic, and odorous, and may be contributors to photochemical smog and tropospheric ozone. Provisions of the Clean Air Act and local air quality management regulations are directed toward (1) minimizing VOC releases at the source, (2) containing wastewater and their VOC emissions (i.e., by adding enclosures), treating wastewater for VOC removal, and collecting and treating vapor emissions from wastewater. Many VOCs, classified as TACs, are discharged to the ambient atmosphere and transported to downwind receptors. Some air management districts are enforcing regulations based on excess cancer risks for lifetime exposures to chemicals such as benzene, trichloroethylene, chloroform, and methylene chloride (Card and Corsi, 1992). Strategies for controlling VOCs at wastewater treatment plants are reviewed in Chap. 5.

Effluents containing chlorine residuals are toxic to aquatic life, and, increasingly, provisions to eliminate chlorine residuals are being instituted. Other important health issues relate to the reduction of disinfection byproducts (DBPs) that are potential carcinogens and are formed when chlorine reacts with organic matter. To achieve higher and more consistent microorganism inactivation levels, improved performance of disinfection systems must be addressed. In many communities, the issues of safety in the transporting, storing, and handling of chlorine are also being examined.

1-4 WASTEWATER CHARACTERISTICS

Prior to about 1940, most municipal wastewater was generated from domestic sources. After 1940, as industrial development in the United States grew significantly, increasing amounts of industrial wastewater have been and continue to be discharged to municipal collection systems. The amounts of heavy metals and synthesized organic compounds generated by industrial activities have increased, and some 10,000 new organic compounds are added each year. Many of these compounds are now found in the wastewater from most municipalities and communities.

As technological changes take place in manufacturing, changes also occur in the compounds discharged and the resulting wastewater characteristics. Numerous compounds generated from industrial processes are difficult and costly to treat by conventional wastewater treatment processes. Therefore, effective industrial pretreatment becomes an essential part of an overall water quality management program. Enforcement of an industrial pretreatment program is a daunting task, and some of the regulated pollutants still escape to the municipal wastewater collection system and must be treated. In the future with the objective of pollution prevention, every effort should be made by industrial dischargers to assess the environmental impacts of any new compounds that may enter the wastewater stream before being approved for use. If a compound cannot be treated effectively with existing technology, it should not be used.

Improved Analytical Techniques

Great strides in analytical techniques have been made with the development of new and more sophisticated instrumentation. While most constituent concentrations are reported in milligrams per liter (mg/L), measurements in micrograms per liter (μg/L) and nanograms per liter (ng/L) are now common. As detection methods become more sensitive and a broader range of compounds are monitored in water supplies, more contaminants that affect humans and the environment will be found. Many trace compounds and microorganisms, such as *Giardia lamblia* and *Cryptosporidium parvum,* have been identified that potentially may cause adverse health effects. Increased analytical sophistication also allows the scientist and engineer to gain greater knowledge of the behavior of wastewater constituents and how they affect process performance and effluent quality.

Importance of Improved Wastewater Characterization

Because of changing wastewater characteristics and the imposition of stricter limits on wastewater discharges and biosolids that are used beneficially, greater emphasis is being placed on wastewater characterization. Because process modeling is widely used in the design and optimization of biological treatment processes (e.g., activated sludge), thorough characterization of wastewater, particularly wastewaters containing industrial waste, is increasingly important. Process modeling for activated sludge as it is currently conceived requires experimental assessment of kinetic and stoichiometric constants. Fractionization of organic nitrogen, chemical oxygen demand (COD), and total organic carbon into soluble and particulate constituents is now used to optimize the performance of both existing and proposed new biological treatment plants designed to achieve nutrient removal. Techniques from the microbiological sciences, such as RNA and DNA typing, are being used to identify the active mass in biological treatment processes. Because an understanding of the nature of wastewater is fundamental to the design and operation of wastewater collection, treatment, and reuse facilities, a detailed discussion of wastewater constituents is provided in Chap. 2.

1–5 WASTEWATER TREATMENT

Wastewater collected from municipalities and communities must ultimately be returned to receiving waters or to the land or reused. The complex question facing the design engineer and public health officials is: What levels of treatment must be achieved in a given application—beyond those prescribed by discharge permits—to ensure protection of public health and the environment? The answer to this question requires detailed analyses of local conditions and needs, application of scientific knowledge and engineering judgment based on past experience, and consideration of federal, state, and local regulations. In some cases, a detailed risk assessment may be required. An overview of wastewater treatment is provided in this section. The reuse and disposal of biosolids, vexing problems for some communities, are discussed in the following section.

Treatment Methods

Methods of treatment in which the application of physical forces predominate are known as *unit operations*. Methods of treatment in which the removal of contaminants is brought about by chemical or biological reactions are known as *unit processes*. At the present time, unit operations and processes are grouped together to provide various levels of treatment known as preliminary, primary, advanced primary, secondary (without or with nutrient removal), and advanced (or tertiary) treatment (see Table 1–4). In preliminary treatment, gross solids such as large objects, rags, and grit are removed that may damage equipment. In primary treatment, a physical operation, usually sedimentation, is used to remove the floating and settleable materials found in wastewater (see Fig. 1–4). For advanced primary treatment, chemicals are added to enhance the removal of suspended solids and, to a lesser extent, dissolved solids. In secondary treatment, biological and chemical processes are used to remove most of the organic matter. In advanced treatment, additional combinations of unit operations and processes are used to remove residual suspended solids and other constituents that are not reduced significantly by conventional secondary treatment. A listing of unit operations and processes used for

Table 1–4
Levels of wastewater treatment[a]

Treatment level	Description
Preliminary	Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems
Primary	Removal of a portion of the suspended solids and organic matter from the wastewater
Advanced primary	Enhanced removal of suspended solids and organic matter from the wastewater. Typically accomplished by chemical addition or filtration
Secondary	Removal of biodegradable organic matter (in solution or suspension) and suspended solids. Disinfection is also typically included in the definition of conventional secondary treatment
Secondary with nutrient removal	Removal of biodegradable organics, suspended solids, and nutrients (nitrogen, phosphorus, or both nitrogen and phosphorus)
Tertiary	Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this definition
Advanced	Removal of dissolved and suspended materials remaining after normal biological treatment when required for various water reuse applications

[a]Adapted, in part, from Crites and Tchobanoglous (1998).

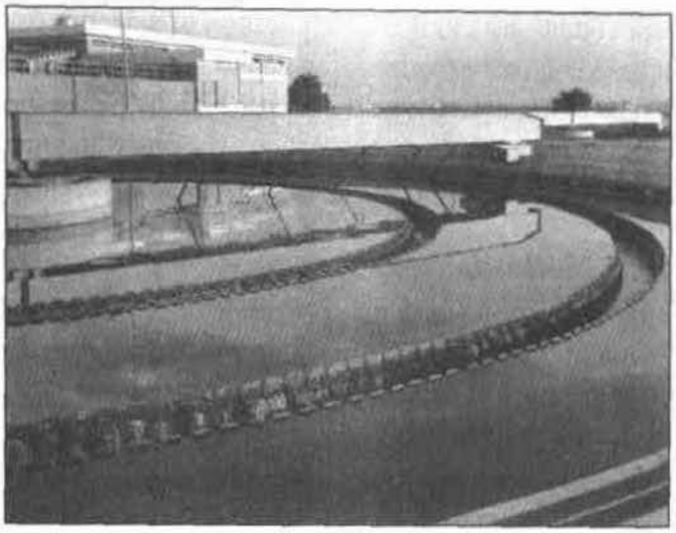


Figure 1–4

Typical primary sedimentation tanks used to remove floating and settleable material from wastewater.

the removal of major constituents found in wastewater and addressed in this text is presented in Table 1–5.

About 20 years ago, biological nutrient removal (BNR)—for the removal of nitrogen and phosphorus—was viewed as an innovative process for advanced wastewater treatment. Because of the extensive research into the mechanisms of BNR, the advantages of its use, and the number of BNR systems that have been placed into operation, nutrient removal, for all practical purposes, has become a part of conventional wastewater treatment. When compared to chemical treatment methods, BNR uses less chemical, reduces the production of waste solids, and has lower energy consumption. Because of the importance of BNR in wastewater treatment, BNR is integrated into the discussion of theory, application, and design of biological treatment systems.

Land treatment processes, commonly termed "natural systems," combine physical, chemical, and biological treatment mechanisms and produce water with quality similar to or better than that from advanced wastewater treatment. Natural systems are not covered in this text as they are used mainly with small treatment systems; descriptions may be found in the predecessor edition of this text (Metcalf & Eddy, 1991) and in Crites and Tchobanoglous (1998) and Crites et al. (2000).

Current Status

Up until the late 1980s, conventional secondary treatment was the most common method of treatment for the removal of BOD and TSS. In the United States, nutrient removal was used in special circumstances, such as in the Great Lakes area, Florida, and the Chesapeake Bay, where sensitive nutrient-related water quality conditions were identified. Because of nutrient enrichment that has led to eutrophication and water quality degradation (due in part to point source discharges), nutrient removal processes have evolved and now are used extensively in other areas as well.

As a result of implementation of the Federal Water Pollution Control Act Amendments, significant data have been obtained on the numbers and types of wastewater facilities used and needed in accomplishing the goals of the program. Surveys are conducted by U.S. EPA to track these data, and the results of the 1996 Needs Assessment Survey (U.S. EPA, 1997*a*) are reported in Tables 1–6 and 1–7. The number and types of

Table 1-5
Unit operations and processes used to remove constituents found in wastewater

Constituent	Unit operation or process	See Chap.
Suspended solids	Screening	5
	Grit removal	5
	Sedimentation	5
	High-rate clarification	5
	Flotation	5
	Chemical precipitation	6
	Depth filtration	11
	Surface filtration	11
Biodegradable organics	Aerobic suspended growth variations	8, 14
	Aerobic attached growth variations	9
	Anaerobic suspended growth variations	10, 14
	Anaerobic attached growth variations	10
	Lagoon variations	8
	Physical-chemical systems	6, 11
	Chemical oxidation	6
	Advanced oxidation	11
	Membrane filtration	8, 11
Nutrients		
Nitrogen	Chemical oxidation (breakpoint chlorination)	6
	Suspended-growth nitrification and denitrification variations	8
	Fixed-film nitrification and denitrification variations	9
	Air stripping	11
	Ion exchange	11
Phosphorus	Chemical treatment	6
	Biological phosphorus removal	8, 9
Nitrogen and phosphorus	Biological nutrient removal variations	8, 9
Pathogens	Chlorine compounds	12
	Chlorine dioxide	12
	Ozone	12
	Ultraviolet (UV) radiation	12
Colloidal and dissolved solids	Membranes	11
	Chemical treatment	11
	Carbon adsorption	11
	Ion exchange	11
Volatile organic compounds	Air stripping	5, 11
	Carbon adsorption	11
	Advanced oxidation	11
Odors	Chemical scrubbers	15
	Carbon adsorption	11, 15
	Biofilters	15
	Compost filters	15

facilities needed in the future (~20 yr) are also shown in Table 1–7. These data are useful in forming an overall view of the current status of wastewater treatment in the United States.

The municipal wastewater treatment enterprise is composed of over 16,000 plants that are used to treat a total flow of about 1400 cubic meters per second (m^3/s) [32,000 million gallons per day (Mgal/d)]. Approximately 92 percent of the total existing flow is handled by plants having a capacity of 0.044 m^3/s [1 million gallons per day (Mgal/d)] and larger. Nearly one-half of the present design capacity is situated in plants

Table 1–6
Number of U.S. wastewater treatment facilities by flow range (1996)[a]

Flow ranges		Number of facilities	Total existing flowrate	
Mgal/d	**m³/s**		**Mgal/d**	**m³/s**
0.000–0.100	0.000–0.00438	6,444	287	12.57
0.101–1.000	0.0044–0.0438	6,476	2,323	101.78
1.001–10.000	0.044–0.438	2,573	7,780	340.87
10.001–100.00	0.44–4.38	446	11,666	511.12
>100.00	>4.38	47	10,119	443.34
Other[b]		38	—	—
Total		16,204	32,175	1,409.68

[a] Adapted from U.S. EPA (1997a)
[b] Flow data unknown.

Table 1–7
Number of U.S. wastewater treatment facilities by design capacity in 1996 and in the future when needs are met[a]

Level of treatment	Existing facilities			Future facilities (when needs are met)		
	Number of facilities	**Mgal/d**	**m³/s**	**Number of facilities**	**Mgal/d**	**m³/s**
Less than secondary	176	3,054	133.80	61	601	26.33
Secondary	9,388	17,734	776.98	9,738	17,795	779.65
Greater than secondary[b]	4,428	20,016	876.96	6,135	28,588	1,252.53
No discharge[c]	2,032	1,421	62.26	2,369	1,803	78.99
Total	16,024	42,225	1,850.00	18,303	48,787	2,137.50

[a] Adapted from U.S. EPA (1997a).
[b] Treatment plants that meet effluent standards higher than those given in Table 1–3.
[c] Plants that do not discharge to a water body and use some form of land application.

providing greater than secondary treatment. Thus, the basic material presented in this text is directed toward the design of plants larger than 0.044 m^3/s (1 Mgal/d) with the consideration that many new designs will provide treatment greater than secondary.

In the last 10 years, many plants have been designed using BNR. Effluent filtration has also been installed where the removal of residual suspended solids is required. Filtration is especially effective in improving the effectiveness of disinfection, especially for ultraviolet (UV) disinfection systems, because (1) the removal of larger particles of suspended solids that harbor bacteria enhances the reduction in coliform bacteria and (2) the reduction of turbidity improves the transmittance of UV light. Effluent reuse systems, except for many that are used for agricultural irrigation, almost always employ filtration.

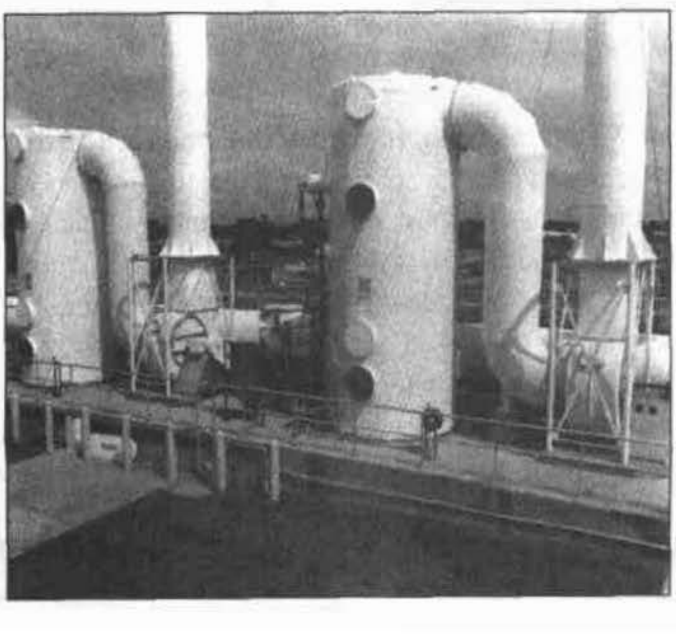
New Directions and Concerns

New directions and concerns in wastewater treatment are evident in various specific areas of wastewater treatment. The changing nature of the wastewater to be treated, emerging health and environmental concerns, the problem of industrial wastes, and the impact of new regulations, all of which have been discussed previously, are among the most important. Further, other important concerns include: (1) aging infrastructure, (2) new methods of process analysis and control, (3) treatment plant performance and reliability, (4) wastewater disinfection, (5) combined sewer overflows, (6) impacts of stormwater and sanitary overflows and nonpoint sources of pollution, (7) separate treatment of return flows, (8) odor control (see Fig. 1–5) and the control of VOC emissions, and (9) retrofitting and upgrading wastewater treatment plants.

Aging Infrastructure. Some of the problems that have to be addressed in the United States deal with renewal of the aging wastewater collection infrastructure and upgrading of treatment plants. Issues include repair and replacement of leaking and undersized sewers, control and treatment of overflows from sanitary and combined collection systems, control of nonpoint discharges, and upgrading treatment systems to achieve higher removal levels of specific constituents. Upgrading and retrofitting treatment plants is addressed later in this section.

Figure 1–5

Facilities used for chemical treatment of odors from treatment facilities.



Portions of the collection systems, particularly those in the older cities in the eastern and midwestern United States, are older than the treatment plants. Sewers constructed of brick and vitrified clay with mortar joints, for example, are still used to carry sanitary wastewater and stormwater. Because of the age of the pipes and ancillary structures, the types of materials and methods of construction, and lack of repair, leakage is common. Leakage is in the form of both infiltration and inflow where water enters the collection system, and exfiltration where water leaves the pipe. In the former case, extraneous water has to be collected and treated, and oftentimes may overflow before treatment, especially during wet weather. In the latter case, exfiltration causes untreated wastewater to enter the groundwater and/or migrate to nearby surface water bodies. It is interesting to note that while the standards for treatment have increased significantly, comparatively little or no attention has been focused on the discharge of untreated wastewater from sewers through exfiltration. In the future, however, leaking sewers are expected to become a major concern and will require correction.

Process Analysis and Control. Because of the changing characteristics of the wastewater (discussed above), studies of wastewater treatability are increasing, especially with reference to the treatment of specific constituents. Such studies are especially important where new treatment processes are being considered. Therefore, the engineer must understand the general approach and methodology involved in: (1) assessing the treatability of a wastewater (domestic or industrial), (2) conducting laboratory and pilot plant studies, and (3) translating experimental data into design parameters.

Computational fluid dynamics (CFD), computer-based computational methods for solving the fundamental equations of fluid dynamics (i.e., continuity, momentum, and energy), is now being used to improve and optimize the hydraulic performance of wastewater treatment facilities. Applications of CFD include the design of new systems or the optimization of systems such as vortex separators, mixing tanks, sedimentation tanks, dissolved-air flotation units, and chlorine contact tanks to reduce or eliminate dead zones and short circuiting. Improved UV disinfection systems are being designed using CFD. One of the main advantages of CFD is simulating a range of operating conditions to evaluate performance before designs and operating changes are finalized. Another advantage is that dynamic models can be integrated with the process control system to optimize ongoing operation.

Treatment Process Performance and Reliability. Important factors in process selection and design are treatment plant performance and reliability in meeting permit requirements. In most discharge permits, effluent constituent requirements, based on 7-day and 30-day average concentrations, are specified (see Table 1–3). Because wastewater treatment effluent quality is variable because of varying organic loads, changing environmental conditions, and new industrial discharges, it is necessary to design the treatment system to produce effluent concentrations equal to or less than the limits prescribed by the discharge permit. Reliability is especially important where critical water quality parameters have to be maintained such as in reuse applications. On-line monitoring of critical parameters such as total organic carbon (TOC), transmissivity, turbidity, and dissolved oxygen is necessary for building a database and for improving process control. Chlorine residual monitoring is useful for dosage control, and pH monitoring assists in controlling nitrification systems.

Treatment plant reliability can be defined as the probability that a system can meet established performance criteria consistently over extended periods of time. Two components of reliability, the inherent reliability of the process and mechanical reliability, are discussed in Chap. 15. As improved microbiological techniques are developed, it will be possible to optimize the disinfection process.

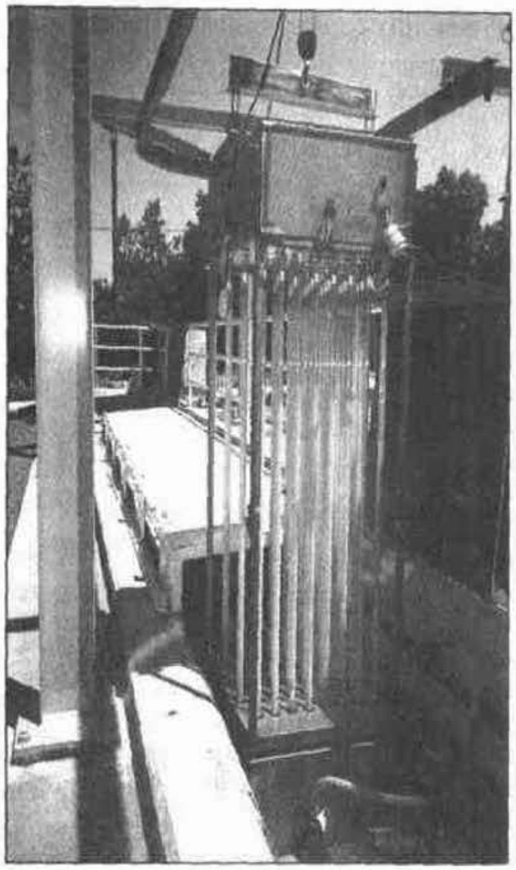
The need to conserve energy and resources is fundamental to all aspects of wastewater collection, treatment, and reuse. Operation and maintenance costs are extremely important to operating agencies because these costs are funded totally with local moneys. Detailed energy analyses and audits are important parts of treatment plant design and operation as significant savings can be realized by selecting energy-efficient processes and equipment. Large amounts of electricity are used for aeration that is needed for biological treatment. Typically, about one-half of the entire plant electricity usage is for aeration. In the design of wastewater treatment plants power use can be minimized by paying more careful attention to plant siting, selecting energy-efficient equipment, and designing facilities to recover energy for in-plant use. Energy management in treatment plant design and operation is also considered in Chap. 15.

Wastewater Disinfection. Changes in regulations and the development of new technologies have affected the design of disinfection systems. Gene probes are now being used to identify where specific groups of organisms are found in treated secondary effluent (i.e., in suspension or particle-associated). Historically, chlorine has been the disinfectant of choice for wastewater. With the increasing number of permits requiring low or nondetectable amounts of chlorine residual in treated effluents, dechlorination facilities have had to be added, or chlorination systems have been replaced by alternative disinfection systems such as ultraviolet (UV) radiation (see Fig. 1-6). Concerns about chemical safety have also affected design considerations of chlorination and dechlorination systems. Improvements that have been made in UV lamp and ballast design within the past 10 years have improved significantly the performance and reliability of UV disinfection systems. Effective guidelines have also been developed for the application and design of UV systems (NWRI, 2000). Capital and operating costs have also been lowered. It is anticipated that the application of UV for treated drinking water and for stormwater will continue to increase in the future. Because UV produces essentially no troublesome byproducts and is also effective in the reduction of NDMA and other related compounds, its use for disinfection is further enhanced as compared to chlorine compounds.

Combined Sewer Overflows (CSOs), Sanitary Sewer Overflows (SSOs), and Nonpoint Sources. Overflows from combined sewer and sanitary sewer collection systems have been recognized as difficult problems requiring solution, especially for many of the older cities in the United States. The problem has become more critical as greater development changes the amount and characteristics of stormwater runoff and increases the channelization of runoff into storm, combined, and sanitary collection systems. Combined systems carry a mixture of wastewater and stormwater runoff and, when the capacity of the interceptors is reached, overflows occur to the receiving waters. Large overflows can impact receiving water quality and can prevent attainment of mandated standards. Recreational beach closings and shellfish

Figure 1-6

UV lamps used for the disinfection of wastewater.



bed closures have been attributed to CSOs (Lape and Dwyer, 1994). Federal regulations for CSOs are still under development and have not been issued at the time of writing this text (2001).

A combination of factors has resulted in the release of untreated wastewater from parts of sanitary collection systems. These releases are termed sanitary system overflows (SSOs). The SSOs may be caused by (1) the entrance of excessive amounts of stormwater, (2) blockages, or (3) structural, mechanical, or electrical failures. Many overflows result from aging collection systems that have not received adequate upgrades, maintenance, and repair. The U.S. EPA has estimated that at least 40,000 overflows per year occur from sanitary collection systems. The untreated wastewater from these overflows represents threats to public health and the environment. The U.S. EPA is proposing to clarify and expand permit requirements for municipal sanitary collection systems under the Clean Water Act that will result in reducing the frequency and occurrence of SSOs (U.S. EPA 2001). At the time of writing this text (2001) the proposed regulations are under review. The U.S. EPA estimates that nearly $45 billion is required for constructing facilities for controlling CSOs and SSOs in the United States (U.S. EPA, 1997*a*).

The effects of pollution from nonpoint sources are growing concerns as evidenced by the outbreak of gastrointestinal illness in Milwaukee traced to the oocysts of *Cryptosporidium parvum*, and the occurrence of *Pfiesteria piscicida* in the waters of Maryland and North Carolina. *Pfiesteria* is a form of algae that is very toxic to fish life. Runoff from pastures and feedlots has been attributed as a potential factor that triggers the effects of these microorganisms.

The extent of the measures that will be needed to control nonpoint sources is not known at this time of writing this text (2001). When studies for assessing TMDLs are completed (estimated to be in 2008), the remedial measures for controlling nonpoint sources may require financial resources rivaling those for CSO and SSO correction.

Treatment of Return Flows. Perhaps one of the significant future developments in wastewater treatment will be the provision of separate facilities for treating return flows from biosolids and other processing facilities. Treatment of return flows will be especially important where low levels of nitrogen are to be achieved in the treated effluent. Separate treatment facilities may include (1) steam stripping for removal of ammonia from biosolids return flows, now typically routed to the plant headworks; (2) high-rate sedimentation for removing fine and difficult-to-settle colloidal material that also shields bacteria from disinfection; (3) flotation and high-rate sedimentation for treating filter backwash water to reduce solids loading on the liquid treatment process; and (4) soluble heavy metals removal by chemical precipitation to meet more stringent discharge requirements. The specific treatment system used will depend on the constituents that will impact the wastewater treatment process.

Control of Odors and VOC Emissions. The control of odors and in particular the control of hydrogen sulfide generation is of concern in collection systems and at treatment facilities. The release of hydrogen sulfide to the atmosphere above sewers and at treatment plant headworks has occurred in a number of locations. The release of excess hydrogen sulfide has led to the accelerated corrosion of concrete sewers, headworks structures, and equipment, and to the release of odors. The control of odors is of increasing environmental concern as residential and commercial development continues to approach existing treatment plant locations. Odor control facilities including covers for process units, special ventilation equipment, and treatment of odorous gases need to be integrated with treatment plant design. Control of hydrogen sulfide is also fundamental to maintaining system reliability.

The presence of VOCs and VTOCs in wastewater has also necessitated the covering of treatment plant headworks and primary treatment facilities and the installation of special facilities to treat the compounds before they are released. In some cases, improved industrial pretreatment has been employed to eliminate these compounds.

Retrofitting and Upgrading Wastewater Treatment Plants. Large numbers of wastewater treatment plants were constructed in the United States during the 1970s and 1980s when large sums of federal money were available for implementation of the CWA. Much of the equipment, now over 20 years old, is reaching the end of its useful life and will need to be replaced. Process changes to improve performance, meet stricter permit requirements, and increase capacity will also be needed. For these reasons, significant future efforts in the planning and design of wastewater treatment plants in the United States will be directed to modifying, improving, and expanding existing treatment facilities. Fewer completely new treatment plants will be constructed. In developing countries, opportunities for designing and building completely new facilities may be somewhat greater. Upgrading and retrofitting treatment plants is addressed in Chap. 15.

Future Trends in Wastewater Treatment

In the U.S. EPA Needs Assessment Survey, the total treatment plant design capacity is projected to increase by about 15 percent over the next 20 to 30 years (see Table 1–7). During this period, the U.S. EPA estimates that approximately 2,300 new plants may have to be built, most of which will be providing a level of treatment greater than secondary. The design capacity of plants providing greater than secondary treatment is expected to increase by 40 percent in the future (U.S. EPA, 1997). Thus, it is clear that the future trends in wastewater treatment plant design will be for facilities providing higher levels of treatment.

Some of the innovative treatment methods being utilized in new and upgraded treatment facilities include vortex separators, high rate clarification, membrane bioreactors, pressure-driven membrane filtration (ultrafiltration and reverse osmosis—see Fig. 1–7), and ultraviolet radiation (low-pressure, low- and high-intensity UV lamps, and medium-pressure, high-intensity UV lamps). Some of the new technologies, especially those developed in Europe, are more compact and are particularly well suited for plants where available space for expansion is limited.

In recent years, numerous proprietary wastewater treatment processes have been developed that offer potential savings in construction and operation. This trend will likely continue, particularly where alternative treatment systems are evaluated or facilities are privatized. Privatization is generally defined as a public-private partnership in which the private partner arranges the financing, design, building, and operation of the treatment facilities. In some cases, the private partner may own the facilities. The reasons for privatization, however, go well beyond the possibility of installing proprietary processes. In the United States, the need for private financing appears to be the principal rationale for privatization; the need to preserve local control appears to be the leading pragmatic rationale against privatization (Dreese and Beecher, 1997).

1–6 WASTEWATER RECLAMATION AND REUSE

In many locations where the available supply of fresh water has become inadequate to meet water needs, it is clear that the once-used water collected from communities and municipalities must be viewed not as a waste to be disposed of but as a resource that

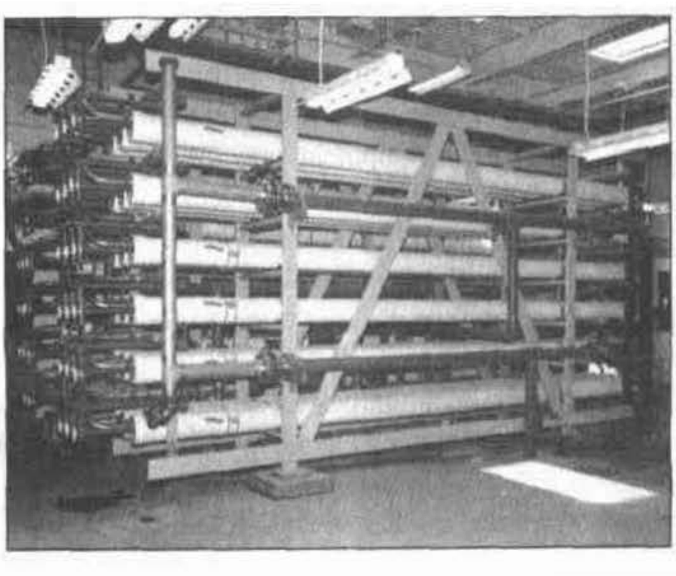


Figure 1–7

Reverse osmosis membrane system used for the removal of residual suspended solids remaining after conventional secondary treatment.

must be reused. The concept of reuse is becoming accepted more widely as other parts of the country experience water shortages. The use of dual water systems, such as now used in St. Petersburg in Florida and Rancho Viejo in California, is expected to increase in the future. In both locations, treated effluent is used for landscape watering and other nonpotable uses. Satellite reclamation systems such as those used in the Los Angeles basin, where wastewater flows are mined (withdrawn from collection systems) for local treatment and reuse, are examples where transportation and treatment costs of reclaimed water can be reduced significantly. Because water reuse is expected to become of even greater importance in the future, reuse applications are considered in Chap. 13.

Current Status

Most of the reuse of wastewater occurs in the arid and semiarid western and southwestern states of the United States; however, the number of reuse projects is increasing in the south especially in Florida and South Carolina. Because of health and safety concerns, water reuse applications are mostly restricted to nonpotable uses such as landscape and agricultural irrigation. In a report by the National Research Council (1998), it was concluded that indirect potable reuse of reclaimed water (introducing reclaimed water to augment a potable water source before treatment) is viable. The report also stated that direct potable reuse (introducing reclaimed water directly into a water distribution system) was not practicable. Because of the concerns about potential health effects associated with the reclaimed water reuse, plans are proceeding slowly about expanding reuse beyond agricultural and landscape irrigation, groundwater recharge for repelling saltwater intrusion, and nonpotable industrial uses (e.g., boiler water and cooling water).

New Directions and Concerns

Many of the concerns mentioned in the National Research Council (NRC, 1998) report regarding potential microbial and chemical contamination of water supplies also apply to water sources that receive incidental or unplanned wastewater discharges. A number of communities use water sources that contain a significant wastewater component. Even though these sources, after treatment, meet current drinking water standards, the growing knowledge of the potential impacts of new trace contaminants raises concern. Conventional technologies for both water and wastewater treatment may be incapable of reducing the levels of trace contaminants below where they are not considered as a potential threat to public health. Therefore, new technologies that offer significantly improved levels of treatment or constituent reduction need to be tested and evaluated. Where indirect potable reuse is considered, risk assessment also becomes an important component of a water reuse investigation. Risk assessment is addressed in Chap. 13.

Future Trends in Technology

Technologies that are suitable for water reuse applications include membranes (pressure-driven, electrically driven, and membrane bioreactors), carbon adsorption, advanced oxidation, ion exchange, and air stripping. Membranes are most significant developments as new products are now available for a number of treatment applications. Membranes had been limited previously to desalination, but they are being tested increasingly for wastewater applications to produce high-quality treated effluent suitable for reclamation. Increased levels of contaminant removal not only enhance the product for reuse but also lessen health risks. As indirect potable reuse intensifies to augment existing water supplies, membranes are expected to be one of the predominant treatment technologies. Advanced wastewater treatment technologies are discussed in Chap. 11, and water reuse is considered in Chap. 13.

1–7 BIOSOLIDS AND RESIDUALS MANAGEMENT

The management of the solids and concentrated contaminants removed by treatment has been and continues to be one of the most difficult and expensive problems in the field of wastewater engineering. Wastewater solids are organic products that can be used beneficially after stabilization by processes such as anaerobic digestion and composting. With the advent of regulations that encourage biosolids use, significant efforts have been directed to producing a "clean sludge" (Class A biosolids—see definition in Table 1–1) that meets heavy metals and pathogen requirements and is suitable for land application. Regulations for Class B biosolids call for reduced density in pathogenic bacteria and enteric viruses, but not to the levels of Class A biosolids. Further, the application of Class B biosolids to land is strictly regulated, and distribution for home use is prohibited (see Table 1–1).

Other treatment plant residuals such as grit and screenings have to be rendered suitable for disposal, customarily in landfills. Landfills usually require some form of dewatering to limit moisture content. With the increased use of membranes, especially in wastewater reuse applications, a new type of residual, brine concentrate, requires further processing and disposal. Solar evaporation ponds and discharge to a saltwater environment are only viable in communities where suitable and environmental geographic conditions prevail; brine concentration and residuals solidification are generally too complex and costly to implement.

Current Status

Treatment technologies for solids processing have focused on traditional methods such as thickening, stabilization, dewatering, and drying. Evolution in the technologies has not occurred as rapidly as in liquid treatment processes, but some significant improvements have occurred. Centrifuges that produce a sludge cake with higher solids content, egg-shaped digesters that improve operation, and dryers that minimize water content are just a few examples of products that have come into use in recent years. These developments are largely driven by the need to produce biosolids that are clean, have less volume, and can be used beneficially.

Landfills still continue to be used extensively for the disposal of treatment plant solids, either in sludge-only monofills or with municipal solid waste. The number and capacity of landfills, however, have been reduced, and new landfill locations that meet public and regulatory acceptance and economic requirements are increasingly difficult to find. Incineration of solids by large municipalities continues to be practiced, but incineration operation and emission control are subject to greater regulatory restrictions and adverse public scrutiny. Alternatives to landfills and incineration include land application of liquid or dried biosolids and composting for distribution and marketing. Land application of biosolids is used extensively to reclaim marginal land for productive uses and to utilize nutrient content in the biosolids. Composting, although a more expensive alternative, is a means of stabilizing and distributing biosolids for use as a soil amendment. Alkaline stabilization of biosolids for land application is also used but to a lesser extent.

New Directions and Concerns

Over the last 30 years, the principal focus in wastewater engineering has been on improving the quality of treated effluent through the construction of secondary and advanced wastewater treatment plants. With improved treatment methods, higher levels of treatment must be provided not only for conventional wastewater constituents but also for the removal of specific compounds such as nutrients and heavy metals. A byproduct of these efforts has been the increased generation of solids and biosolids per person served by a municipal wastewater system. In many cases, the increase in solids production clearly taxes the capacity of existing solids processing and disposal methods.

In addition to the shear volume of solids that has to be handled and processed, management options continue to be reduced through stricter regulations. Limitations that affect options are: (1) landfill sites are becoming more difficult to find and have permitted, (2) air emissions from incinerators are more closely regulated, and (3) new requirements for the land application of biosolids have been instituted. In large urban areas, haul distances to landfill or land application sites have significantly affected the cost of solids processing and disposal. Few new incinerators are being planned because of difficulties in finding suitable sites and obtaining permits. Emission control regulations of the Clean Air Act also require the installation of complex and expensive pollution control equipment.

More communities are looking toward (1) producing Class A biosolids to improve beneficial reuse opportunities or (2) implementing a form of volume reduction, thus lessening the requirements for disposal. The issue—"are Class A biosolids clean enough?"—will be of ongoing concern to the public. The continuing search for better methods of solids processing, disposal, and reuse will remain as one of the highest priorities in the future. Additionally, developing meaningful dialogue with the public about health and environmental effects will continue to be very important.

Future Trends in Biosolids Processing

New solids processing systems have not been developed as rapidly as liquid unit operations and processes. Anaerobic digestion remains the principal process for the stabilization of solids. Egg-shaped digesters, developed in Europe for anaerobic digestion, are being used more extensively in the United States because of advantages of easier operation, lower operation and maintenance costs, and, in some cases, increased volatile solids destruction (which also increases the production of reusable methane gas) (see Fig. 1–8). Other developments in anaerobic and aerobic digestion include temperature-phased anaerobic digestion and autothermal aerobic digestion (ATAD), another process developed in Europe. These processes offer advantages of improved volatile solids destruction and the production of stabilized biosolids that meet Class A requirements.

High solids centrifuges and heat dryers are expected to be used more extensively. High solids centrifuges extract a greater percentage of the water in liquid sludge, thus providing a dryer cake. Improved dewatering not only reduces the volume of solids

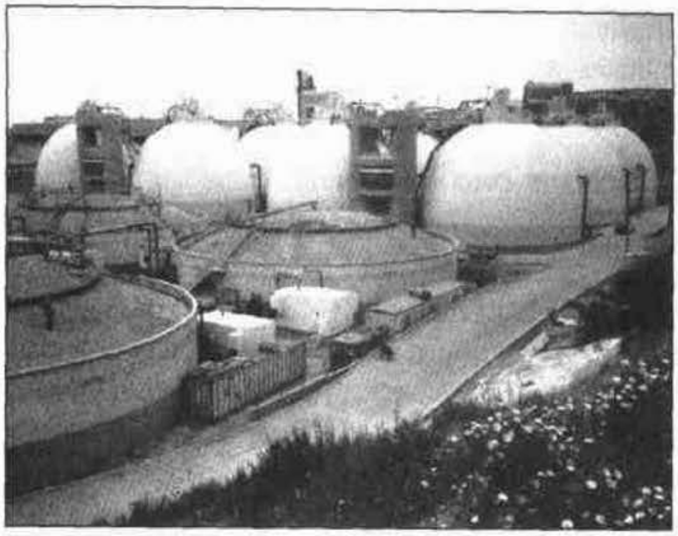


Figure 1-8

Egg-shaped digesters used for the anaerobic treatment of biosolids.

requiring further processing and disposal, but allows composting or subsequent drying to be performed more efficiently. Heat drying provides further volume reduction and improves the quality of the product for potential commercial marketing. Each of the newer methods of biosolids processing is described in Chap. 14.

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