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Municipal Wastewater, Sewage Sludge, and Agriculture

HISTORICAL PERSPECTIVES

Wastewater

Large-scale cropland application of municipal wastewater was first practiced about 150 years ago after flush toilets and sewerage systems were introduced into cities in western Europe and North America. The wastewater was discharged without any treatment, and receiving watercourses became heavily polluted. The problem is illustrated by the situation in London in the 1850s when the "stink" from the River Thames obliged the House of Parliament to drench their drapes in chloride of lime (Snow, 1936). Water supplies drawn from the river below the sewage outfall were found by Dr. John Snow to be the source of the cholera outbreaks of the period. The partial solution to the problem was the construction by Sir John Bazalgete of a vast interceptor along the north bank of the River Thames, creating the famed Thames Embankment. This gave relief to central London, but moved the pollution problem downstream. Sir Edwin Chadwick, a lawyer and crusader for public health at the time, was a strong advocate of separate sanitary sewers, and he coined the slogan, "the rain to the river and the sewage to the soil." In this spirit, and to reduce pollution of the Thames downstream, "sewage farms" were es-tablished to take the discharges from the interceptor. The agricultural benefits from the farms were incidental to their service in the disposal of the wastewater.

The practice of sewage farms quickly spread. By 1875, there were about 50 such farms providing land treatment in England, and many similar farms served major cities in Europe. By the turn of the century, there were about a dozen sewage farms in the United States. However, the need for a reliable outlet for wastewater was not entirely compatible with the seasonal nature of nutrient and water requirements of crop production. While sewage farms alleviated pollution in the receiving streams, they created a different set of environmental sanitation problems. Hydraulic and pollutant overloading caused clogging of soil pores, waterlogging, odors, and contamination of food crops. The performance improved over the years as operators gained experience with balancing the needs of wastewater disposal and crop growth. Nevertheless, the farms were gradually phased out when the land areas required to accommodate wastes from large cities grew too great to be practical and more effective technologies were developed to remove pollutants from wastewater. The processes of primary sedimentation and secondary bio-logical treatment, which were developed in the early part of this century, required much smaller areas for their operations and were capable of producing clarified effluents for direct discharge into a surface water body. These technologies eliminated the need for sewage farms.

In the United States, an estimated 0.69 m^3 (182 gal) per capita per day of municipal wastewater is generated (Solley et al., 1993). Municipal wastewater treatment plants (otherwise known as publicly-owned treatment works or "POTWs") currently serve around 75 percent of the U.S. population (EPA, 1995). The remainder are largely served by individual household septic systems. For those served by centralized facilities, the municipal wastewater is collected through a sewer network and centrally treated in a wastewater treatment plant. The collected wastewater contains pollutants originating from households, business and commercial estab-lishments, and industrial production facilities. The general composition of municipal wastewater is well understood. For the purpose of water-quality management, pollutants in municipal wastewater may be classified into the following five categories:

- Organic matter (measured as biochemical oxygen demand or BOD),
- Disease-causing microorganisms (pathogens),
- Nutrients (nitrogen and phosphorus),
- Toxic contaminants (both organic and inorganic), and
- Dissolved minerals.

Although the exact composition may differ from community to community, all municipal wastewater contains constituents belonging to the above categories. Pollutants belonging to the same category exhibit similar water quality impacts. The objective of wastewater treatment is to remove pollutants so that the effluent meets the water quality requirement for discharge or reuse.

In modern society, thousands of potentially hazardous chemicals are used in household products and commercial and industrial activities. They may be inadvertently or intentionally discharged into the wastewater collection system. Municipal wastewater also contains many types of infectious, disease-causing organisms that originate in the fecal discharge of infected individuals.

In wastewater treatment, the physical and chemical state of pollutants determine the approaches that are employed to remove impurities. For this purpose, pollutants may be further classified (as per Camp and Messerve, 1974) into:

- Settleable impurities,
- Suspended impurities,
- Colloidal impurities, and
- Dissolved impurities.

Pollutants sharing the same physical state behave similarly during conventional wastewater treat-ment.

With more than one hundred years of continuous development, municipal wastewater treatment technology in use today can achieve almost any degree of treatment and removal of impurities desired. The conventional municipal wastewater treatment system consists of a series of processes, through which pollutants are removed, step by step, from the water and are concentrated into the solid fraction or sludge (see Chapter 3 for a further description of mun-icipal wastewater and sludge treatment).

Treated effluents are customarily discharged into a surface water body. With advances in wastewater treatment technology, wastewater effluents can achieve consistently high quality and are increasingly reclaimed for reuse. The value of reclaimed water in crop irrigation has long been recognized, particularly where fresh water resources are limited (Webster, 1954; Mertz, 1956; Sepp, 1971). Some wastewater reclamation programs (e.g., in Florida) are also motivated by the need to avoid nutrient overload to sensitive receiving waters. In these cases, beneficial reuse can be more economical and/or technically feasible than employing the advanced wastewater treatment needed to meet the requirements for surface water disposal.

In the United States, irrigating crops with reclaimed wastewater has been generally well accepted, both in the semiarid western states and in Florida. The suitability of water for reuse is influenced by the chemical composition of the source water, mineral pickup due to water use, and the extent of wastewater treatment. These characteristics vary seasonally and from one municipality to another (Pettygrove and Asano, 1985). Dowdy et al. (1976) derived a "typical" chemical composition of treated wastewater effluent from a selected number of cities. This "typical" composition is compared to that of water from the Colorado River—a source for crop production in several western states—for many of the water quality criteria important in irrigation (Table 2.1). Judged against existing guidelines for irrigation water quality criteria (National Academy of Sciences, 1973; Westcot and Ayers, 1985), the chemical composition of treated wastewater effluents, although widely varied, is acceptable for crop irrigation. In add-ition, treated effluents contain significantly higher amounts of nitrogen and phosphorus—fertilizer elements essential for plant growth.

There are numerous examples of successful agricultural reuse projects in the United States. The wastewater from Bakersfield, California has been used for irrigation since 1912 when raw sewage was used (Pettygrove and Asano, 1985). Currently, reclaimed water from Bakersfield irrigates approximately 2,065 ha (5,100 acres) of corn, alfalfa, cotton, barley, and sugar beets productions with more than 64,000 m^3/day (16.9 million gal/day) of primary and secondary effluents from three treatment plants (Pettygrove and Asano, 1985). To avoid wastewater discharge to sensitive receiving waters, the city of Tallahassee, Florida has been using treated effluent for agricultural irrigation on city-owned farmland since 1966. About 68,000 m^3/day (18 million gal/day) of secondary effluent are pumped approximately 13.7 km (8.5 miles) and irrigate about 700 ha (1,729 acres) (Roberts and Bidak, 1994).

A seven-year agricultural wastewater reclamation demonstration study was conducted at Castroville, California, and completed in 1987. This study used a wastewater treatment pro-cess of secondary (biological) treatment, coagulation, filtration, and disinfection, with the final effluent meeting a quality standard of 2.2 total coliform/100 ml (the standard enforced by California's regulations for wastewater reclamation). The study concluded that the treatment process was acceptable for the spray irrigation of food crops to be eaten raw (Sheikh et al., 1990). The study detected no pathogenic organisms in the treated effluent, and spray irrigation with the treated effluent did not adversely affect soil permeability, did not result in heavy metal accumulation in the soil or plant tissue, and did not adversely affect crop yield, quality, or shelf

TABLE 2.1 Composition of Secondary Treated Municipal Wastewater Effluents and Irrigation Water

Parameter	Secondary Effluent[a] Range	Typical	Colorado River[b]	Irrigation Water Quality Criteria[c]
Total Solids	U	425	U	NA
Total Dissolved Solids	200-1300	400	668.0	<2000
pH	6.8-7.7	7.0	7.9	6.5-8.4
Biochemical Oxygen Demand	2-50	25	U	NA
Chemical Oxygen Demand	25-100	70	U	NA
Total Nitrogen	10-30	20	U	<30
Ammonia Nitrogen	0.1-25	10	U	NA
Nitrate Nitrogen	1-20	8	0.1-1.2	NA
Total Phosphorus	5-40	10	<0.02	NA
Chloride	50-500	75	55-77	<350
Sodium	50-400	100	71-97	<70
Potassium	10-30	15	4-6	NA
Calcium	25-100	50	66-163	NA
Magnesium	10-50	20	23-28	NA
Boron	0.3-2.5	0.5	0.10-0.54	<3.0
Cadmium (*u*g/L)	<5-220	<5	<1-69	10
Copper (*u*g/L)	5-50	20	<10-10	200
Nickel (*u*g/L)	5-500	10	<1-4	200
Lead (*u*g/L)	1-200	5	<5	5000
Zinc (*u*g/L)	10-400	40	<3-12	2000
Chromium (*u*g/L)	<1-100	1	<1	100
Mercury (*u*g/L)	<2-10	2	<0.1-0.1	NA
Molybdenum (*u*g/L)	1-20	5	2-8	10
Arsenic (*u*g/L)	<5-20	<5	4-16	100

All units in milligrams per liter unless otherwise noted as micrograms per liter (*u*g/L). U: unavailable. NA: not applicable.

[a] Adapted from Asano et al., 1984 and Treweek, 1985

[b] Radtke, et. al., 1988

[c] from Westcot and Ayers, 1985 and National Academy of Sciences, 1973

life. Over a 10-year period, Yanko (1993) assayed 590 filtered and chlorine-treated secondary effluent samples from wastewater treatment plants in Los Angeles County for enteric viruses. All of the effluent samples had met California's wastewater reclamation standard of 2.2 coli-form/100 ml, and only one was found positive for virus (Coxsackie B3).

State regulations of the use of reclaimed wastewater on food crops are aimed at protecting consumers from possible exposure to pathogens (discussed in Chapter 7). The potential health hazard of trace elements (including heavy metals) and toxic organic chemicals has been ad-dressed for a variety of end uses of reclaimed wastewater, but they have not been regulated for purposes of agricultural irrigation. As mentioned, concentrations of trace elements in waste-water effluents that have undergone secondary or higher levels of treatment are normally within existing guidelines for irrigation water quality criteria (see Chapter 4 for a discussion of trace elements and organic chemicals).

Sewage Sludge

Before the era of wastewater treatment, municipal wastewater was untreated and sludge did not exist. Sewage sludge is an end product of municipal wastewater treatment and contains many of the pollutants removed from the influent wastewater. Sludge is a concentrated sus-pension of solids, largely composed of organic matter and nutrient-laden organic solids, and its consistency can range in form from slurry to dry solids, depending on the type of sludge treatment. Agricultural utilization of sewage sludge has been practiced since it was first produced. Given agricultural experience with the use of human excrement, sewage, and animal manure on croplands, the application of municipal wastewater sludge to agricultural lands was a logical development. As an early example, municipal sludge from Alliance, Ohio was used as a fertilizer as early as 1907. During the same period, Baltimore, Maryland used domestic septage in agricultural production (Allen, 1912). The plant nutrient value of sludge has been evaluated by many investigators (Rudolfs and Gehm, 1942; Sommers, 1977; Tabatabai and Frankenberger, 1979), and the nutrient composition is considered to be similar to other organic waste-based soil amendments that are routinely applied on cropland, such as animal manures (as shown in Table 2.2). In addition to major plant nutrients, sludge also contains trace elements that are essential for plant growth. Soils which have been tilled for decades are often deficient in certain trace elements, such as zinc and copper (Martens and Westermann, 1991). Certain calcareous soils are deficient in iron (Martens and Westermann, 1991). Land applications of municipal sludge can help to remedy these trace metal deficiencies (Logan and Chaney, 1983). Early agricultural sludge use projects were often carried out with little regard for possible adverse impacts to soil or crops (Allen, 1912). A common goal was to maximize the application rate to minimize the cost of sludge disposal. Since the early 1970s, more emphasis has been placed on applying sludge to cropland at an agronomic rate (Hinesly et al., 1972; Kirkham, 1974).

Wastewater treatment authorities attempt to manage the volume of wastewater and type of pollutants discharged into sewers to protect the integrity of the infrastructure, health and well-being of sanitation workers, the performance of wastewater treatment processes, and the impact on receiving waters. Federal and state regulations exert control over the quality of the treated

TABLE 2.2 Chemical Composition of Sewage Sludge and Animal Manure

Constituent (Unit)	Animal Manure[a]	Sewage Sludge	
	Range	Range	Typical
Nitrogen (% dry weight)	1.7-7.8	<0.1-17.6[b]	3.0
Total phosphorus (% dry weight)	0.3-2.3	<0.1-14.3[b]	1.5
Total sulfur (% dry weight)	0.26-0.68	0.6-1.5[b]	1.0
Calcium (% dry weight)	0.3-8.1	0.1-25[b]	4.0
Magnesium (% dry weight)	0.29-0.63	0.03-2.0[b]	0.4
Potassium (% dry weight)	0.8-4.8	0.02-2.6[b]	0.3
Sodium (% dry weight)	0.07-0.85	0.01-3.1[b]	-
Aluminum (% dry weight)	0.03-0.09	0.1-13.5[b]	0.5
Iron (% dry weight)	0.02-0.13	<0.1-15.3[b]	1.7
Zinc (mg/kg dry weight)	56-215	101-27,800[b]	1200
Copper (mg/kg dry weight)	16-105	6.8-3120[c]	750
Manganese (mg/kg dry weight)	23-333	18-7,100[b]	250
Boron (mg/kg dry weight)	20-143	4-757[b]	25
Molybdenum (mg/kg dry weight)	2-14	2-976[b]	10
Cobalt (mg/kg dry weight)	1	1-18[b]	10
Arsenic (mg/kg dry weight)	12-31	0.3-316[c]	10
Barium (mg/kg dry weight)	26	21-8,980[b]	-

[a] Data summarized from Azevado and Stout, 1974

[b] Data summarized from Dowdy et al., 1976

[c] Data summarized from Kuchenrither and Carr, 1991

effluent in order to keep contaminants below concentrations that would be harmful to humans and the environment.

Nevertheless, toxic chemicals in low concentrations are introduced into municipal waste-water. Many of these toxic chemicals are removed from the wastewater and concentrated into the sewage sludge by the wastewater treatment process. Sewage sludge also contains human pathogens, although it can be treated to significantly reduce the number of pathogens present. Pathogens and toxic chemical pollutants may be introduced into sludge-amended soil.

Since about 1970, there has been an intense and concerted effort of scientific research world-wide to better understand the fate of potentially toxic and pathogenic constituents in sludge when sludge is applied to agricultural soils. A search of agricultural research articles (from the computer database, AGRICOLA) revealed more than 2,300 articles published since 1970. The surge of technical information regarding agricultural application of sewage sludge has led to the development of pollutant loading guidelines by the United States and western European countries (McGrath et al., 1994). The World Health Organization is also investigating ways to develop human health-related chemical guidelines for using treated municipal wastewater effluents and sewage sludge in agriculture production (Chang, et al., 1993).

Since the late 1970s and early 1980s, source control and industrial wastewater pre-treatment programs have been initiated to limit the discharge of industrial pollutants into municipal sewers, and these programs have resulted in a dramatic reduction of toxic pollutants in wastewater and in sludge (see Chapter 3 for a discussion of industrial pretreatment). Municipal wastewater sludge, particularly from industrialized cities, now has significantly lower levels of toxic contaminants—specially heavy metals—than in earlier decades when much of the research on sludge application to cropland was conducted. Tables 2.3, 2.4, and 2.5 show decreasing levels of metals in wastewater or sludge for municipal sewage treatment facilities in Chicago, Baltimore, and Philadelphia from about 1970 through 1985. More recently, a comparison of sludge quality was made between two EPA surveys (Kuchenrither and McMillan, 1990): a study of 40 cities conducted in the late 1970's (EPA, 1982) and the National Sewage Sludge Survey (NSSS) conducted in the late 1980s (EPA, 1990). While the two studies used different sampling and analytic techniques, the comparison (in Table 2.6) shows that most metals have significantly lower concentrations in the NSSS than in the 40-city study, largely as a result of industrial pretreatment programs. The data on organic compounds is difficult to compare as the limits of detection between the two studies varied. EPA's 1991 report to Congress (EPA, 1991) also documents a reduction in sludge metal concentrations from about 1985 to 1990 in a number of POTWs across the country.

For a long time, wastewater treatment authorities in the United States managed land applications of sewage sludge with little governmental attention. Early regulations governing sewage sludge disposal were developed by state public health agencies with the intention of controlling infectious disease. Although federal guidelines for land application of sewage sludge were proposed as early as 1974, comprehensive federal regulations did not exist until 1993. EPA first developed sludge management regulations under the 1972 Federal Water Pollution Control Act to prevent sludge-borne pollutants from entering the nation's navigable waters. In 1977, Congress amended the Act to add a new section, 405(d), that required EPA to develop regulations containing guidelines to (1) identify alternatives for sludge use and disposal; (2) specify what factors must be accounted for in determining the methods and practices applicable to each of these identified uses; and (3) identify concentrations of pollutants that would interfere with each use. In 1987, Congress amended section 405 again and established a timetable for developing sewage sludge use and disposal guidelines. Through this amendment, Congress directed EPA to: (1) identify toxic pollutants that may be present in sewage sludge in con-centrations that may affect the public health and the environment and (2) promulgate regulations that specify acceptable management practices and numerical concentration limits for these pollutants in sludge.

TABLE 2.3 Metal Loadings in Raw Wastewater (in kg/day) Entering the Chicago Area Treatment Facilities in Response to Pretreatment Programs

	Cd	Cr	Cu	Pb	Ni	Zn
1971	398	5,197	2,166	2,049	2,443	6,972
1972	343	3,321	1,996	1,793	1,377	4,641
1973	301	2,463	961	1,063	957	4,260
1974	213	1,894	652	735	643	3,403
1975	113	1,522	538	497	386	2,537
1976	132	1,527	685	368	416	2,400
1977	168	1,422	588	536	436	2,587
1984	121	1,185	949	396	702	2,322

Note: Table 2.3 combines data from two different POTWs within the Metropolitan Sewerage District of Greater Chicago. Pretreatment programs began in 1972.

SOURCE: Adapted from Page et al., 1987.

The intent of the 1987 amendment was to "adequately protect human health and the environment from any reasonably anticipated adverse effect of each pollutant" [Section 405 (d)(2)(D)]. Section 405 also states that any permit issued to a POTW or other treatment works for wastewater discharge should specify technical standards for sludge use or disposal. *The Standards for the Use and Disposal of Sewage Sludge,* Code of Federal Regulations, Title 40, Part 503 (EPA, 1993) were promulgated in 1993, and are collectively referred to in this report as the "Part 503 Sludge Rule."

IRRIGATION WITH RECLAIMED WATER

Crop Irrigation

The nation encompasses 930.8 million hectares (2,300 million acres) of land, of which 125 million hectares (309 million acres), or 14 percent were used to grow crops in 1993 (USDA, 1992). Figure 2.1 shows the proportion of cropland devoted to different categories of crops. The category "fresh food" includes such produce crops as broccoli, potatoes, or fruit that are bought and consumed fresh, and this is the smallest category in terms of total acreage. Other food crops, such as small grains, vegetables used for commercial processing (canning and processing), peanuts, sugar beets, and sugar cane, are grown on roughly 24 percent of cropland. Crops for domestic animal consumption—feed and hay—occupy the bulk of cropland. Farmers

TABLE 2.4 Metal Concentrations in Digested Sludge Filter Cake (in mg/kg dry weight) at the Back River POTW, Baltimore, Maryland in Response to Pretreatment Programs

Year	Cd	Cu	Pb	Ni	Zn
1978	51	2,750	680	423	5,000
1979	23	2,540	539	397	3,540
1980	18	2,840	433	381	3,400
1981	19	2,070	493	374	3,410
1982	18	1,110	398	193	2,360
1983	23	1,060	324	214	2,620
1984	26	1,010	372	266	2,750
1985	22	681	346	126	2,030

Note: Source identification began in 1980 and source reduction began in 1981. Based on monthly composites in early years, then biweekly and weekly.

SOURCE: Adapted from Page et al., 1987.

often practice crop rotation, so a variety of crops may be grown on the same piece of land over a period of several years.

Irrigated crop production expanded in the United States from nearly 7.7 million hectares (19 million acres) in 1945 to more than 20.5 million hectares (51 million acres) in 1978. The total amount of irrigated cropland dropped by 1987 to 18.8 million hectares (46 million acres) (Figure 2.2, Council for Agricultural Science and Technology, 1992; USDA, 1992). About 15 percent of harvested crops are grown on the 5 percent of farmland that is irrigated. Irrigation is essential in semiarid and arid regions to produce of many crops including orchard crops, and vegetables (Figure 2.3). Irrigated crops represent 38 percent of the total revenue from crop production in the United States (Bajwa, et al. 1992).

Demand for Irrigation Water

Much of the nation's water withdrawal is used for crop irrigation. In 1990, crop irrigation accounted for 518 million m^3/day (137,000 million gal/day) of water or 41 percent of all fresh water withdrawn for all uses from well and surface water (Solley et al., 1993). Irrigation is also a highly consumptive use of water; about 56 percent of the quantity withdrawn is lost to evaporation and plant transpiration, and so is not available as return-flow to surface waters. By comparison, domestic, commercial, industrial and mining uses consume an average of 17 percent of the water withdrawn for these purposes.

TABLE 2.5 Metal Concentrations in Sludges (in mg/kg dry weight) at Two Philadelphia Wastewater Treatment Plants in Response to Pretreatment Programs

Year	Cd	Cu	Pb	Ni	Zn
			Southwest		
1974	31	825	1,540	100	3,043
1976	27	1,110	2,710	103	2,650
1977	27	1,400	2,170	185	3,940
1978	16	1,020	1,800	275	4,050
1980	18	986	740	98	2,780
1981	25	971	562	117	2,300
1982	20	940	1,030	113	2,440
1983	12.5	736	421	79	1,700
1984	14.3	1,140	427	111	1,830
1985	15.0	880	373	80	1,730
			Northeast		
1974	108	1,610	2,270	391	5,391
1976	97	2,240	2,570	372	5,070
1977	71	2,320	2,680	459	3,920
1978	57	1,240	1,620	319	5,910
1980	26	1,210	728	275	3,890
1982	14	985	423	185	2,570
1983	10.9	1,020	351	130	2,110
1984	12.4	1,200	360	130	1,980
1985	17.3	1,270	382	187	2,100

Note: Source identification began in 1976. Liquid sludge analyzed until 1982, and sludge filter cake from 1983 on. No data available for 1975 and 1979.

SOURCE: Page et al., 1987.

TABLE 2.6 Comparison of Organics and Trace Elements From the 40-Cities Study Conducted in the Late 1970s and the National Sewage Sludge Survey (NSSS) Conducted in the Late 1980s

Organic Pollutants (µg/kg,unless noted by * = mg/kg)	Percent Detection		Mean Values		
	40 Cities	NSSS	40 Cities	NSSS	
Aldrin	16	3	6.4	1.9	
Benzene	93	0	1782	--	
Benzo(a)pyrene	21	3	138	--	
Bis(2-ethylhexyl)phthalate	100	62	155*	74.7*	
Chlorodane	16	0	6.4	--	
Dieldrin	16	4	6.4	--	
Heptachlor	16	0	6.4	--	
Hexachlorobenzene	16	0	155	--	
Hexachlorobutadiene	5	0	23	--	
Lindane	16	0	6.4	--	
Dimethylnitrosamine	5	0	57	--	
PCB's	N/A	N/A	--	--	
Toxaphene	16	0	6.4	--	
Trichloroethene	84	1	8139	--	
DDD/DDE/DDT	N/A	N/A	--	--	
Trace Elements (mg/kg, values in () denote composited means by mass in NSSS)					
Arsenic	100	60	6.7	9.9	(10)
Beryllium	100	23	1.67	0.4	(1)
Cadmium	100	69	69.0	7.0	(22)
Chromium	100	91	429	119	(268)
Copper	100	100	602	741	(730)
Lead	100	80	969	134	(205)
Mercury	100	63	2.8	5.2	(3)
Molybdenum	75	53	17.7	9.2	(11)
Nickel	100	66	135.1	42.7	(70)
Selenium	100	65	7.3	5.2	(5)
Zinc	100	100	1594	12	(1550)

SOURCE: EPA, 1990.

FIGURE 2.1 The proportion of U.S. cropland devoted to different crops. Categories defined by U.S. Department of Agriculture. SOURCE: USDA, 1992.

FIGURE 2.2 The expansion and also, in four regions, the contraction of irrigated area of the United States. SOURCE: Council for Agricultural Science and Technology, 1992.

FIGURE 2.3 Irrigated acreage of principal crops in the United States and the percentages of total crop acreage that is irrigated. SOURCE: Bajwa et al., 1992.

Reclaimed wastewater provides a very small volume of the nation's crop irrigation water although it is a significant source of water in some areas. Nationally, the United States produces 134 million m^3/day (35,400 million gal/day) of municipal wastewater. Approximately 3 percent of this quantity, or 3.5 million m^3/day (925 million gal/day), is reclaimed (Solley et al., 1993). About 70 percent of this reclaimed water goes towards irrigation, but the national estimates do not distinguish between urban and agricultural irrigation. In Florida, agricultural irrigation accounts for approximately 34 percent of the total volume of reclaimed water used within the state (Florida Department of Environmental Regulation, 1992). In California, agricultural irr-igation accounts for approximately 63 percent of the total volume of reclaimed water (California State Water Resources Control Board, 1990). Even so, only 5 percent of California's reclaimed water irrigates land used to grow crops classified for human consumption (Figure 2.4, EPA, 1992). It is probable that reclaimed water accounts for less than 0.5 percent of the water used nationally for agricultural irrigation.

Although the total volume of treated wastewater produced in the United States could theoretically satisfy 26 percent of the need for agricultural irrigation, this magnitude of reuse is not likely. The volume of wastewater produced by a community does not often match the volume of water needed for crop irrigation in the nearby vicinity. In fact, much of the waste-water in the United States is produced in areas where crop irrigation is not needed or is only occasionally required. Figure 2.5 shows the distribution of U.S. irrigated agriculture and Table 2.7 illustrate regional imbalances in irrigation needs relative to the amount of wastewater pro-duced. For the purpose of Table 2.7, the 18 water resource regions defined by U.S. Water Re-sources Council (Solley et al., 1993) have been simplified to six (Figure 2.6).

The Northeast region has about half of the population of the U.S. and produces about half

FIGURE 2.4 Proportion of different crop types irrigated by reclaimed water in California. SOURCE: California State Water Resources Control Board, 1990.

FIGURE 2.5 The distribution of irrigated agriculture in the United States. SOURCE: Bajwa et al., 1992.

TABLE 2.7 Relation of Reclaimed Water Generated to Agricultural Needs by Region

Region	Wastewater Return Flow (bgd)[a]	Reclaimed Water		Water Drawn for Agricultural Irrigation (bgd)	Reclaimed Water as a Percent of Water Drawn for Agriculture Irrigation
		Percent	bgd		
Northeast	20.0	0.3	0.06	1.0	6.0
Southeast	6.0	4.6	0.276	17.0	1.6
California	3.0	8.5	0.255	28.0	0.9
Great Plains	2.3	1.0	0.023	38.0	0.06
Northwest	2.2	0.5	0.011	32.0	0.03
Southwest	1.1	26.2	0.288	19.0	1.5

[a] billion gallons per day

SOURCE: Derived from information in Solley, et al., 1993.

of the wastewater. This region has a relatively short growing season and a humid-climate; thus the demand for crop irrigation is low. In all other regions, the amount of water required by irrigation far exceeds the volume of wastewater produced (Solley, et al., 1993). Water conveyance is a significant cost of a water reuse project and even in the semi-arid and arid western states, the distance between generators and potential users of reclaimed water will determine its feasibility.

Wastewater Reclamation Motivated by Disposal Priorities

In 1976, the city of St. Petersburg, Florida initiated a wastewater reuse program which included diverting its treated wastewater effluent to urban reuse purposes to avoid the pollution of Tampa Bay (EPA, 1992). It was considered a pioneering effort then. It is interesting to note that the reclaimed water was initially not metered in St. Petersburg; customers were urged to use as much as they wanted at a flat rate per acre. Currently, reclaimed water is valued for its ability to reduce water demand, and meters are now being retrofitted. The publication of *Quality Criteria for Water* (EPA, 1976) set minimum national in-stream water quality limits that include numerical limits for metals and toxic organics. When effluents are discharged into a large or fast-flowing water body, the water quality standard can more easily be met because of the dilution that occurs in the receiving stream. However, POTWs that discharge into small or intermittent streams are not able to take advantage of dilution, and their discharge limits may be as stringent as the in-stream water quality standards. In many cases, the local or state requirements are even more restrictive than the national requirements. Often, the pollutants of concern are nutrients such as phosphorus rather than toxic chemicals.

To meet these strict in-stream requirements, and to control treatment costs, many communities are considering water reuse to achieve regulatory compliance (Shacker and Koby-

FIGURE 2.6 Water resource regions referred to in Table 2.7. For purposes of Table 2.7, the 18 water resource regions as established by the U.S. Water Resources Council have been simplified to six as follows: "Northeast" includes New England, Mid-Atlantic, Tennessee, Ohio, Great Lakes, Upper Mississippi, and Sorris-Red-Rainey regions; "Southeast" includes South Atlantic-Gulf, Lower Mississippi, and Texas-Gulf regions; "Southwest" includes Lower Colorado, Upper Colorado, and Great Basin regions; "Great Plains" includes Missouri, Arkansas-White-Red, and Rio Grande regions; "Northwest" is the Pacific Northwest region; and "California" is the California region. SOURCE: modified from Solley et al., 1993.

linski, 1994). Therefore, both water shortage and waste disposal are driving forces for the use of reclaimed wastewater, and the dominance of one over the other will depend on local con-ditions. A recent survey of water reuse projects in California indicated that two thirds of the projects were initiated exclusively for water supply purposes. Only 4 percent of the projects were motivated by the need for pollution control, and the rest were mixed (Water Reuse Ass-ociation of California, 1993).

Miller (1990) found that urban landscape irrigation (e.g, for golf courses and highway median strips) is one of the fastest growing uses of reclaimed wastewater in the United States In Florida, two-thirds of the reclaimed water is used for urban landscape purposes (Paret and Elsner, 1993). The Irvine Ranch Water District in California irrigates about twice as much urban land as farmland, and the expectation is that water use on urban land will increase as agri-cultural land is taken out of production and replaced by residential development (Parsons, 1990). Throughout California, nonagricultural use of reclaimed wastewater is expected to increase faster over the next 20 years as achievement of state goals for water reuse is approached, and it is estimated that the proportion of reclaimed water for crop irrigation will shrink from 21 to 13 percent of all reclaimed water uses (Water Reuse Association of California, 1993).

Value of Reclaimed Wastewater

The costs to reclaim wastewater vary depending on the level of treatment required by state water reuse programs. The total cost of reclaiming 1 acre-foot (1,233 m^3) of municipal wastewater are estimated at roughly \$500/acre-foot (\$406 per 1,000 m^3) in both Denver, Colorado and Orange County, California (Miller, 1990), which is roughly equivalent to the cost that southern California utilities pay to the Metropolitan Water District for imported water. The value of reclaimed water to the farmer will depend on its cost relative to other off-farm water supplies. In 1988, the average cost to the farmer of an off-farm water supply in the United States was \$34/acre-foot (\$27.50 per 1,000 m^3) and ranged from about \$89/acre-foot (\$72.10 per 1,000 m^3) in Arizona to \$1/acre-foot (\$0.81 per 1,000 m^3) in Arkansas (1988 prices from Bajwa et al, 1992). These rates are considerably less than the amortized unit cost for developing and maintaining a water reclamation facility. If the farmers currently obtain irrigation water at low prices, they are not expected to pay more for using reclaimed water. In areas where the motivation for a water reclamation project is pollution abatement rather than water savings, reclaimed water is likely to have a low market value, and farmers may receive the treated effluent free of charge. In these situations, it may be more attractive for POTWs to seek other alternatives, such as reclaiming water for industrial users who are paying higher water rates.

Treated effluent contains plant nutrients and has potential value as a fertilizer. Even so, the value of effluent as a fertilizer is not significant when total farm production costs are considered. Fertilizer comprised about 6 percent of the \$108 billion total production expenses of U.S. farming in 1987 (U.S. Bureau of the Census, 1990). Projected 1992 production costs for several high-value food crops predicted fertilizer costs ranging from 0.03 to 11.5 percent (Table 2.8).

For crops to grow properly, the correct fertilizers must be applied at appropriate intervals in the appropriate amounts. When reclaimed water is used, irrigation needs rather than nutrient requirements may determine fertilizer inputs. The nutrients contained in the irrigation water may not be appropriate in terms of type, amounts, and timing. Effluent irrigation takes place during the warmest part of the season, and fertilization will occur even though fertilizer may only be needed during the early, cool part of the season. Heavy fertilization during the warm season can encourage undesirable vegetative growth (Bouwer and Idelovitch, 1987).

TABLE 2.8 The Cost of Fertilizer As a Percentage of All Costs for the Production of Some Food Crops

Crop	Percent of Total Costs	State
Fresh apples	0.6	Pennsylvania
Processing apples	1.3	Pennsylvania
Green tomatoes	2.4	California
Ripe tomatoes	2.6	Pennsylvania
Carrots	3.4	California
Fresh broccoli	4.1	California
Iceberg lettuce	4.9	California
Sweet corn	6.8	California
Tomatoes for processing	10.2	California
Potatoes	11.5	Pennsylvania

SOURCES: University of California Imperial County Cooperative Extension 1992; Harper, 1993.

USE OF SEWAGE SLUDGE IN AGRICULTURE

Potential Role of Sewage Sludge in Crop Production

Based on estimates of the amount of solids produced in typical primary and secondary wastewater treatment processes (Metcalf and Eddy, 1991), the national production of sewage sludge is approximately 7 million metric tons/year. Secondary and higher levels of treatment account for 5.3 million metric tons/year, and the remainder comes from coastal discharges and sewage ponds (EPA, 1993). The quantity of sewage sludge is expected to increase as a greater percentage of the population is served by sewers and as advanced wastewater treatment processes are brought on-line (refer back to Figure 1.1). Currently, 36 percent of sewage sludge is applied to the land for several beneficial purposes, such as agriculture, turfgrass production, or reclamation of surface mining areas. 38 percent is landfilled, 16 percent is incinerated, and the remainder is surface disposed by other methods (EPA, 1993). With the promulgation of the Part 503 Sludge Rule, EPA encouraged agricultural use of sewage sludge.

From a national perspective, sludge has very little impact on agriculture. If all sludge produced in the United States was used agriculturally and applied according to agronomic nitrogen requirements, it would only require an estimated 1.59 percent of the nation's cropland (assuming that the average concentration of available nitrogen in the sludge is 4 percent dry weight and it is applied at 100 kg nitrogen/ha/yr).

Regional and local availability of farmland will, however, affect the potential for in-creased agricultural use of treated municipal sludge. The ratio of available farmland to sludge produced is an initial consideration in agricultural use of sludge. North Dakota, for example, would require only 0.05 percent of its agricultural land to take up all sludge produced in the state at agronomic rates for nitrogen. The Madison Metro Sewerage District has applied an-aerobically digested sludge to private farmland since 1974, and the demand for sludge outstrips the supply (Taylor and

Northouse, 1992). Rhode Island, on the other hand, would need to utilize 100 percent of its cropland to use up its sludge supply; because that is unlikely, other use or disposal options are required. Table 2.9 shows a comparison of the amounts of cropland required to accommodate in-state sludge applications at agronomic rates. Unlike wastewater effluents, sludge can be transported further distances. For example, contractors are currently shipping some of New York City's treated sludge to northeastern Texas and eastern Colorado for cropland application. Boston, Massachusetts ships a portion of its sludge in the form of heat-dried pellets to Florida for application to cropland and pastures. Some of the sludge from the Los Angeles Basin is being transported by truck for cropland application in Yuma, Arizona.

The cost of transporting sludge for land application must be weighed against the cost and environmental consequence of other sludge disposal options on a case by case basis. If wastewater treatment authorities in urban centers cannot overcome the variety of obstacles to use sludge within reasonable transportation distances, they face the consequences of long distance transportation and its associated costs. These geographical and economical constraints on land application create uncertainty over how much of the nation's sewage sludge will be applied on cropland in the long run.

From the farmer's perspective, other factors limit agriculture use of sewage sludge. Sewage sludge is inherently more difficult to use than chemical fertilizers. In part, this is because the composition of plant nutrients and trace elements vary due to differences among types of sludges (e.g., different water contents or treatment processes) and differences among municipalities and their industrial contributors. The composition of commercial fertilizers are formulated to meet crop requirements. Some have argued that any cost savings derived from substituting sludges for chemical fertilizers may be insignificant (White-Stevens, 1977) and that unless the waste generators offer them payment, the financial incentive for farmers to apply sewage sludge to cropland may be marginal. Others point out that sludge has significant nutrient value, which can range from $100 to $140 per acre (EPA, 1994), and that its effect on soil physical properties can increase crop yield (e.g., Logdson, 1993). Generally, the POTW makes arrangements for hauling and spreading sewage sludge on farmland.

Ecological Linkages Between Urban and Agricultural Systems

The land application of sewage sludge can ecologically link nutrient usage within urban and rural landscapes (Millner, 1994). If nutrients and organic matter are returned to agricultural soil via land application of sludges, the need to supplement the agroecosystem in terms of nutrients will diminish. In this sense, cropland recycling of sewage sludge close to its urban source can conserve energy as does the recycling of crop residues and farm animal manures.

In natural ecosystems, the external inputs to primary food production are solar energy and water (Figure 2.7). Natural ecosystem productivity is sustained through the recycling of nutrients extracted by primary producers (plants) and made available again in the process of organic matter mineralization. In contrast, conventional crop production is enhanced by external inputs of energy, water, nutrients, and chemical herbicides and pesticides (Figure 2.7). The capacity of modern agroecosystems for natural feedback and regulation has been greatly reduced in order to increase crop yields (Risser, 1985; Barrett et al., 1990). When these external inputs

TABLE 2.9 Amount of Cropland Required to Accommodate In-state Sludge Applications at Agronomic Rates

State	Population[a] (millions)	Sludge Produced[b] (thousands of metric tons)	Cropland Required[c] (thousands of hectares)	Cropland[d] (thousands of hectares)	Percent of State Cropland
New England					
Maine	1.24	24.78	9.91	158	6.3
New Hampshire	1.12	22.38	8.95	43	20.8
Vermont	0.57	11.39	4.56	177	2.6
Massachusetts	6.01	120.10	48.0	79	60.8
Rhode Island	1.00	19.98	7.99	8	100.0
Connecticut	3.27	65.35	26.1	62	42.1
Middle Atlantic					
New York	18.70	363.63	149.4	1,539	9.7
New Jersey	7.87	157.27	62.9	166	37.9
Pennsylvania	12.05	240.80	96.3	1,716	5.6
East North Central					
Ohio	11.10	221.82	88.7	3,921	2.3
Indiana	5.71	114.11	45.6	4,335	1.1
Illinois	11.70	233.81	93.5	8,162	1.1
Michigan	9.47	189.25	75.7	2,591	2.9
Wisconsin	5.04	100.72	40.3	3,339	1.2
West North Central					
Minnesota	4.52	90.33	36.1	7,086	0.51
Iowa	2.81	56.15	22.5	8,359	0.27
Missouri	5.23	104.52	41.8	4,987	0.84
North Dakota	0.63	12.59	5.04	10,305	0.05
South Dakota	0.71	14.19	5.68	6,889	0.08
Nebraska	1.60	31.99	12.8	7,285	0.18
Kansas	2.53	50.58	20.2	10,433	0.19
South Atlantic					
Delaware	0.70	13.99	5.6	202	2.8
Maryland	4.96	99.12	39.6	578	6.9
Dist. of Columbia	0.58	11.59	4.64	0	0.0
Virginia	6.49	129.69	51.9	1,081	4.8
West Virginia	1.82	36.36	14.5	274	5.3
North Carolina	6.94	138.69	55.5	1,647	3.4
South Carolina	3.64	72.74	29.1	786	3.7
Georgia	6.92	138.29	55.3	1,516	3.6
Florida	13.68	273.38	109.4	931	11.8

State	Population[a] (millions)	Sludge Produced[b] (thousands of metric tons)	Cropland Required[c] (thousands of hectares)	Cropland[d] (thousands of hectares)	Percent of State Cropland
East South Central					
Kentucky	3.79	75.74	30.3	1,923	1.6
Tennessee	5.10	101.92	40.8	1,731	2.4
Alabama	4.19	83.73	33.5	959	3.5
Mississippi	2.64	52.76	21.1	1,635	1.3
West South Central					
Arkansas	2.42	48.36	19.3	2,711	0.71
Louisiana	4.29	85.73	34.3	1,612	2.1
Oklahoma	3.23	64.55	25.8	3,871	0.67
Texas	18.03	360.31	144.1	7,911	1.8
Mountain					
Montana	0.84	16.79	6.72	6,200	0.11
Idaho	1.10	21.98	8.79	2,065	0.43
Wyoming	0.47	9.39	3.76	870	0.43
Colorado	3.56	71.14	28.5	3,514	0.81
New Mexico	1.61	32.17	12.9	493	2.6
Arizona	3.93	78.54	31.4	427	7.4
Utah	1.86	37.17	14.9	517	2.9
Nevada	1.39	27.78	11.1	236	4.7
Pacific					
Washington	5.25	104.91	42.5	2,701	1.6
Oregon	3.03	60.55	24.2	1,495	1.6
California	31.21	623.69	249.5	3,516	7.1
Alaska		11.99	4.8	13	36.9
Hawaii	0.60	23.38	9.35	66	14.2
	1.17				

[a] Estimate of July 1993 population from U.S. Census Bureau.

[b] Sludge production estimates assume 75% of population is sewered and produces .073 kg of sludge per person per day.

[c] State cropland required if all sludge produced in-state were to be applied at agronomic rates using the assumption of 4 percent available nitrogen dry weight and an application rate of 100 kilograms per hectare per year.

[d] 1987 land utilization from U.S. Department of Agriculture, 1992.

exceed the capacity of the agroecosystem to accommodate them, the result is an increase in system outputs of both natural and unnatural byproducts that can cause environmental harm. Society often bears the financial costs required to restore environmental quality and to maintain high crop yields.

Frequently, cropland is removed from crop production and permitted to lie fallow for several years. These fallow fields are often referred to as old-field communities or old-field ecosystems. Various studies on the effects of sludge application to old-field ecosystems have focused on ecological trophic levels, including producers (Maly and Barrett, 1984; Hyder and

FIGURE 2.7 Diagrams depicting a) natural, and b) human inputs into agroecosystems. SOURCE: Adapted from Barrett et al., 1990.

Barrett, 1986), primary consumers (Anderson and Barrett, 1982; Brewer et al., 1994), secondary consumers (Brueske and Barrett, 1991), detritivores (Kruse and Barrett, 1985; Levine et al., 1989) and decomposers (Sutton et al., 1991,; Brewer et al., 1994). Thus far, the research indicates that old-field ecosystems are ecologically safe and economically viable sites for sludge disposal (Maly and Barrett, 1984; Carson and Barrett, 1988; Levine et al., 1989; and Brewer et al., 1994). These old-fields may again revert to cropland usage due to improved productivity and soil conditioning.

SUMMARY

With continuing advancement in wastewater treatment technology and increasingly stringent wastewater discharge requirements, treated wastewater effluents produced by municipal treatment plants in the United States have achieved consistent high water quality and are increasingly being considered for nonpotable reuse. In the semiarid and arid western states, treated wastewater has been used as a new source of water to help alleviate shortages faced by water-deficient communities. More recently, the need to meet local minimum in-stream water quality limits when treated effluents are discharged into surface water bodies has motivated many municipalities to consider effluent irrigation.

The chemical composition of most treated effluents is within the range defined by accepted irrigation water quality criteria and is comparable to that of water commonly used in crop and landscaping irrigation. At present, treated municipal wastewater probably accounts for much less than one percent of national irrigation water requirements, and it is likely that the level of agricultural use will not significantly increase. Effective barriers to increased use include the limited availability of irrigated agricultural land near municipal centers, and the competition with more cost-effective, higher-value urban uses for reclaimed water.

Much of the wastewater in the United States is produced in regions where agricultural irrigation is not needed or is only occasionally needed. Judging from the acreage of irrigated cropland compared to the availability of reclaimed wastewater and the current pattern of reclaimed water use, only a very small fraction of the food crops in the United States would ever be exposed to reclaimed wastewater.

Treated sewage sludge is an end product of municipal wastewater treatment and contains many of the pollutants that are removed from the influent wastewater during treatment. The nutrients and organic matter in treated sludge resembles those in other organic waste-based soil amendments such as animal manure and organic composts. The use of sludge as a soil conditioner serves to improve soil physical properties in a manner similar to other organic-based soil amendments. While sewage sludge has been land applied since it was first produced, most of the early operations were carried out with little regard for possible adverse impacts to soil, crops, or ground water. In the past two decades, more emphasis has been placed on applying treated sludges to cropland at agronomic rates.

The financial incentive for farmers to use sewage sludge in crop production is debatable. Fertilizers presently account for a relatively small percentage of total crop production costs, and sewage sludge may be more difficult to use than commercial fertilizer. However, the nutrient value of sludge is promoted as a benefit, and the POTW often provides for transport and application of sludge for free or at a nominal cost.

Community-wide source control and industrial wastewater pretreatment programs have resulted in significant reduction of toxic pollutants in wastewater and thus in sewage sludge. Still, land application of treated effluents and treated sludge will increase the level of toxic chemicals and pathogens in the soil. The public is concerned about pollutants and pathogens that may contaminate food crops or be transported elsewhere in the environment.

If the total amount of municipal sludge produced in the United States were applied to cropland at agronomic rates, less than 2 percent of the nation's cropland would be necessary to accept it. However, there are some regions where limited cropland acreage may constrain sludge management options. A lack of available disposal options near densely populated urban centers has forced many municipalities to seek distant disposal and land application sites at considerable costs. Given these economic and geographic constraints, it is not likely that all of the sewage sludge will be applied to cropland in the foreseeable future, and thus only a very small percentage of the food crops grown in the United States would ever be exposed to sewage sludge.

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