

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 33 percent of the U.S. total.¹ Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of N_2O emissions; however, methodologies are not currently available to develop a complete estimate. Nitrous oxide emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Overall, in 2000, waste activities generated emissions of 240.6 Tg CO_2 Eq., or 3.4 percent of total U.S. greenhouse gas emissions.

Landfills

Landfills are the largest anthropogenic source of methane (CH_4) emissions in the United States. In 2000, landfill CH_4 emissions were approximately 203.5 Tg CO_2 Eq. (9,690 Gg). Emissions from municipal solid waste (MSW) landfills, which received about 61 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Over 2,100 operational landfills exist in the United States (*BioCycle* 2001), with the largest landfills receiving most of the waste and generating the majority of the methane.

Methane emissions result from the decomposition of organic landfill materials such as paper, food scraps, and yard trimmings. This decomposition process is a biological process through which microorganisms derive energy. After being placed in a landfill, organic waste is initially digested by aerobic (in the presence of oxygen) bacteria. After the oxygen supply has been depleted, the remaining waste is consumed by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane-

¹ Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land-Use Change and Forestry chapter.

Figure 7-1

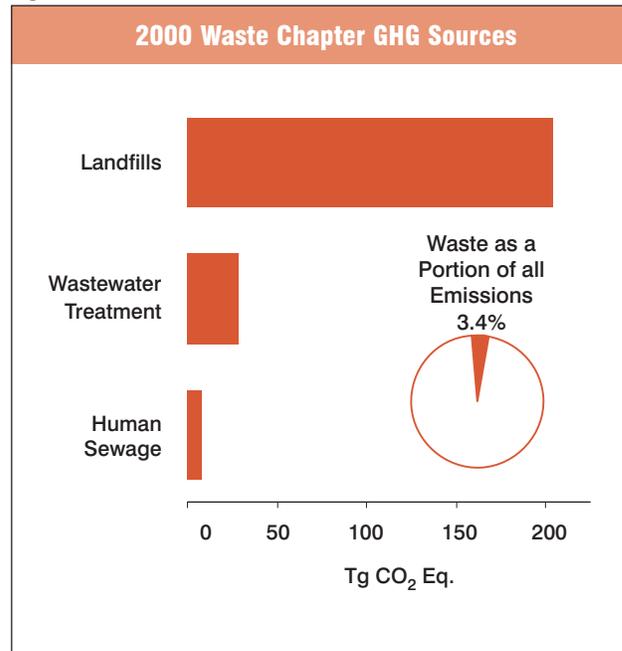


Table 7-1: Emissions from Waste (Tg CO₂ Eq.)

Gas/Source	1990		1995	1996	1997	1998	1999	2000
CH₄	237.7		243.4	238.5	233.9	228.8	231.4	232.2
Landfills	213.4		216.6	211.5	206.4	201.0	203.1	203.5
Wastewater Treatment	24.3		26.8	27.0	27.5	27.8	28.3	28.7
N₂O	7.0		7.7	7.8	7.9	8.1	8.4	8.5
Human Sewage	7.0		7.7	7.8	7.9	8.1	8.4	8.5
Total	244.7		251.1	246.3	241.9	236.9	239.8	240.6

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (Gg)

Gas/Source	1990		1995	1996	1997	1998	1999	2000
CH₄	11,317		11,591	11,359	11,138	10,897	11,021	11,056
Landfills	10,162		10,315	10,072	9,827	9,571	9,671	9,690
Wastewater Treatment	1,155		1,275	1,287	1,311	1,326	1,350	1,367
N₂O	23		25	25	26	26	27	27
Human Sewage	23		25	25	26	26	27	27

Note: Totals may not sum due to independent rounding.

Box 7-1: Biogenic Emissions and Sinks of Carbon

For many countries, CO₂ emissions from the combustion or degradation of biogenic materials are important because of the significant amount of energy they derive from biomass (e.g., burning fuelwood). The fate of biogenic materials is also important when evaluating waste management emissions (e.g., the decomposition of paper). The carbon contained in paper was originally stored in trees during photosynthesis. Under natural conditions, this material would eventually degrade and cycle back to the atmosphere as CO₂. The quantity of carbon that these degradation processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic greenhouse gas sources. But the focus of the United Nations Framework Convention on Climate Change is on anthropogenic emissions—emissions resulting from human activities and subject to human control—because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and enhancing the atmosphere's natural greenhouse effect.

Carbon dioxide emissions from biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO₂ that was originally removed by photosynthesis. However, CH₄ emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH₄ formation that exist in landfills, and are consequently included in this Inventory.

The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials—which occurs when wastes of biogenic origin are deposited in landfills—sequesters carbon. When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. Landfilling of forest products and yard trimmings results in long-term storage of about 70 Tg CO₂ Eq. and 7 to 18 Tg CO₂ Eq. per year, respectively. Carbon storage that results from forest products and yard trimmings disposed in landfills is accounted for in the Land-Use Change and Forestry chapter, as recommended in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) regarding the tracking of carbon flows.

Box 7-2: Recycling and Greenhouse Gas Emissions and Sinks

U.S. waste management patterns changed dramatically over the past decade in response to changes in economic and regulatory factors. Perhaps the most significant change from a greenhouse gas perspective was the increase in the national average recycling rate, which climbed from 16 percent in 1990 to 28 percent in 1999 (EPA 2000).

This change has affected emissions in several ways, primarily by reducing emissions from waste and energy activities, as well as by enhancing forestry sinks. The impact of increased recycling on greenhouse gas emissions can be best understood when emissions are considered from a life cycle perspective (EPA 1998). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed and managed as waste. The substitution of recycled inputs for virgin inputs reduces three types of emissions throughout the product life cycle. First, manufacturing processes involving recycled inputs generally require less energy than those using virgin inputs. Second, the use of recycled inputs leads to reductions in process non-energy emissions (e.g., perfluorocarbon emissions from aluminum smelting). Third, recycling reduces disposal and waste management emissions, including methane from landfills and nitrous oxide and non-biogenic carbon dioxide emissions from combustion. In addition to greenhouse gas emission reductions from manufacturing and disposal, recycling of paper products—the largest component of the U.S. wastestream—results in increased forest carbon sequestration. When paper is recycled, fewer trees are needed as inputs in the manufacturing process; reduced harvest levels result in older average forest ages, with correspondingly more carbon stored.

producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO₂) and 50 percent methane (CH₄), by volume.² Methane production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

Between 1990 and 2000, net methane emissions from landfills were relatively constant (see Table 7-3 and Table 7-4). The roughly constant emissions estimates are a result of two offsetting trends: (1) the amount of MSW in landfills contributing to methane emissions increased, thereby increasing the potential for emissions; and (2) the amount of landfill gas collected and combusted by landfill operators also increased, thereby reducing emissions.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of MSW in landfills, which is related to total MSW landfilled annually for the last 30 years; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place; size, climate); (3) the amount of methane that is recovered and either flared or used for energy purposes; and (4) the amount of methane oxidized in landfills instead of being released into the atmosphere. The estimated total quantity of waste-in-place contributing to emissions increased from about

4,926 Tg in 1990 to 6,147 Tg in 2000, an increase of 25 percent (see Annex O). During this period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1,119 Gg of methane was recovered and combusted (i.e., used for energy or flared) from landfills. In 2000, the estimated quantity of methane recovered and combusted increased to 4,874 Gg.

Over the next several years, the total amount of MSW generated is expected to increase slightly. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a 1996 regulation that requires large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc and WWW).

Methodology

Based on available information, methane emissions from landfills were estimated to equal the methane produced from municipal landfills, minus the methane recovered and combusted, minus the methane oxidized before being released into the atmosphere, plus the methane produced by industrial landfills.

² The percentage of CO₂ in biogas released from a landfill may be smaller because some CO₂ dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is composed of non-methane volatile organic compounds (NMVOCs).

Table 7-3: CH₄ Emissions from Landfills (Tg CO₂ Eq.)

Activity	1990	1995	1996	1997	1998	1999	2000
MSW Landfills	221.6	255.5	261.8	268.4	274.0	280.9	286.5
Industrial Landfills	15.3	17.5	17.8	18.2	18.5	19.0	19.3
Recovered							
Gas-to-Energy	(14.5)	(21.4)	(24.6)	(29.7)	(36.3)	(41.7)	(46.1)
Flared	(9.0)	(35.0)	(43.5)	(50.5)	(55.3)	(55.1)	(56.2)
Total	213.4	216.6	211.5	206.4	201.0	203.1	203.5

Note: Totals may not sum due to independent rounding.

Table 7-4: CH₄ Emissions from Landfills (Gg)

Activity	1990	1995	1996	1997	1998	1999	2000
MSW Landfills	10,551	12,165	12,465	12,779	13,050	13,374	13,642
Industrial Landfills	731	833	850	868	883	904	921
Recovered							
Gas-to-Energy	(692)	(1,017)	(1,171)	(1,415)	(1,729)	(1,984)	(2,196)
Flared	(427)	(1,665)	(2,073)	(2,405)	(2,633)	(2,623)	(2,678)
Total	10,162	10,315	10,072	9,827	9,571	9,671	9,690

Note: Totals may not sum due to independent rounding.

The methodology for estimating CH₄ emissions from municipal landfills is based on a model that updates the population of U.S. landfills each year. This model is based on the pattern of actual waste disposal, as evidenced in an extensive landfill survey by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population (EPA 1993). For each landfill in the data set, the amount of waste-in-place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emissions by emission factors (EPA 1993). For further information see Annex O.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment and a database of landfill gas-to-energy (LFGTE) projects. Based on the information provided by vendors, the methane combusted by the 585 flares in operation from 1990 to 2000

were estimated. This quantity likely underestimates flaring. Additionally, the database provided sufficient data on landfill gas flow and energy generation for 306 of the approximately 314 operational LFGTE projects. If both flare data and LFGTE recovery data for a particular landfill were available, then the emissions recovery was based on the LFGTE data, which provides actual landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project was likely to also have had a flare, double counting reductions from flares and LFGTE projects was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.³

Emissions from industrial landfills were assumed to be equal to 7 percent of the total methane emissions from municipal landfills. The amount of methane oxidized was assumed to be 10 percent of the methane generated that is

³ Due to the differences in referencing landfills and incomplete data on the national population of flares, matching flare vendor data with the LFGTE data was problematic and a flare could not be identified for each of the LFGTE projects. Because each LFGTE project likely has a flare, the aggregate estimate of emission reductions through flaring was reduced by the LFGTE projects for which a specific flare could not be identified. This approach eliminated the potential for double counting emissions reductions at landfills with both flares and a LFGTE project.

not recovered (Liptay et al. 1998). To calculate net methane emissions, both methane recovered and methane oxidized were subtracted from methane generated at municipal and industrial landfills.

Data Sources

The landfill population model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA's Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1990 through 2000 were obtained from *BioCycle* (2001). Documentation on the landfill methane emissions methodology employed is available in the EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993). Information on flares was obtained from vendors, and information on landfill gas-to-energy projects was obtained from the EPA's Landfill Methane Outreach Program database.

Uncertainty

Several types of uncertainties are associated with the estimates of methane emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is lacking on the area landfilled and total waste-in-place—the fundamental factors that affect methane production. In addition, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty in the landfill methane emission rate is estimated to be roughly ± 30 percent.

Wastewater Treatment

Wastewater from domestic sources (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur off-site or on-site. For example, in the United States, approximately 25 percent of domestic wastewater is treated in septic systems or other on-site systems. Soluble organic matter is generally removed using biological processes in which

microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces methane. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. Untreated wastewater may also produce methane if contained under anaerobic conditions.

The organic content, expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. COD refers to the amount of oxygen consumed under specified conditions in the oxidation of the organic and oxidizable inorganic matter and is a parameter typically used to characterize industrial wastewater. Under anaerobic conditions and with all other parameters, such as temperature, being the same, wastewater with higher organic content will produce more methane than wastewater with lower BOD or COD.

In 2000, methane emissions from domestic wastewater treatment were 13.9 Tg CO₂ Eq. (660 Gg). Emissions have increased since 1990 in response to the increase in the U.S. human population. Industrial emission sources include wastewater from the pulp and paper, meat and poultry processing, and the vegetables, fruits and juices processing industry.⁴ In 2000, methane emissions from industrial wastewater treatment were 14.8 Tg CO₂ Eq. (707 Gg). Table 7-5 and Table 7-6 provide emission estimates from domestic and industrial wastewater treatment.

Methodology

Domestic wastewater methane emissions were estimated using the default IPCC methodology (IPCC 2000). The total population for each year was multiplied by a per capita wastewater BOD production rate to determine total

⁴ Industrial wastewater emissions from petroleum systems is included in the petroleum systems section in the Energy chapter.

Table 7-5: CH₄ Emissions from Domestic and Industrial Wastewater Treatment (Tg CO₂ Eq.)

Activity	1990		1995	1996	1997	1998	1999	2000
Domestic	12.3		13.1	13.2	13.4	13.5	13.7	13.9
Industrial*	12.0		13.7	13.8	14.2	14.3	14.6	14.8
Total	24.3		26.8	27.0	27.5	27.8	28.3	28.7

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

Table 7-6: CH₄ Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990		1995	1996	1997	1998	1999	2000
Domestic	584		622	630	637	645	653	660
Industrial*	571		653	658	674	681	697	707
Total	1,155		1,275	1,287	1,311	1,326	1,350	1,367

* Industrial activity includes the pulp and paper, meat and poultry, and the vegetables, fruits and juices processing industry.
Note: Totals may not sum due to independent rounding.

wastewater BOD produced. It was assumed that, per capita, 0.065 kilograms of wastewater BOD⁵ was produced per day and that 16.25 percent of wastewater BOD₅ was anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.6 kg CH₄/kg BOD₅.

A top-down approach was used to develop estimates of methane emissions from industrial wastewater according to the methodology described in the IPCC *Good Practice Guidance* (IPCC 2000). Industry categories identified by IPCC were analyzed to identify industries likely to have significant methane emissions from industrial wastewater. Industries were chosen that typically have both a high volume of wastewater generated and a high organic COD wastewater load. The top three industries that met these criteria were:

- Pulp and paper manufacturing
- Meat and poultry packing
- Vegetables, fruits and juices processing

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m³/ton of output), the organics loading in the outflow (grams of organic COD/

m³), the emission factor (grams CH₄/grams COD), and the percentage of organic COD assumed to degrade anaerobically.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (Worldbank 1999, Nemerow 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment). In developing estimates for this category BOD was used instead of COD, because more accurate BOD numbers were available. In determining the percent that degraded anaerobically, both primary and secondary treatment were considered. Primary treatment lagoons are aerated to reduce anaerobic activity. However, the lagoons are large and zones of anaerobic activity may occur. Approximately 42 percent of the BOD passes on to secondary treatment, which are less likely to be aerated (EPA 1993). It was assumed that 25 percent of the BOD in secondary treatment lagoons degrades anaerobically, while 10 percent passes through to be discharged with the effluent (EPA 1997a). Overall, the percentage of wastewater organics that degrade anaerobically was determined to be 10.3 percent. The emission factor that was used is 0.6 kg CH₄/kg BOD, which is the default emission factor from IPCC (2000).

⁵ The 5-day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1991).

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence to screening, fat traps and dissolved air flotation, and it was estimated that 77 percent of all wastewater organics from this industry degrades anaerobically (EPA 1997b).

Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to the sewer. Therefore, it was assumed that this industry is likely to use lagoons intended for aerobic operation, but that the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used. Consequently, it was estimated that 5 percent of these wastewater organics degrade anaerobically.

Data Sources

National population data for 1990 to 2000, used in the domestic wastewater emissions estimates, were supplied by the U.S. Census Bureau (2000). Per-capita production of BOD₅ for domestic wastewater was obtained from the EPA (1997b). The emission factor (0.6 kg CH₄/kg BOD₅) employed for domestic wastewater treatment was taken from IPCC (2000). The same emission factor was used for pulp and paper wastewater, whereas the emission factor for meat and poultry, and vegetables, fruits and juices category is 0.25 kg CH₄/kg COD (IPCC 2000).

Table 7-7 provides U.S. population and wastewater BOD data.

Table 7-7: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD ₅
1990	249.4	5,920
1991	252.0	5,984
1992	254.9	6,052
1993	257.7	6,118
1994	260.2	6,179
1995	262.7	6,238
1996	265.2	6,296
1997	267.7	6,356
1998	270.2	6,415
1999	272.6	6,473
2000	275.1	6,531

For pulp and paper, a time series of methane emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post Directory 1992-2001). The overall wastewater outflow was estimated to be 85 m³/ton and the average BOD loading entering the secondary treatment lagoons was estimated to be 0.4 gram BOD/liter. Both values are based on information from multiple handbooks.

Production data for the meat and poultry industry were obtained from the U.S. Census (2001). EPA (1997b) provides wastewater outflows of 13 (out of a range of 8 to 18) m³/ton and an average COD value of 4.1 (out of a range of 2 to 7) g/liter.

The USDA National Agricultural Statistics Service (USDA 2001) provided production data for the fruits, vegetables, and juices processing sector. Outflow data for various subsectors (canned fruit, canned vegetables, frozen vegetables, fruit juices, jams, baby food) were obtained from World Bank (1999) and an average wastewater outflow of 5.6 m³/ton was used. For the organics loading, a COD value of 5 (out of a range of 2 to 10) g/liter was used (EPA 1997b).

Table 7-8 provides U.S. pulp and paper; meat and poultry; and vegetables, fruits, and juices production data.

Uncertainty

Domestic wastewater emissions estimates are uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences.

Table 7-8: U.S. Pulp and Paper, Meat and Poultry, and Vegetables, Fruits and Juices Production (Million Metric Tons)

Year	Pulp and Paper	Meat and Poultry	Vegetables, Fruits and Juices
1990	128.9	28.2	29.7
1991	129.2	29.0	30.8
1992	134.5	30.0	32.9
1993	134.1	31.0	33.6
1994	139.3	32.0	36.7
1995	140.9	33.6	36.2
1996	140.3	34.2	35.9
1997	145.6	34.6	37.1
1998	144.0	35.7	35.9
1999	145.1	37.0	36.8
2000	144.4	38.0	38.0

Large uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loadings may vary greatly for different plants and different sub-sectors (e.g. paper vs. board, poultry vs. beef, baby food vs. juices, etc.). Also, the degree to which anaerobic degradation occurs in treatment systems is very difficult to assess. In addition, it is believed that pulp and paper, meat and poultry and vegetables, fruits and juices are the most significant industrial sources, but there may be additional sources that also produce wastewater organics that may degrade under anaerobic conditions (e.g., organic chemicals and plastics production).

Human Sewage

Domestic human sewage (termed “blackwater”) is usually mixed with other household wastewater (known as “graywater”), which includes shower drains, sink drains, washing machine effluent, etc. and transported by a collection system to either a direct discharge, an on-site or decentralized wastewater system, or a centralized wastewater system. Decentralized wastewater systems are septic systems and package plants that may include several process steps. Centralized treatment systems may include a variety of treatment processes, ranging from lagooning to advanced tertiary wastewater treatment technology for removing nutrients. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary, etc.), applied to soils, or disposed of below the surface.

Nitrous oxide (N_2O) may be generated during both nitrification and denitrification of the nitrogen that is present, usually in the form of urea and proteins. Some of these primary nitrogen-containing compounds are rapidly broken down to ammonia-nitrogen while others persist as organic nitrogen. Both forms are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3^-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide (N_2O) can be an intermediate product of

Table 7-9: N_2O Emissions from Human Sewage

Year	Tg CO_2 Eq.	Gg
1990	7.0	23
1995	7.7	25
1996	7.8	25
1997	7.9	26
1998	8.1	26
1999	8.4	27
2000	8.5	27

both processes, but is more often associated with denitrification. In general, temperature, pH/alkalinity, biochemical oxygen demand (BOD), and nitrogen concentration affect N_2O generation from domestic wastewater treatment processes, while the amount of protein consumed by humans determines the quantity of nitrogen contained in sewage. Emissions of N_2O from sewage nitrogen discharged into aquatic environments were estimated to be 8.5 Tg CO_2 Eq. (27 Gg) in 2000. (See Table 7-9).

Methodology

Nitrous oxide emissions from human sewage effluent disposal were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) with one modification. The IPCC methodology assumes that nitrogen disposal and thus N_2O emissions associated with land disposal, subsurface disposal, as well as sewage treatment are negligible and all sewage nitrogen is discharged directly into aquatic environments. In the United States, however, a certain amount of sewage nitrogen is incinerated or applied to soils or landfills via sewage sludge applications, and therefore, not all sewage nitrogen enters aquatic environments.⁶ The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.

⁶ The IPCC methodology is based on the total amount of nitrogen in sewage, which is in turn based on human protein consumption and the fraction of nitrogen in protein (i.e., $Frac_{NPR}$). A portion of the total nitrogen in sewage in the United States is incinerated or applied to soils or landfills in the form of sewage sludge each year. This amount is subtracted here from total nitrogen in human sewage to estimate sewage N_2O emissions. The amount applied to soils is estimated as part of agricultural soil management (see Chapter 6).

With the modification described above, N₂O emissions from human sewage were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = \{[(\text{Protein}) \times (\text{Frac}_{\text{NPR}}) \times (\text{U.S. Population})] - N_{\text{sludge}}\} \times (\text{EF}) \times ({}^{44}/_{28})$$

where,

N₂O(s) = N₂O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = Fraction of nitrogen in protein

N_{sludge} = Quantity of sewage sludge N not entering aquatic environments

EF = Emission factor (kg N₂O-N/kg sewage-N produced)

(⁴⁴/₂₈) = The molecular weight ratio of N₂O to N₂

Data Sources

U.S. population data were taken from the U.S. Census Bureau (2001). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2001) (see Table 7-10). Because data on protein intake were unavailable for 2000, the value of per capita protein consumption for the previous year was used. An emission factor has not been specifically estimated for the United States, so the default IPCC value (0.01 kg N₂O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

The U.S. population, per capita protein intake data (Protein), and fraction of nitrogen in protein (Frac_{NPR}) are believed to be fairly accurate. Significant uncertainty exists, however, in the emission factor (EF). This uncertainty is due to regional differences in the receiving waters that would likely affect N₂O emissions but are not accounted for in the default IPCC factor. Moreover, the underlying methodological assumption that negligible N₂O emissions result from sewage treatment may be incorrect. A related uncertainty results from assuming all sewage nitrogen is

discharged directly into aquatic environments. Although the above methodology takes this into account for a portion of emissions, there are additional discharge pathways that need to be investigated. Taken together, these uncertainties present significant difficulties in estimating N₂O emissions from human sewage.⁷

Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 2000 are provided in Table 7-11.

Methodology and Data Sources

These emission estimates were taken directly from the EPA (2001). This EPA report provides emission estimates of these gases by sector, using a “top down” estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies.

Table 7-10: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	252.2	39.2
1991	255.5	39.8
1992	258.8	40.0
1993	262.1	40.2
1994	265.4	41.2
1995	268.7	40.6
1996	272.0	40.7
1997	275.3	41.0
1998	278.6	41.1
1999	281.9	41.9
2000	285.2	41.9

⁷ The 1999 protein consumption estimate was used as a proxy for the 2000 estimate, as these data are not yet available.

Table 7-11: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1995	1996	1997	1998	1999	2000
NO_x	83	89	78	78	79	79	81
Landfills	+	1	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion ^a	82	88	75	75	76	76	78
Miscellaneous ^b	+	1	1	1	1	1	1
CO	979	1,075	3,215	3,217	3,220	3,220	3,273
Landfills	1	2	5	5	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion ^a	978	1,073	3,210	3,211	3,214	3,214	3,268
Miscellaneous ^b	+	1	+	+	+	+	+
NMVOCs	895	968	508	509	513	518	528
Landfills	58	68	32	32	33	33	34
Wastewater Treatment	57	61	61	62	63	64	65
Waste Combustion ^a	222	237	352	352	353	354	360
Miscellaneous ^b	558	602	64	64	65	67	69

^a Includes waste incineration and open burning (EPA 2001)

^b Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 Gg

Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of

information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.