8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills were the largest source of anthropogenic methane (CH_4) emissions, accounting for 32 percent of total U.S. CH_4 emissions.[1] Smaller amounts of CH_4 are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (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 8-1 and Table 8-2.

Figure 8-1: 2002 Waste Chapter Greenhouse Gas Sources

Overall, in 2002, waste activities generated emissions of 237.2 Tg CO_2 Eq., or 3.4 percent of total U.S. greenhouse gas emissions.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1996	1997	1998	1999	2000	2001	2002
CH_4	**234.1**	**235.7**	**230.8**	**224.3**	**226.0**	**227.7**	**221.4**	**221.7**
Landfills	210.0	208.8	203.4	196.6	197.8	199.3	193.2	193.0
Wastewater Treatment	24.1	26.9	27.4	27.7	28.2	28.4	28.1	28.7
N_2O	**12.8**	**14.2**	**14.4**	**14.7**	**15.2**	**15.3**	**15.4**	**15.6**
Human Sewage	12.8	14.2	14.4	14.7	15.2	15.3	15.4	15.6
Total	**246.9**	**249.9**	**245.2**	**239.0**	**241.2**	**243.0**	**236.8**	**237.2**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1996	1997	1998	1999	2000	2001	2002
CH_4	**11,147**	**11,224**	**10,990**	**10,679**	**10,763**	**10,841**	**10,541**	**10,557**
Landfills	9,998	9,942	9,685	9,360	9,419	9,491	9,202	9,192
Wastewater Treatment	1,149	1,281	1,305	1,320	1,343	1,350	1,339	1,365
N_2O	**41**	**46**	**47**	**47**	**49**	**49**	**50**	**50**
Human Sewage	41	46	47	47	49	49	50	50

Note: Totals may not sum due to independent rounding.

8.1. Landfills (IPCC Source Category 6A1)

Landfills are the largest anthropogenic source of CH_4 emissions in the United States. In 2002, landfill CH_4 emissions were approximately 193 Tg CO_2 Eq. (9,192 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 CH_4.

[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.

After being placed in a landfill, biogenic waste (such as paper, food scraps, and yard trimmings) is initially digested by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which can 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-producing anaerobic bacteria convert these fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and may last from 10 to 60 years.

From 1990 to 2002, net CH_4 emissions from landfills decreased by approximately 8 percent (see Table 8-3 and Table 8-4), with small increases occurring in some interim years. This slightly downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted by landfill operators, which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of municipal solid waste in landfills, which is related to total municipal solid waste 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 CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 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 6,385 Tg in 2002, an increase of 30 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and flared from landfills increased as well. In 1990, for example, approximately 1,302 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills. In 2002, the estimated quantity of CH_4 recovered and combusted increased to 6,073 Gg.

Over the next several years, the total amount of municipal solid waste 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 CH_4 that is recovered and either flared or used for energy purposes is expected to increase, as a result of a 1996 regulation that requires large municipal solid waste landfills to collect and combust landfill gas (see 40 CFR Part 60, Subparts Cc 2002), and an EPA program that encourages voluntary CH_4 recovery and use at landfills not affected by the regulation.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	**1990**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
MSW Landfills	243.6	283.9	289.8	295.0	302.1	307.8	314.0	319.6
Industrial Landfills	17.1	19.9	20.3	20.6	21.1	21.5	22.0	22.4
Recovered								
Gas-to-Energy	(17.3)	(28.6)	(34.0)	(40.7)	(45.7)	(49.9)	(55.2)	(57.7)
Flared	(10.0)	(43.2)	(50.2)	(56.5)	(57.7)	(58.0)	(66.1)	(69.8)
Oxidized[1]	(23.3)	(23.2)	(22.6)	(21.8)	(22.0)	(22.1)	(21.5)	(21.4)
Total	**210.0**	**208.8**	**203.4**	**196.6**	**197.8**	**199.3**	**193.2**	**193.0**

Note: Totals may not sum due to independent rounding.

[1] Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	**1990**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
MSW Landfills	11,599	13,520	13,802	14,047	14,385	14,659	14,954	15,221

[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 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).

Industrial Landfills	812		946	966	983	1,007	1,026	1,047	1,065
Recovered									
Gas-to-Energy	(824)		(1,360)	(1,618)	(1,938)	(2,177)	(2,376)	(2,630)	(2,748)
Flared	(478)		(2,059)	(2,390)	(2,692)	(2,750)	(2,764)	(3,146)	(3,325)
Oxidized[a]	(1,111)		(1,105)	(1,076)	(1,040)	(1,047)	(1,055)	(1,022)	(1,021)
Total	**9,998**		**9,942**	**9,685**	**9,360**	**9,419**	**9,491**	**9,202**	**9,192**

Note: Totals may not sum due to independent rounding.

[a] Includes oxidation at municipal and industrial landfills.

Methodology

Methane emissions from landfills were estimated to equal the CH_4 produced from municipal landfills, minus the CH_4 recovered and combusted, plus the CH_4 produced by industrial landfills, minus the CH_4 oxidized before being released into the atmosphere.

The methodology for estimating CH_4 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 1986. 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 CH_4 generation was estimated using its year of opening, its waste acceptance rate, year of closure, and design capacity. Data on national municipal waste landfilled 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 3.14.

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 generation and disposal data for 1991 through 2002 were obtained from *BioCycle* (2001). Because *BioCycle* does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2000) and per capita municipal solid waste generation from EPA's *Municipal Solid Waste Disposal in the United States* report (2002a). Documentation on the landfill CH_4 emissions methodology employed is available in EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993).

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 compiled by EPA's Landfill Methane Outreach Program (LMOP). Based on the information provided by vendors, the CH_4 combusted by 712 flares in operation from 1990 to 2002 was estimated. This quantity likely underestimates flaring, because EPA does not have information on all flares in operation. Additionally, the LFGTE database provided data on landfill gas flow and energy generation for 382 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] Information on flares was obtained from vendors (ICF 2002, RTI

[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.

2003), and information on landfill gas-to-energy projects was obtained from the EPA's Landfill Methane Outreach Program database (EPA 2003).

Emissions from industrial landfills were assumed to be equal to seven percent of the total CH_4 emissions from municipal landfills (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (Liptay et al. 1998). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available for waste in place for every landfill—a fundamental factor that affects CH_4 production. The heterogeneity of waste disposed in landfills is uncertain as well. The approach used here assumes that the landfill set is representative of waste composition and reflects this heterogeneity. Also, the approach used to estimate the contribution of industrial non-hazardous wastes to total CH_4 generation employs introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation efficiency.

The preliminary results of the quantitative uncertainty analysis (see Table 8-5), indicate that, on average, in 19 out of 20 times (i.e., there is a 95 percent probability), the total greenhouse gas emissions estimate from this source is within the range of approximately 135.1 to 250.9 Tg CO_2 Eq. (or that the actual CH_4 emissions are likely to fall within the range of approximately 30 percent below and 30 percent above the emissions estimate of 193.0 Tg CO_2 Eq.).

The N_2O emissions from application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. The total nitrogen (N) in sewage sludge increased from 189 to 247 Gg total N between 1990 and 2002. The quantity of sewage sludge applied to landfills decreased from 28 to 11 percent from 1990 to 2001 (EPA 1993).

Table 8-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2002 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH_4	193.0	135.1	250.9	-30%	+30%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.

Recalculations Discussion

The estimates for the current inventory are based on the same basic methodology as the estimates for the previous inventory; however, a few minor improvements were made. For the previous inventory estimates, the nationwide emissions avoided by LFGTE projects for which flares could not be identified in the flare database were subtracted from the nationwide estimate of emissions avoided by flaring. This conservative approach was used to avoid double counting of emissions avoided by LFGTE projects and flaring. For the current estimates, this correction was made on a state-by-state basis rather than a nationwide basis. This approach is still conservative and avoids double counting; however, it resulted in slightly higher estimates of emissions avoided by flaring. The emissions avoided by flaring increased by about 1.6 percent over the time series as a result of this change.

Another change to the estimates for flaring resulted from additional vendors supplying information for flares that were installed from 1994 to 2002. As a result of identifying more landfills with flares, the emissions avoided by flaring increased by about 3 percent over the period from 1994 to 2001.

The procedure used to estimate emissions avoided by LFGTE projects that generate electricity were revised to improve the estimates and to develop a uniform set of calculation procedures. Adjustments were made to the availability factor (the fraction of the time a system is available for producing power), the heat rate, and the methane heating value. The new approach increased emissions avoided by LFGTE projects by 12 to 14 percent and reduced net methane emissions by 1 to 3 percent over the time series.

Changes were also made to the LFGTE database used to estimate emissions avoided by these projects. The changes included corrections to megawatt capacity and gas flow rates, adding new projects that started in 2002, and accounting for projects that shut down. These changes decreased emissions avoided by LFGTE projects by an average of about 2 percent and increased net methane emissions by about 0.3 percent over the time series.

Planned Improvements

For the future inventories, the regression equations used for methane generation will be re-evaluated using a database of several hundred landfills provided by the Landfill Methane Outreach Program. The database contains information on landfill gas collection rates and waste in place for LFTGE projects. This analysis will allow for an update of emission factors due to changing wastestream and waste management characteristics. Additional information will be obtained on landfills in the United States to develop a representative sample and improve the landfill population database used for the inventory.

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater from domestic (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.

In 2002, methane emissions from domestic wastewater treatment were 14.0 Tg CO_2 Eq. (668 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 2002, CH_4 emissions from industrial wastewater treatment were estimated to be 14.6 Tg CO_2 Eq. (697

[4] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter.

Gg). The increase compared to the 2001 estimates is due to increases in production outputs in all three sectors. Table 8-6 and Table 8-7 provide emission estimates from domestic and industrial wastewater treatment.

Table 8-6: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1996	1997	1998	1999	2000	2001	2002
Domestic	12.1	13.1	13.3	13.4	13.6	13.7	13.9	14.0
Industrial*	12.0	13.8	14.2	14.3	14.6	14.6	14.3	14.6
Total	**24.1**	**26.9**	**27.4**	**27.7**	**28.2**	**28.4**	**28.1**	**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 8-7: CH_4 Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1996	1997	1998	1999	2000	2001	2002
Domestic	578	624	631	639	646	653	660	668
Industrial*	571	658	674	681	698	697	679	697
Total	**1,149**	**1,281**	**1,305**	**1,320**	**1,343**	**1,350**	**1,339**	**1,365**

* 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.

Methodology

Domestic wastewater CH_4 emissions were estimated using the default IPCC methodology. National population data for 1990 to 2002, used in the domestic wastewater emissions estimates, were based on data from the U.S. Census Bureau (2002). Per-capita production of BOD_5[5] for domestic wastewater was obtained from EPA (1997b). The emission factor (0.6 kg CH_4/kg BOD_5) was taken from IPCC *Good Practice Guidance* (IPCC 2000). The percent of wastewater BOD_5 that was anaerobically digested was assumed to be 16.25 percent. This value also accounts for U.S. septic systems and is based on expert judgment and on septic system usage data from EPA (1996).

Table 8-8: U.S. Population (Millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD_5
1990	249.6	5,926
1995	266	6,322
1996	269	6,396
1997	273	6,473
1998	276	6,549
1999	279	6,625
2000	282	6,700
2001	285	6,774
2002	288.4	6,846

Methane emissions estimates from industrial wastewater were developed according to the methodology described in the IPCC (2000). Industry categories that are likely to have significant CH_4 emissions from their wastewater treatment were identified. High volumes of wastewater generated and a high organic COD wastewater load were the main criteria. The top three industries that met these criteria included pulp and paper manufacturing, meat and poultry packing, and vegetables, fruits and juices processing.[6]

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

[6] Industrial wastewater emissions from petroleum systems are included in the petroleum systems section in the Energy chapter.

Methane emissions from these categories were estimated by multiplying the annual product output (metric tons/year) by the average outflow (m^3/ton of output), the organics loading in the outflow (grams of organic COD/m^3), the emission factor (grams CH_4/grams COD), and the percentage of organic COD assumed to degrade anaerobically. In developing estimates for the pulp and paper category, BOD was used instead of COD, because more accurate BOD numbers were available. The emission factor used for pulp and paper wastewater was 0.6 kg CH_4/kg BOD_5, whereas the emission factor for meat and poultry, and vegetables, fruits and juices category is 0.25 kg CH_4/kg COD (IPCC 2000). The pertinent industry-specific parameters are specified below.

Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999, Nemerow and Dasgupta 1991). The most important step is lagooning for storage, settling, and biological treatment (secondary treatment). 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. A time series of CH_4 emissions for post-1990 years was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post, 2002). The overall wastewater outflow was estimated to be 85 m^3/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.

The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence to screening, fat traps and dissolved air flotation. An estimated 77 percent of all wastewater organics from this industry degrades anaerobically (EPA 1997b). Production data for the meat and poultry industry were obtained from the U.S. Census (2002). EPA (1997b) provides wastewater outflows of 13 (out of a range of 8 to 18) m^3/metric ton and an average COD value of 4.1 (out of a range of 2 to 7) g/liter. These parameters are currently undergoing review, based on a recent comprehensive survey conducted by EPA's Office of Water (EPA 2002).

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. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta, 1991). Consequently, it was estimated that 5 percent of these wastewater organics degrade anaerobically. The USDA National Agricultural Statistics Service (USDA 2002) 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 m^3/metric ton was used. For the organics loading, a COD value of 5 g/liter was used (EPA 1997b).

Table 8-9: 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	30.2
1991	129.2	29.0	31.2
1992	134.5	30.0	33.5
1993	134.1	31.0	34.1
1994	139.3	32.0	37.3
1995	140.9	33.6	36.8
1996	140.3	34.2	36.4
1997	145.6	34.6	37.7
1998	144.0	35.7	36.5
1999	145.1	37.0	37.4
2000	142.8	37.4	38.9

2001	134.3	37.5	35.0
2002	137.5	38.6	36.9

Uncertainty

The uncertainty associated with the emission factor for CH_4 emissions from wastewater is estimated to be 30 percent (IPCC 2000). For domestic wastewater, uncertainty associated with the occurrence of anaerobic conditions in treatment systems was estimated to be 25 percent, based on septic tank usage data from EPA (1996) and expert judgment. Also, the per-capita BOD uncertainty is 30 percent (IPCC 2000). The combined uncertainty for domestic wastewater was estimated to be 49 percent.

Large uncertainties are associated with the industrial wastewater emission estimates. Wastewater outflows and organics loadings vary considerably for different plants and different sub-sectors (e.g., paper vs. board, poultry vs. beef, or baby food vs. juices). Uncertainties for outflows are between 38 and 55 percent for the different source categories and are based on expert judgment and the literature (Nemerow and Dasgupta, 1991; World Bank, 1999). Uncertainties for organic loadings are based on similar references and are estimated at 25, 51, and 60 percent for pulp and paper, meat and poultry, and fruits, vegetables and juices, respectively. The uncertainty associated with the degree in which anaerobic degradation occurs in treatment systems is estimated at 50 percent for all three industrial categories. The composite uncertainty for the industrial wastewater subcategory is approximately 59 percent. The overall uncertainty for the wastewater category is estimated to be 39 percent (see Table 4-51).

Table 8-10: Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

IPCC Source Category	Gas	Year 2002 Emissions (Tg CO_2 Eq.)	Uncertainty (%)	Uncertainty Range Relative to 2002 Emission Estimate (Tg CO_2 Eq.)	
				Lower Bound	Upper Bound
Wastewater Treatment	CH_4	28.7	39%	17.5	39.8

Recalculations Discussion

The time series for domestic wastewater has been updated relative to the previous inventory due to an increase in the per capita protein intake. The time series for industrial wastewater also changed due to updated production estimates for the red meat, poultry, and fruit and vegetable industries.

Planned Improvements Discussion

EPA's Office of Water is finalizing the Effluent Limitations Guidelines and New Source Performance Standards for the Meat and Poultry Products Point Source Category. It is anticipated that research data from this effort can be used to improve the methodology for estimating CH_4 emissions from this category.

8.3. Human Sewage (Domestic Wastewater) (IPCC Source Category 6B)

Domestic human sewage is usually mixed with other household wastewater, 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 treatment system, or a centralized wastewater treatment system. Decentralized wastewater treatment systems are septic systems and package plants. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Often, centralized wastewater treatment systems also treat certain flows of industrial, commercial, and institutional wastewater. After processing, treated effluent is discharged to a receiving water environment (e.g., river, lake, estuary, etc.), or applied to soils, or disposed of below the surface.

Nitrous oxide may be generated during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These 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 can be an intermediate product of both processes, but is more often associated with denitrification.

The United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from wastewater treatment processes; and emissions from effluent that has been discharged into aquatic environments. The 2002 emissions of N_2O from wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (0.9 Gg) and 15.3 Tg CO_2 Eq. (49 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 15.6 Tg CO_2 Eq. (50 Gg) (see Table 8-11). Emissions from wastewater treatment processes have gradually increased as a result of increasing U.S. population and protein consumption.

Table 8-11: N_2O Emissions from Human Sewage

Year	Tg CO_2 Eq.	Gg
1990	12.8	41
1996	14.1	46
1997	14.4	47
1998	14.6	47
1999	15.1	49
2000	15.1	49
2001	15.4	50
2002	15.6	50

Methodology

The IPCC default methodology (IPCC/UNEP/OECD/IEA 1997) assumes that nitrogen disposal, and thus N_2O emissions associated with land disposal, subsurface disposal, and domestic wastewater treatment are negligible and all nitrogen is discharged directly into aquatic environments. For the United States, N_2O emissions from domestic wastewater (human sewage) were estimated using the IPCC methodology with three modifications:

- In the United States, a certain amount of nitrogen is removed with the sewage sludge, which is land applied, incinerated or landfilled (N_{sludge}). The nitrogen disposal into aquatic environments is reduced to account for the sewage sludge application.

- The IPCC methodology uses annual, per capita protein consumption (kg/year). This number is likely to underestimate the amount of protein entering the sewer or septic system. Food (waste) that is not consumed is often washed down the drain, as a result of the use of garbage disposals. Also, bath and laundry water can be expected to contribute to nitrogen loadings. A factor of 1.4 is introduced to account for this nitrogen. Furthermore, industrial wastewater co-discharged with domestic wastewater is not accounted for in the existing methodology. To correct for this, a factor of 1.25 is used. The fraction of non-consumption protein in domestic wastewater (combined value of 1.75) is based on expert judgment and on Metcalf & Eddy (1991) and Mullick (1987).

- Process emissions from wastewater treatment plants are not accounted for in the current IPCC methodology. To estimate N_2O emissions from U.S. wastewater treatment plants, an overall emission factor (4 g N_2O/person.year) was introduced. This emission factor is based on a factor of 3.2 g N_2O/person.year (Czepiel 1995) multiplied by a factor of the 1.25 factor mentioned above, which adjusts for co-discharged industrial nitrogen and which is based on expert judgment. The nitrogen quantity associated with these emissions (N_{WWT}) is calculated by multiplying the N_2O emitted by $^{(2 \times 14)}/_{44}$ and it is subtracted from the total quantity of nitrogen that is ultimately disposed into the aquatic environment.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the IPCC default methodology (IPCC/UNEP/OECD/IEA 1997). This methodology is illustrated below:

$$N_2O(s) = (US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) + \{[(Protein \times 1.75 \times Frac_{NPR} \times US_{POP}) - N_{WWT} - N_{sludge}] \times EF_2 \times {}^{44}/_{28}\}$$

where,

$N_2O(s)$ = N_2O emissions from domestic wastewater ("human sewage") [kg/year]
US_{POP} = U.S. population
0.75 = Fraction of population using wastewater treatment plants (as opposed to septic systems)
EF_1 = Emission factor (4 g N_2O/person.year) expressing emissions from the wastewater treatment plants
Protein = Annual, per capita protein consumption
1.75 = Fraction of non-consumption protein in domestic wastewater
$Frac_{NPR}$ = Fraction of nitrogen in protein
N_{WWT} = Quantity of wastewater nitrogen removed by wastewater treatment processes [$(US_{POP} \times 0.75 \times EF_1 \times 10^{-3}) \times {}^{28}/_{44}$]
N_{sludge} = Quantity of sewage sludge N not entering aquatic environments
EF_2 = Emission factor (kg N_2O-N/kg sewage-N produced)
$({}^{44}/_{28})$ = The molecular weight ratio of N_2O to N_2.

U.S. population data were taken from the U.S. Census Bureau (2002). The fraction of the U.S. population using wastewater treatment plants is from the NEEDS Survey (EPA 1996). The emission factor (E_1) to estimate emissions from wastewater treatment is based on Czepiel, et al. (1995). Data on annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 2001). See Table 8-12.

Because data on protein intake were unavailable for 2002, the value of per capita protein consumption for the previous year was used. An emission factor to estimate emissions from effluent (EF_2) has not been specifically estimated for the United States, thus the default IPCC value (0.01 kg N_2O-N/kg sewage-N produced) was applied. The fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 8-12: U.S. Population (Millions) and Average Protein Intake (kg/Person/Year)

Year	Population	Protein
1990	250	39.2
1996	269	40.7
1997	273	40.9
1998	276	41.2
1999	279	42.0
2000	282	41.9
2001	285	41.8
2002	288	41.8

Uncertainty

Nitrous oxide emissions from wastewater treatment are estimated to be substantially less than emissions from effluent-surface water. Thus, this wastewater treatment subcategory was not considered in the uncertainty analysis. The U.S. population, per capita protein intake data (Protein), and fraction of nitrogen in protein ($Frac_{NPR}$) are believed to be fairly accurate. The uncertainty in activity data was estimated to be 26 percent. The fraction that expresses the ratio of non-consumption nitrogen was estimated to have an uncertainty of 25 percent, based on expert judgment. The emission factor for effluent (EF_2) is the default emission factor from IPCC (1996) where it is expressed as 0.01 based on a range of 0.002 to 0.02 kg N_2O per kg N-sewage. Consequently, EF_2 was allocated an uncertainty of 80 percent. The combined uncertainty for N_2O emissions from human sewage was estimated to be 84 percent (see Table 8-13).

Table 8-13: Quantitative Uncertainty Estimates for N_2O Emissions from Human Sewage (Tg CO_2 Eq. and Percent)

IPCC Source	Gas	Year 2002	Uncertainty	Uncertainty Range Relative to

Category		Emissions (Tg CO_2 Eq.)	(%)	2002 Emission Estimate (Tg CO_2 Eq.)	
				Lower Bound	Upper Bound
Human Sewage	N_2O	15.6	84%	2.5	28.6

Recalculations Discussion

The time series for domestic wastewater has changed slightly relative to that reported in the previous inventory due to an increase in per capita protein intake.

8.4. Waste Sources of Ambient Air Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of ambient air pollutant emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2002 are provided in Table 8-14.

Table 8-14: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1996	1997	1998	1999	2000	2001	2002
NO_x	**+**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Landfills	+	2	2	2	3	3	3	3
Wastewater Treatment	+	+	+	+	+	+	+	+
Miscellaneous[a]	+	1	1	1	+	+	+	+
CO	**1**	**5**	**5**	**5**	**14**	**14**	**14**	**15**
Landfills	1	5	5	5	13	13	13	14
Wastewater Treatment	+	+	+	+	1	1	1	1
Miscellaneous[a]	+	+	+	+	+	+	+	+
NMVOCs	**673**	**158**	**157**	**161**	**151**	**153**	**158**	**158**
Landfills	58	32	32	33	29	29	30	30
Wastewater Treatment	57	61	62	63	64	65	68	68
Miscellaneous[a]	558	65	64	65	58	59	60	60

[a] 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

Methodology and Data Sources

These emission estimates were obtained from preliminary data (EPA 2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided 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. 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 data bases.

Uncertainty

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

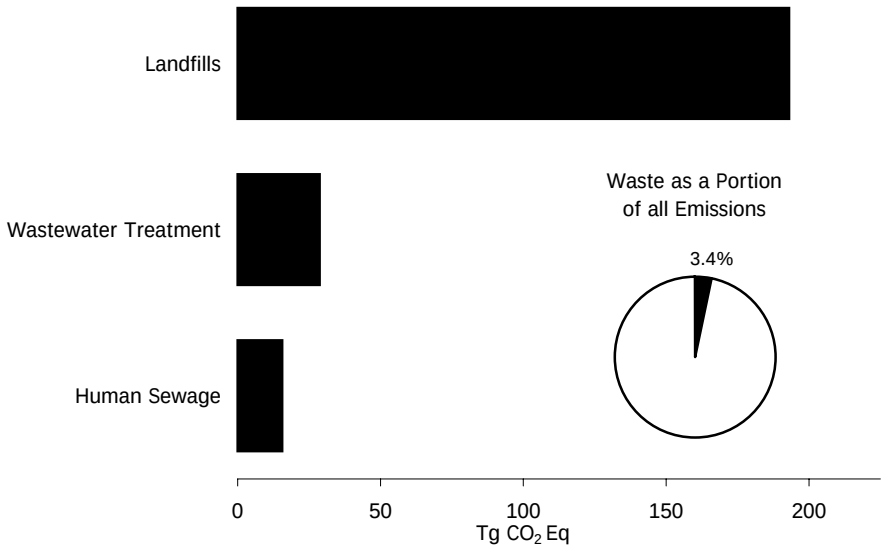

Figure 8-1: 2002 Waste Chapter Greenhouse Gas Sources

Descriptions of Figures: Waste

Figure 8-1 illustrates the data presented in Table 8-1. In addition, there is a pie chart that indicates that waste made up 3.4 % of U.S. greenhouse gas emissions in 2002.