

# **CHAPTER 6**

---

# **WASTEWATER TREATMENT AND DISCHARGE**

## **Authors**

Deborah Bartram (USA), Michael D. Short (Australia), Yoshitaka Ebie (Japan), Juraj Farkaš (Slovakia), Céline Gueguen (France), Gregory M. Peters (Sweden), Nuria Mariana Zanzottera (Argentina), M. Karthik (India)

## **Contributing Authors**

Shuhei Masuda (Japan)

## Contents

6	Wastewater Treatment and Discharge.....	6.7
6.1	Introduction .....	6.7
6.1.1	Centralised treatment systems .....	6.10
6.1.2	Decentralised treatment systems of domestic wastewater (onsite sanitation).....	6.11
6.1.3	Emissions from receiving waters.....	6.12
6.1.4	Changes compared to <i>1996 Guidelines and Good Practice Guidance</i> .....	6.12
6.1.5	Changes compared to 2006 IPCC Guidelines.....	6.12
6.2	Methane emissions from wastewater .....	6.13
6.2.1	Methodological issues .....	6.13
6.2.2	Domestic wastewater .....	6.14
6.2.2.1	Choice of method .....	6.14
6.2.2.2	Choice of emission factors .....	6.18
6.2.2.3	Choice of activity data.....	6.21
6.2.2.4	Time series consistency.....	6.29
6.2.2.5	Uncertainties.....	6.29
6.2.2.6	QA/QC, Completeness, Reporting and Documentation .....	6.30
6.2.3	Industrial wastewater .....	6.30
6.2.3.1	Choice of method .....	6.30
6.2.3.2	Choice of emission factors .....	6.33
6.2.3.3	Choice of activity data.....	6.35
6.2.3.4	Time series consistency.....	6.35
6.2.3.5	Uncertainties.....	6.35
6.2.3.6	QA/QC, Completeness, Reporting and Documentation .....	6.35
6.3	Nitrous oxide emissions from domestic wastewater.....	6.35
6.3.1	Methodological issues .....	6.35
6.3.1.1	Choice of method .....	6.36
6.3.1.2	Choice of emission factors .....	6.38
6.3.1.3	Choice of activity data.....	6.39
6.3.2	Time series consistency .....	6.43
6.3.3	Uncertainties.....	6.43
6.3.4	QA/QC, Completeness, Reporting and Documentation .....	6.44
6.4	Nitrous oxide emissions from industrial wastewater .....	6.44
6.4.1	Methodological issues .....	6.44
6.4.1.1	Choice of method .....	6.44
6.4.1.2	Choice of emission factors .....	6.47
6.4.1.3	Choice of activity data.....	6.47
6.4.2	Time series consistency .....	6.48
6.4.3	Uncertainties.....	6.49
6.4.4	QA/QC, Completeness, Reporting and Documentation .....	6.49

---

Appendix 6A.1	Non-biogenic (fossil) CO <sub>2</sub> emissions from wastewater treatment and discharge: Basis for Future Methodological Development.....	6.51
Annex 6A.1	Summary data for pit latrine use, no sanitation facility, and groundwater use by country.....	6.54
Annex 6A.2	Derivation of the maximum CH <sub>4</sub> producing potential (B <sub>o</sub> ) for domestic wastewater .....	6.57
Annex 6A.3	Estimation of default methane conversion factors for CH <sub>4</sub> in centralised wastewater treatment plants treating domestic wastewater.....	6.58
Annex 6A.4	Calculation of MCF for methane emissions from sewage discharges.....	6.59
Annex 6A.5	Estimation of default emission factors for N <sub>2</sub> O in domestic wastewater treatment plants.....	6.61
Annex 6A.6	Estimation of default emission factors for N <sub>2</sub> O in effluent .....	6.63
Annex 6A.7	List of countries by region included in Table 6.10a.....	6.64
References	.....	6.65

## Equations

Equation 6.1 (Updated)	CH <sub>4</sub> emissions from domestic wastewater for each treatment/discharge pathway or system, <i>j</i> .....	6.17
Equation 6.1a (New)	Total CH <sub>4</sub> emissions from domestic wastewater treatment and discharge .....	6.17
Equation 6.2	CH <sub>4</sub> emission factor for each domestic wastewater treatment/discharge pathway or system .....	6.18
Equation 6.3 (Updated)	Total organically degradable material in domestic wastewater .....	6.21
Equation 6.3a (New)	Total organics in domestic wastewater by treatment/discharge pathway or system ...	6.22
Equation 6.3b (New)	Organic component removed as sludge from aerobic treatment plants .....	6.27
Equation 6.3c (New)	Organic component removed as sludge from septic systems .....	6.28
Equation 6.3d (New)	Total organics in treated domestic wastewater effluent .....	6.28
Equation 6.4	Total CH <sub>4</sub> emissions from industrial wastewater .....	6.33
Equation 6.5	CH <sub>4</sub> emission factor for industrial wastewater .....	6.33
Equation 6.9 (Updated)	N <sub>2</sub> O emissions from domestic wastewater treatment plants .....	6.37
Equation 6.7 (Updated)	N <sub>2</sub> O emissions from domestic wastewater effluent .....	6.38
Equation 6.10 (New)	Total nitrogen in domestic wastewater by treatment pathway .....	6.40
Equation 6.10a (New)	Estimation of protein consumed .....	6.41
Equation 6.8 (Updated)	Total nitrogen in domestic wastewater effluent .....	6.42
Equation 6.11 (New)	N <sub>2</sub> O emissions from industrial wastewater treatment plants .....	6.44
Equation 6.12 (New)	N <sub>2</sub> O emissions from industrial wastewater effluent .....	6.47
Equation 6.13 (New)	Total nitrogen in industrial wastewater .....	6.47
Equation 6.14 (New)	Total nitrogen in industrial wastewater effluent .....	6.48

## Figures

Figure 6.1 (Updated)	Wastewater treatment systems and discharge pathways .....	6.8
Figure 6.1a (New)	Percentage of low-income country populations using pit latrines as a primary sanitation facility .....	6.12
Figure 6.2 (Updated)	Decision tree for CH <sub>4</sub> emissions from domestic wastewater .....	6.15
Figure 6.3 (Updated)	Decision tree for CH <sub>4</sub> emissions from industrial wastewater treatment .....	6.32
Figure 6.4 (New)	Decision tree for N <sub>2</sub> O emissions from domestic wastewater .....	6.37
Figure 6.5 (New)	Nitrogen in domestic wastewater treatment .....	6.40
Figure 6.6 (New)	Decision tree for N <sub>2</sub> O emissions from industrial wastewater .....	6.46
Figure 6A.1 (New)	Correlation between influent total nitrogen (TN) loading and N <sub>2</sub> O emissions .....	6.61

## Tables

Table 6.1 (Updated)	CH <sub>4</sub> and N <sub>2</sub> O emission potentials for wastewater and sludge treatment and discharge systems .....6.9
Table 6.2	Default maximum CH <sub>4</sub> producing capacity (B <sub>o</sub> ) for domestic wastewater .....6.18
Table 6.3 (Updated)	Default MCF values and resultant EFs for domestic wastewater by type of treatment system and discharge pathway, j .....6.20
Table 6.4	Estimated BOD <sub>5</sub> values in domestic wastewater for selected regions and countries .....6.22
Table 6.5	Suggested values for urbanisation (U) and degree of utilisation of treatment, discharge pathway or method (T <sub>i,j</sub> ) for each income group for selected countries .....6.24
Table 6.6	Example of the application of default values for degrees of treatment utilisation (T) by income groups .....6.26
Table 6.6a (New)	Removal of organic component from wastewater as sludge (K <sub>rem</sub> ) according to treatment type.....6.27
Table 6.6b (New)	Wastewater treatment organics removal fractions (TOW <sub>REM</sub> ) according to treatment type.....6.28
Table 6.7 (Updated)	Default uncertainty ranges for domestic wastewater .....6.29
Table 6.8 (Updated)	Default MCF values and resultant EFs for industrial wastewater .....6.34
Table 6.8a (New)	Default EF values for domestic and industrial wastewater .....6.39
Table 6.10a (New)	Default factors for domestic wastewater .....6.41
Table 6.10b (New)	Estimate on use of food waste disposal in sewer .....6.42
Table 6.10c (New)	Wastewater treatment nitrogen removal fractions (N <sub>REM</sub> ) according to treatment type.....6.43
Table 6.11 (Updated)	N <sub>2</sub> O methodology default data .....6.43
Table 6.12 (New)	Examples of industrial wastewater data .....6.48
Table 6.13 (New)	Default uncertainty ranges for industrial wastewater .....6.49
Table 6Ap.1 (New)	Summary of literature investigating fossil organic carbon in wastewater .....6.52
Table 6A.1 (New)	Summary data for pit latrine use, no sanitation facility, and groundwater use by country .....6.54
Table 6A.2 (New)	MCFs based on measured CH <sub>4</sub> in full-scale domestic wastewater treatment plants ...6.58
Table 6A.3 (New)	Summary of literature investigating methane emissions from wastewater discharge .....6.60
Table 6A.4 (New)	Default N <sub>2</sub> O emission factors for domestic wastewater treatment plants .....6.61
Table 6A.5 (New)	N <sub>2</sub> O emission factors in full-scale domestic wastewater treatment plants .....6.62
Table 6A.6 (New)	List of countries by region included in Table 6.10a .....6.64

## 6 WASTEWATER TREATMENT AND DISCHARGE

*Users are expected to go to Mapping Tables in Annex 1, before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.*

### 6.1 INTRODUCTION

Wastewater can be a source of methane (CH<sub>4</sub>) when treated or disposed anaerobically or when dissolved CH<sub>4</sub> enters aerated treatment systems. It can also be a source of nitrous oxide (N<sub>2</sub>O) emissions. Carbon dioxide (CO<sub>2</sub>) emissions from wastewater are not considered in the IPCC Guidelines because these are generally derived from modern (biogenic) organic matter in human excreta or food waste and should not be included in national total emissions. Appendix 6Ap.1 presents a discussion of non-biogenic (fossil) CO<sub>2</sub> emissions from wastewater treatment and discharge, where fossil organic carbon is present in wastewater or treatment sludge.

Wastewater originates from a variety of domestic, commercial and industrial sources and may be treated on site (uncollected), sewer to a centralised plant (collected) or disposed untreated nearby or via an outfall. Domestic wastewater is defined as wastewater from household water use, while industrial wastewater is from industrial practices only.<sup>1</sup> Treatment and discharge systems can sharply differ between countries and for rural and urban areas. Also, treatment and discharge systems can differ for rural and urban users, and for urban high income and urban low-income users.

Sewer systems may consist of networks of open channels or closed underground pipes. Occasional stagnant conditions and heat provide favourable anaerobic condition for methane generation in closed and open sewers. In urban areas in developing countries and some developed countries, sewer systems may consist of networks of open canals, gutters, and ditches, which are referred to as open sewers. These systems are subject to heating from the sun and the sewers may be stagnant allowing for anaerobic conditions to emit CH<sub>4</sub> (Doorn *et al.* 1997). In most developed countries and in high-income urban areas in other countries, sewers are usually closed and underground. Wastewater in closed underground sewers likely generate CH<sub>4</sub>, but there are insufficient data available to quantify the emissions from these collection systems. However, research shows that significant amounts of CH<sub>4</sub> can be formed within closed sewer collection systems and enters centralised wastewater treatment plants (WWTPs) as dissolved CH<sub>4</sub> in the wastewater, where it is then emitted during treatment.

The degree of wastewater treatment varies in most developing countries. In some cases, industrial wastewater is discharged directly into bodies of water, while major industrial facilities may have comprehensive in-plant treatment. Domestic wastewater is treated in centralised plants, pit latrines, septic systems or disposed of in unmanaged lagoons or waterways, via open or closed sewers. In some coastal cities domestic wastewater is discharged directly into the ocean. Pit latrines are lined or unlined holes of up to several metres deep, which may be fitted with a toilet for convenience. The pits are used alternatively, and the contents used as manure after few months' usage.

The most common wastewater treatment methods in developed countries are centralised aerobic wastewater treatment plants and lagoons for both domestic and industrial wastewater. To avoid high discharge fees or to meet regulatory standards, many large industrial facilities pre-treat their wastewater before releasing it into the sewage system. Domestic wastewater may also be treated in on-site septic systems. These are advanced systems that may treat wastewater from one or several households. They consist of an anaerobic underground tank and a drainage field for the treatment of effluent from the tank. Some developed countries continue to dispose of untreated domestic wastewater via an outfall or pipeline into a water body, such as the ocean.

Centralised wastewater treatment methods can be classified as primary, secondary, and tertiary treatment. In primary treatment, physical barriers remove larger solids from the wastewater. Remaining particulates are then allowed to settle. Secondary treatment consists of a combination of biological processes that promote biodegradation of wastewater constituents by microorganisms. Secondary treatment processes include aerobic stabilisation ponds, trickling filters, and activated sludge processes, as well as anaerobic reactors and lagoons. Tertiary treatment processes are used to further purify the wastewater of pathogens, contaminants, and remaining

<sup>1</sup> Because the methodology is on a per person basis, emissions from commercial wastewater are estimated as part of domestic wastewater. To avoid confusion, the term municipal wastewater is not used in this text. Municipal wastewater is a mix of household, commercial and non-hazardous industrial wastewater, treated at wastewater treatment plants.

nutrients such as nitrogen and phosphorus compounds. This is achieved using one or a combination of processes that can include maturation/polishing ponds, biological processes, advanced filtration, carbon adsorption, ion exchange, and disinfection.

Sludge is produced in all of the primary, secondary and tertiary stages of treatment. Sludge that is produced in primary treatment consists of solids that are removed from the wastewater.

Sludge produced in secondary and tertiary treatment results from biological growth in the biomass, as well as the collection of small particles. This sludge must be treated further before it can be safely disposed of. Methods of sludge treatment include aerobic and anaerobic stabilisation (digestion), conditioning, centrifugation, composting, and drying. Some sludge is incinerated before land disposal. Emissions from anaerobic sludge digestion, where the digester's primary use is for treatment of wastewater treatment solids, should be reported under Wastewater Treatment. Land disposal, composting, and incineration of sludge is considered in Volume 5, Section 2.3.2 in Chapter 2, Waste Generation, Composition, and Management Data, Section 3.2 in Chapter 3, Solid Waste Disposal, Section 4.1 in Chapter 4, Biological Treatment and Disposal, and Chapter 5, Incineration and Open Burning of Waste, respectively. N<sub>2</sub>O emissions from sludge and wastewater spread on agricultural land are considered in Section 11.2, N<sub>2</sub>O emissions from managed soils, in Chapter 11, N<sub>2</sub>O Emissions from Managed Soils, and CO<sub>2</sub> Emissions from Lime and Urea Application, in Volume 4 of the Agriculture, Forestry, and Other Land Use (AFOLU) Sector.

Figure 6.1 from the 2006 IPCC Guidelines has been updated and simplified to show the different pathways for wastewater treatment and discharge, for wastewater that is not collected and for wastewater that is collected. The figure specifies whether the discharge or end use of the wastewater is reported in this chapter. Figure 6.1 (Updated) also shows sludge treatment pathways in grey and clarifies whether the emissions are reported in this chapter. Table 6.1 has been updated to reflect the main wastewater treatment and discharge systems in developed and developing countries and their potential to emit CH<sub>4</sub> and N<sub>2</sub>O.

**Figure 6.1 (Updated) Wastewater treatment systems and discharge pathways**

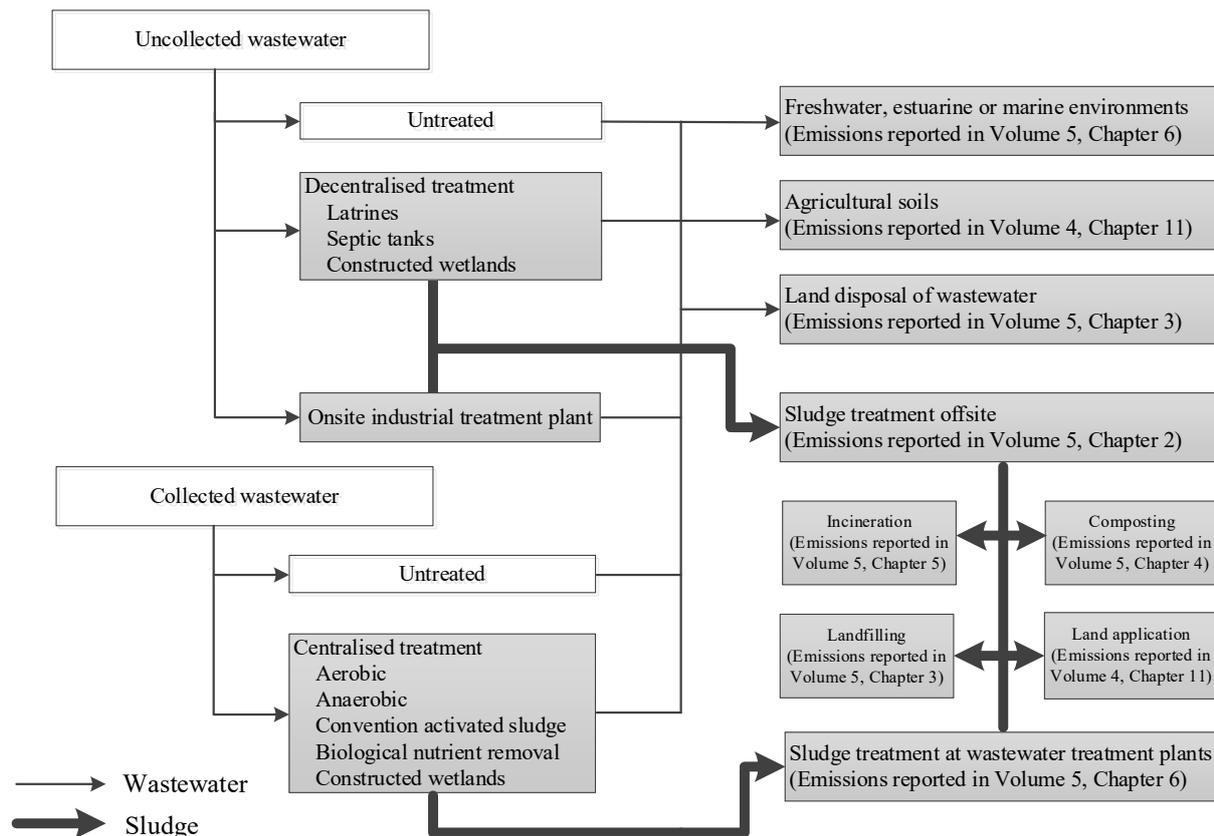


TABLE 6.1 (UPDATED)				
CH <sub>4</sub> AND N <sub>2</sub> O EMISSION POTENTIALS FOR WASTEWATER AND SLUDGE TREATMENT AND DISCHARGE SYSTEMS				
Types of treatment and disposal			CH <sub>4</sub> and N <sub>2</sub> O emission potentials	
Discharge from Collected or Uncollected Systems	Untreated or Treated Systems	Freshwater, estuarine, or marine discharge	While modulated by oxygen status, CH <sub>4</sub> is generated in a range of freshwater and estuarine environments. Among them, stagnant or oxygen deficient environments are probable sources of N <sub>2</sub> O.	
		Non-aquatic environment (soils)	Emissions are considered in Volume 4 when applied to agricultural land.	
Collected	Untreated	Sewers (closed and underground)	Likely source of CH <sub>4</sub> /N <sub>2</sub> O. However, insufficient data exist to quantify emission factors that address the variation in sewer type and operational conditions.	
		Sewers (open)	Stagnant, overloaded open collection sewers or ditches/canals are likely significant sources of CH <sub>4</sub> .	
	Treated	Aerobic treatment	Centralised aerobic wastewater treatment plants	May produce limited CH <sub>4</sub> from anaerobic pockets. May also liberate CH <sub>4</sub> generated in upstream sewer networks during turbulent and/or aerobic treatment processes. Poorly designed or managed aerobic treatment systems produce higher CH <sub>4</sub> due to reduced removal of organics in sludge during primary treatment. Plants with nutrient removal processes are sources of CH <sub>4</sub> and N <sub>2</sub> O.
			Aerobic shallow ponds	Unlikely source of CH <sub>4</sub> /N <sub>2</sub> O. Poorly designed or managed aerobic systems produce CH <sub>4</sub> .
		Anaerobic treatment	Anaerobic lagoons	May be a significant source of CH <sub>4</sub> . Insignificant source of N <sub>2</sub> O.
			Facultative lagoons <sup>2</sup>	Source of CH <sub>4</sub> from anaerobic layer.
			Constructed wetlands	May be source of CH <sub>4</sub> and N <sub>2</sub> O. See <i>2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands</i> (IPCC 2014).
		Anaerobic reactors	May be a significant source of CH <sub>4</sub> if emitted CH <sub>4</sub> is not recovered or flared.	
		Onsite sludge treatment <sup>1</sup>	Sludge anaerobic treatment in centralised aerobic wastewater treatment plant	Sludge may be a significant source of CH <sub>4</sub> if emitted CH <sub>4</sub> is not recovered or flared. In addition, sludge digestion and handling may be a source of fugitive CH <sub>4</sub> from biogas recovery operations. See Chapter 4 for more details.
	Composting		Emissions are considered in Volume 5, Chapter 4.	
Incineration and open burning	Emissions are considered in Volume 5, Chapter 5.			

Types of treatment and disposal		CH <sub>4</sub> and N <sub>2</sub> O emission potentials
<b>Uncollected</b>	Septic tanks (without dispersion field)	Source of CH <sub>4</sub> . Frequent solids removal reduces CH <sub>4</sub> production.
	Septic system (including a septic tank and a soil dispersal system)	Source of CH <sub>4</sub> (tank) and N <sub>2</sub> O (soil dispersal system). Frequent solids removal reduces CH <sub>4</sub> production.
	Open pits/Latrines	Pits/latrines are likely to produce CH <sub>4</sub> when temperature and retention time are favourable.
<p><sup>1</sup> For onsite sludge treatment, see Chapters 4 and 5 for emissions methodology, but note that emissions for onsite systems should be reported under the Wastewater Treatment and Discharge category.</p> <p><sup>2</sup> Facultative organisms can function in the presence or absence of molecular oxygen. In a facultative lagoon, the layer of water near the surface contains dissolved oxygen due to atmospheric reaeration and algal respiration, a condition that supports aerobic and facultative organisms. The bottom layer of the lagoon includes sludge deposits and supports anaerobic organisms. The intermediate anoxic layer—the facultative zone—ranges from aerobic near the top to anaerobic at the bottom (US EPA 2002b).</p>		

## 6.1.1 Centralised treatment systems

Centralised wastewater treatment systems may include a variety of treatment processes spanning the hierarchy of treatment levels. Primary treatment involves mechanical processes such as screening, grit removal and sedimentation. Secondary treatment involves biological processes in which microorganisms convert inorganic and organic nutrients into settleable solids which can be removed by sedimentation and degradation metabolites which are transferred to the atmosphere. Secondary biological treatment processes may be augmented with chemical disinfection. Commonly used secondary treatment processes include activated sludge, trickling filters and lagoons. In some countries simple disinfection process concludes tertiary treatment; however, elsewhere more advanced tertiary treatment involves the use of enhanced biological nutrient removal processes (nitrification–denitrification), and other advanced physical and chemical processes.

Wastewater treatment processes can range from simple technologies such as lagooning and wetlands, to more technologically advanced treatment technology designed for stringent nutrient removal. Wetlands can be constructed or semi-natural systems and may be used as the primary method of wastewater treatment, or as a polishing treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants through a combination of biodegradation, volatilisation, sorption and sedimentation process (IPCC 2014).

Sewer collection systems provide an environment conducive to the formation of CH<sub>4</sub>, which can be substantial depending on the configuration and operation of the collection system (Guisasola *et al.* 2008). Recent research has shown that at least a portion of CH<sub>4</sub> formed with the collection system enters the centralised system where it contributes to CH<sub>4</sub> emissions from the treatment system (Foley *et al.* 2015). Although there are insufficient data to quantify emissions directly from the sewer collection system, the emission factors presented for centralised treatment plants account for dissolved methane entering the treatment 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 receiving environments. Microorganisms can biodegrade soluble organic material in wastewater under aerobic and/or anaerobic conditions, where the latter condition produces CH<sub>4</sub>. 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, such as with anaerobic digestion.

The generation of N<sub>2</sub>O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia. Ammonia N is converted to nitrate (NO<sub>3</sub><sup>-</sup>) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby aerobic or facultative organisms reduce oxidized forms of nitrogen (e.g., nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N<sub>2</sub>). N<sub>2</sub>O is an intermediate product of both nitrification and denitrification processes. No matter where N<sub>2</sub>O is formed it is usually stripped to the air in aerated parts of the treatment process.

A common example of a centralised treatment system configuration is an activated sludge wastewater treatment system. Following grit removal and primary treatment for solids removal, wastewater is sent to an activated sludge reactor for carbonaceous biochemical oxygen demand removal, followed by secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent may be disinfected prior to discharge.

Secondary clarifier sludge is pumped out from the bottom of the clarifier. Of this sludge, a portion is sent back to the activated sludge treatment process (return activated sludge) and the remainder (waste activated sludge) is combined with primary treatment sludge before being sent to sludge handling (such as gravity thickening). The thickened sludge may also be processed onsite in an anaerobic digester followed by further dewatering, such as by centrifuge. Recovered wastewater from thickening and dewatering operations, such as filtrate from the gravity thickener or centrate from the centrifuge) are returned to the influent stream at the headworks to the wastewater treatment system.

CH<sub>4</sub> generated in the sewer system enters the treatment plant as dissolved methane and is emitted during turbulent/aerated treatment steps (Daelman *et al.* 2012). Although the CH<sub>4</sub> emissions from centralised aerobic plants may be small, they are not zero and may be substantial for some plants receiving sewage from expansive sewer networks (Willis 2017). In addition, anaerobic conditions can form within the treatment system increasing the potential for CH<sub>4</sub> generation from an otherwise aerobic system. These refinements introduce a new MCF associated with these systems, as well as a revised N<sub>2</sub>O emission factor for centralised wastewater treatment systems.

Occasionally wastewater treatment plants could be hydraulically or organically overloaded, resulting in degraded plant performance. In these cases, organic matter and nutrients that would normally be removed by the treatment system instead pass through untreated and are discharged to the aquatic environment. The 2006 IPCC Guidelines previously provided different emission factors for “well managed” centralised aerobic treatment systems versus “not well managed” centralised aerobic treatment systems. However, these refinements remove those factors and instead provide one factor for these types of systems. In the case of overloaded systems, the amount of organics removed by the system in sludge (S) should reflect the performance achieved by the system.

## 6.1.2 Decentralised treatment systems of domestic wastewater (onsite sanitation)

Depending on national circumstances, domestic wastewater not connected to a centralised wastewater treatment plant may be directly discharged in natural aquatic environments (rivers, lakes, oceans, etc.) or treated using onsite sanitation. The most common onsite treatment systems are holding tanks, septic systems and latrines.

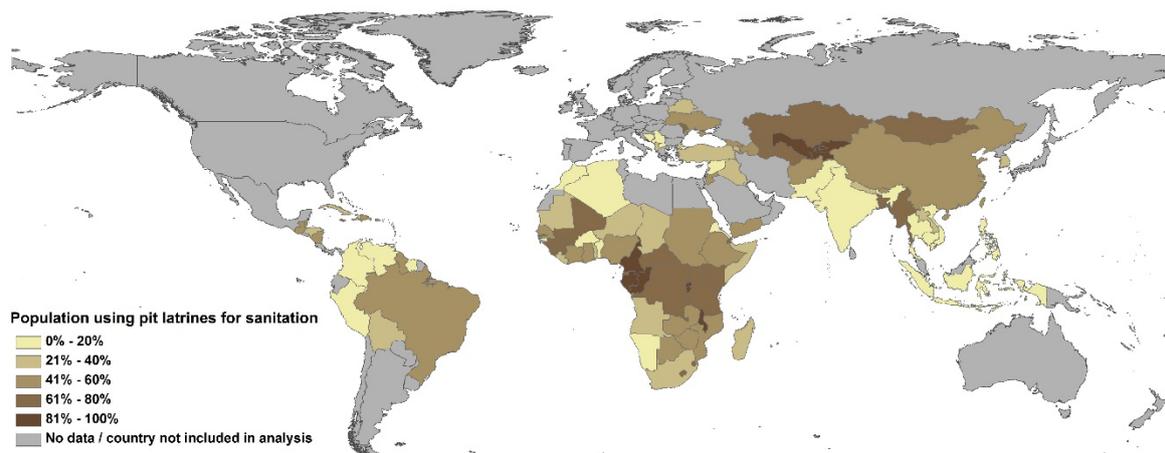
A septic system is usually composed of a septic tank, generally buried in the ground, and a soil dispersal system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tanks as sludge. Floatable material (scum) is also retained in the tank. The sludge settled on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the dispersal system. The liquid fraction remains in the tank for only a short period, with the hydraulic retention time (HRT) varying from 24 to 72 hours depending on tank volume and hydraulic load. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The solids retention time (SRT) depends on the sludge withdrawal frequency. The gas produced from anaerobic sludge digestion (mainly CH<sub>4</sub> and largely biogenic CO<sub>2</sub>) rise to the liquid surface and are usually released through vents. Gases produced in the effluent dispersal system (mainly N<sub>2</sub>O and biogenic CO<sub>2</sub>) are released through the soil.

A latrine usually consists of a slab over a pit which may be two metres or more in depth. A wide range of configuration options exists for latrines (simple pit latrines, ventilated latrines, composting latrines, etc.) having in common that little (e.g., pour flush latrines) or no water is used to flush excreta into the pit. Pit latrines are utilised by more than 1.5 billion people throughout the world, especially in low-income countries (see new Figure 6.1a and new Annex 6A.1). Pit latrine gaseous emissions depend in part on local groundwater level. Anaerobic conditions favourable to CH<sub>4</sub> emissions occur when the water table is high and the organic waste in the pit is submerged.

In the absence of latrines, people resort to open defecation. Open defecation is not considered as a source of CH<sub>4</sub>, as anaerobic conditions are considered unlikely.

In some high-income countries, onsite aerated wastewater treatment systems are used and enable a more advanced level of treatment than septic tanks in reducing the load of organics and nutrients in domestic effluent. The process usually involves a first step of sedimentation and anaerobic digestion, a second step of aerobic treatment and last step of clarification and disinfection. The treated effluent is discharged into the environment via surface irrigation or infiltration through an absorption trench.

**Figure 6.1a (New) Percentage of low-income country populations using pit latrines as a primary sanitation facility (Graham & Polizzotto 2013)**



### 6.1.3 Emissions from receiving waters

Dissolved  $\text{CH}_4$  and  $\text{N}_2\text{O}$  that is generated in sewers, or present in untreated or treated discharges, has the potential to be released (Short *et al.* 2014; Short *et al.* 2017). A strong correlation between the condition of the aquatic environment and the generation of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  has been observed (e.g., Smith *et al.* 2017). Therefore, where wastewater is then discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), the additional organic matter in the discharged wastewater is expected to increase emissions. Many waterways are naturally eutrophic, while others have been altered by human impacts and are subject to eutrophication as a result. Surface marine waters are typically supersaturated (Ward *et al.* 1987; Conrad & Seiler 1988) and freshwaters highly supersaturated (Stanley *et al.* 2016) with  $\text{CH}_4$  irrespective of their trophic state, so this refinement does not distinguish between eutrophic and oligotrophic receiving waters, but it does distinguish between default waters (rivers and streams) and lakes and reservoirs where  $\text{CH}_4$  emissions are higher.

### 6.1.4 Changes compared to 1996 Guidelines and Good Practice Guidance

No refinement.

### 6.1.5 Changes compared to 2006 IPCC Guidelines

The 2006 IPCC Guidelines included combined equations to estimate  $\text{CH}_4$  emissions from wastewater and from sludge removed from the wastewater. However, in some cases, this combined equation caused confusion among inventory compilers when calculating  $\text{CH}_4$  emissions from aerobic systems with anaerobic sludge digestion. In these cases, some compilers estimated zero  $\text{CH}_4$  emissions from well operated wastewater treatment systems, and then subtracted emissions associated with sludge digestion operations without first estimating the  $\text{CH}_4$  emissions from sludge treatment, resulting in negative emissions. In this refinement, we discuss the proper way to use the equation in such situations, and we present an update to provide guidance on the calculation of the organic component removed in sludge. Countries must estimate the amount (mass) of sludge they generate from wastewater treatment and default data are provided for a number of countries. With this additional guidance, the use of a default value of zero for sludge removal from aerobic treatment systems and septic systems is no longer applicable.

In addition, certain emission factors for  $\text{CH}_4$  emissions from domestic and industrial wastewater treatment have been updated to reflect additional measurement data on emissions from septic systems and centralised WWTPs. Furthermore, the  $\text{CH}_4$  emission factors for wastewater discharged to aquatic environments have been updated and a new emission factor for discharge to reservoirs, lakes, and estuaries is introduced. The calculation of  $\text{CH}_4$  emissions from effluent discharged to aquatic systems has been updated to include the discharge of treated effluent and to reflect the removal of organics that occurs during treatment.

The *2019 Refinement* also includes new guidance on how to estimate N<sub>2</sub>O emissions from domestic and industrial wastewater and presents updated guidance to estimate N<sub>2</sub>O emissions from centralised WWTPs. Furthermore, the N<sub>2</sub>O emission factors for wastewater discharged to aquatic environments have been updated and the calculation of N<sub>2</sub>O emissions from effluent discharged to aquatic systems has been updated to reflect the removal of nitrogen that occurs during treatment.

## 6.2 METHANE EMISSIONS FROM WASTEWATER

### 6.2.1 Methodological issues

Emissions are a function of the amount of organic waste generated and an emission factor that characterises the extent to which this waste generates CH<sub>4</sub>.

Three tier methods for CH<sub>4</sub> from this category are summarised below:

The Tier 1 method applies default values for the emission factor and activity parameters. This method is considered *good practice* for countries with limited data.

The Tier 2 method follows the same method as Tier 1 but allows for incorporation of a country specific emission factor and country specific activity data. For example, a specific emission factor for a prominent treatment system based on field measurements could be incorporated under this method. The amount of sludge removed for incineration, landfills, composting, and agricultural land should be taken into consideration. In addition, countries that are able to categorize wastewater discharge by the type of waterbody should use Tier 2 emission factors for estimating emissions from discharge.

For a country with good data and advanced methodologies, a country specific method could be applied as a Tier 3 method. For example, a more advanced country-specific method could be based on plant-specific data from large wastewater treatment facilities, using country-specific measurements of organics discharged to aquatic environments, or may draw on country-specific water quality data for aquatic environments receiving wastewater inputs.

Wastewater treatment facilities that receive wastewater from collection systems, particularly pressurized sewers and gravity-fed sewers that are closed, can liberate CH<sub>4</sub> in aerobic systems from dissolved CH<sub>4</sub> that enters the treatment system (Daelman *et al.* 2012; Short *et al.* 2017).

Wastewater treatment facilities can include anaerobic process steps. CH<sub>4</sub> generated at such facilities can be recovered and combusted in a flare or energy device. The amount of CH<sub>4</sub> that is flared or recovered for energy use should be subtracted from total emissions through the use of a separate CH<sub>4</sub> recovery parameter. The amount of CH<sub>4</sub> which is recovered or flared is expressed as R in updated Equation 6.1. R refers to CH<sub>4</sub> recovered from wastewater treatment, such as methane captured on filters exhausted from covered (anaerobic) treatment ponds, as well as CH<sub>4</sub> recovered from anaerobic sludge digestion. The approach to estimation of emissions from wastewater treatment in this chapter covers all emission sources and sinks (recovery) at a wastewater treatment plant.

Note that only a few countries may have sludge removal data and CH<sub>4</sub> recovery data. The information on sludge generation has improved and statistical data on sludge can be found in databases of Eurostat and Organization for Economic Co-operation and Development (OECD). The lack of data for CH<sub>4</sub> recovery was taken into account in this refinement by recommending the use of the methodology in Section 4.1, Chapter 4 of Volume 5, *2006 IPCC Guidelines* which estimates emissions on the basis of total sludge anaerobically digested; thus, the information on R is not required in this calculation. Default sludge removal factors are provided in this refinement. The default for CH<sub>4</sub> recovery is zero. If a country selects to report CH<sub>4</sub> recovery, it is *good practice* to distinguish between flaring and CH<sub>4</sub> recovery for energy generation, which should be reported in the Energy Sector taking into account the avoidance of double counting emissions from flaring and energy used.

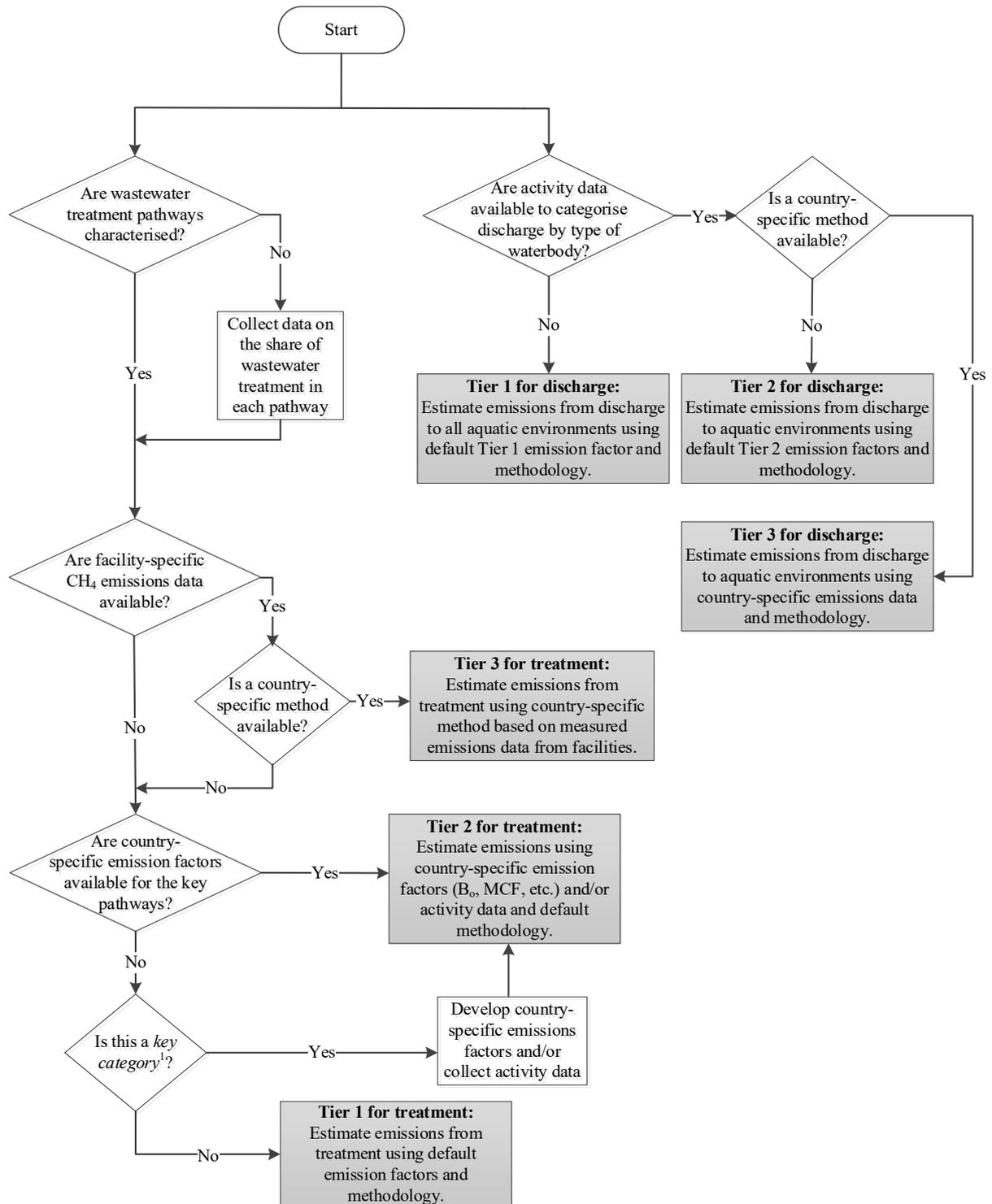
Emissions from flaring are not significant, as the majority of CO<sub>2</sub> emissions are of biogenic origin, and the CH<sub>4</sub> and N<sub>2</sub>O emissions are very small so *good practice* in the Waste Sector does not require their estimation. However, if it is wished to do so these emissions should be reported under the Waste Sector. A discussion of emissions from flares and more detailed information are given in Volume 2, Energy, Chapter 4.2. Emission from flaring is not treated at Tier 1.

## **6.2.2 Domestic wastewater**

### **6.2.2.1 CHOICE OF METHOD**

An updated decision tree for domestic wastewater is included as updated Figure 6.2 and should be used to determine the tier approach that is applicable to the country.

This section is an update to the *2006 IPCC Guidelines*. In general, the overall steps for *good practice* in inventory preparation for CH<sub>4</sub> from domestic wastewater have been updated as follows:

Figure 6.2 (Updated) Decision tree for CH<sub>4</sub> emissions from domestic wastewater

<sup>1</sup> See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

- Step 1:** Use updated Equation 6.3 to estimate organically degradable material TOW in wastewater prior to treatment. Use new Equation 6.3a to estimate total organics in domestic wastewater for each wastewater treatment/discharge pathway or system,  $j$  ( $TOW_j$ ). Use new Equation 6.3d to estimate total organics in treated wastewater effluent discharged ( $TOW_{EFFtreat}$ ).
- Step 2:** Use new Equations 6.3b and 6.3c to estimate the amount of organic component removed in sludge,  $S$ , from aerobic treatment plants and septic systems.
- Step 3:** Select the pathway and systems (see updated Figure 6.1) according to country activity data. Use Equation 6.2 or the updated Table 6.3 to obtain the emission factor for each domestic wastewater treatment/discharge pathway or system.
- Step 4:** Use updated Equation 6.1 to estimate emissions and adjust for possible sludge removal and/or  $CH_4$  recovery of treatment/discharge pathway or system,  $j$ , in inventory year. Use new Equation 6.1a to sum the emissions across all treatment/discharge pathways or systems.
- Step 5:** Use Equation 4.1 and emission factors in Table 4.1 to estimate methane emissions from anaerobic digestion of sludge.

To determine the use of each type of treatment or discharge system, it is *good practice* to refer to national statistics (e.g., from regulatory authorities). If these data are not available, wastewater associations or international organisations such as the World Health Organization (WHO) may have data on the system usage.

Otherwise, consultation with sanitation experts can help, and expert judgment can also be applied (see Chapter 2, Approaches to Data Collection, in Volume 1). Urbanisation statistics may provide a useful tool, e.g., city sizes and income distribution.

These updates are presented because, in some cases, the original Equation 6.1 caused confusion among inventory compilers when calculating  $CH_4$  emissions across multiple wastewater treatment/discharge pathways or systems across multiple income groups. These updates allow for a more stepwise process in estimating emissions throughout the country.

It is *good practice* for countries to treat the wastewater treatment system and onsite sludge treatment system as separate pathways. As an example, for an activated sludge treatment process, calculate the emissions directly associated with the aerobic treatment system as one pathway, and calculate the emissions and report any  $CH_4$  recovery directly associated with the anaerobic sludge digestion system as a separate pathway using the emissions methodology provided in Table 4.1, Chapter 4 of Volume 5. Net emissions from both systems should be summed together and reported under wastewater treatment and discharge. In no circumstances should a country report negative emissions. As discussed in Chapter 4, the reporting of anaerobic digestion of sludge is under biological treatment only if transferred from the wastewater treatment plant to anaerobic facilities co-digesting sludge with MSW or other waste.

It is important that  $CH_4$  emissions from sludge that is managed using landfills, incineration, composting, biogas production, or used in agriculture are not included in the wastewater treatment and discharge category. The data should be consistent across the sectors, and categories, amount disposed at SWDS, applied to agricultural land, incinerated or used elsewhere should be equal to the amount organic component removed as sludge in updated Equation 6.1. Wastewater and sludge that is applied on agricultural land should be considered in Volume 4 for AFOLU Sector, Section 11.2,  $N_2O$  emissions from managed soils, in Chapter 11,  $N_2O$  Emissions from Managed Soils, and  $CO_2$  Emissions from Lime and Urea Application.

Wastewater treatment system/pathway usage often differs for rural and urban residents. Also, in developing countries, there are likely to be differences between urban high-income and urban low-income residents. Hence, emissions are calculated by each income group fraction. It is *good practice* to treat the three categories: rural population, urban high-income population, and urban low-income population separately. It is suggested to use a spreadsheet, as shown in Table 6.5.

Equation 6.1 should be used to estimate  $CH_4$  emissions from every treatment system and discharge pathway  $j$  (hereafter referred to as treatment/discharge pathway or system), presented in Table 6.3 (Updated) that are appropriate for the country, including the discharge of treated or untreated wastewater.

$CH_4$  emissions from the following discharge pathways must be considered in the inventory for treated and untreated wastewaters (if occurring in the country):

- Discharge to reservoirs, lakes, and estuaries;
- Discharge to aquatic environments other than to reservoirs, lakes, and estuaries;
- Discharge to sewers (with a distinction between stagnant and flowing (open or closed) sewers).

For the discharge of treated wastewater, the TOW should reflect the organics in the wastewater as discharged (see Equation 6.3d (New)). As noted in the table, discharges to soil should be reported in Volume 4.

CH<sub>4</sub> emissions from the following wastewater treatment systems must be considered in the inventory (if occurring in the country):

- Centralised, aerobic treatment plant;
- Anaerobic reactor (e.g., upflow anaerobic sludge blanket digestion (UASB));
- Anaerobic lagoons (with a distinction between shallow and facultative lagoons and deep lagoons);
- Constructed wetlands;
- Septic systems (with a distinction between stand-alone septic tanks and septic tanks with land dispersal field);
- Latrines (depending of the climate).

Emissions from anaerobic digestion of wastewater treatment sludge should be estimated using Equation 4.1 and included in the sum of emissions using Equation 6.1A (New). The emission factor used in Equation 4.1 accounts for CH<sub>4</sub> recovery, therefore the amount of methane recovered from anaerobic digestion should not be subtracted.

**EQUATION 6.1 (UPDATED)**  
**CH<sub>4</sub> EMISSIONS FROM DOMESTIC WASTEWATER FOR EACH TREATMENT/DISCHARGE PATHWAY OR SYSTEM, J**

$$CH_4 \text{ Emissions}_j = [(TOW_j - S_j) \cdot EF_j - R_j]$$

Where:

- CH<sub>4</sub> Emissions<sub>j</sub> = CH<sub>4</sub> emissions from treatment/discharge pathway or system, j, in inventory year, kg CH<sub>4</sub>/yr
- TOW<sub>j</sub> = organics in wastewater of treatment/discharge pathway or system, j, in inventory year, kg BOD/yr. See Equation 6.3a.
- S<sub>j</sub> = organic component removed from wastewater (in the form of sludge) from treatment/discharge pathway or system, j, in inventory year, kg BOD/yr. See Equations 6.3b and 6.3c. For wastewater discharged to aquatic environments, there is no sludge removal (S<sub>j</sub> = 0) and no CH<sub>4</sub> recovery (R<sub>j</sub> = 0). For wastewater treatment systems, please see Section 6.2.2.3 for additional guidance on how to estimate S, organic component removed as sludge, if country-specific data are not available.
- j = each treatment/discharge pathway or system
- EF<sub>j</sub> = emission factor for treatment/discharge pathway or system, j, kg CH<sub>4</sub>/kg BOD. See Equation 6.2 or updated Table 6.3.
- R<sub>j</sub> = amount of CH<sub>4</sub> recovered or flared from treatment/discharge pathway or system, j, in inventory year, kg CH<sub>4</sub>/yr. Default value is zero.

**EQUATION 6.1A (NEW)**  
**TOTAL CH<sub>4</sub> EMISSIONS FROM DOMESTIC WASTEWATER TREATMENT AND DISCHARGE**

$$CH_4 \text{ Emissions} = \sum_j [CH_4 \text{ Emissions}_j] \cdot [10^{-6}]$$

Where:

- CH<sub>4</sub> Emissions = CH<sub>4</sub> emissions in inventory year, Gg CH<sub>4</sub>/yr
- CH<sub>4</sub> Emissions<sub>j</sub> = CH<sub>4</sub> emissions from treatment/discharge pathway or system, j, in inventory year, kg CH<sub>4</sub>/yr
- j = each treatment/discharge pathway or system
- 10<sup>-6</sup> = conversion of kg to Gg

### 6.2.2.2 CHOICE OF EMISSION FACTORS

This section represents an update to Section 6.2.2.2 of the *2006 IPCC Guidelines*.

The emission factor for a wastewater treatment and discharge pathway and system is a function of the maximum CH<sub>4</sub> producing potential (B<sub>o</sub>) and the methane correction factor (MCF) for the wastewater treatment and discharge system, as shown in Equation 6.2. The B<sub>o</sub> is the maximum amount of CH<sub>4</sub> that can be produced from a given quantity of organics (as expressed in Biochemical Oxygen Demand (BOD) or Chemical Oxygen Demand (COD) in the wastewater and represents the complete conversion of organic C to biogas. The MCF indicates the extent to which the CH<sub>4</sub> producing capacity (B<sub>o</sub>) is realised in each type of treatment and discharge pathway and system. Thus, it is an indication of the degree to which the system is anaerobic.

**EQUATION 6.2**  
**CH<sub>4</sub> EMISSION FACTOR FOR**  
**EACH DOMESTIC WASTEWATER TREATMENT/DISCHARGE PATHWAY OR SYSTEM**

$$EF_j = B_o \bullet MCF_j$$

Where:

- EF<sub>j</sub> = emission factor, kg CH<sub>4</sub>/kg BOD  
 j = each treatment/discharge pathway or system  
 B<sub>o</sub> = maximum CH<sub>4</sub> producing capacity, kg CH<sub>4</sub>/kg BOD  
 MCF<sub>j</sub> = methane correction factor (fraction). See updated Table 6.3.

Table 6.2 includes default maximum CH<sub>4</sub> producing capacity (B<sub>o</sub>) for domestic wastewater. It is *good practice* to use country-specific data if available for emission factors, which are made up of B<sub>o</sub> and MCF values. If a country chooses to introduce country-specific data for B<sub>o</sub> based on independent wastewater analyses, they must also update the MCF because the MCFs presented in Table 6.3 were developed using the default B<sub>o</sub> values. For domestic wastewater, a COD-based value of B<sub>o</sub> can be converted into a BOD-based value by multiplying with a factor of 2.4. New Annex 6A.2 provides further explanation of the basis for these default B<sub>o</sub> values to allow countries to consider if these values are appropriate for the specific characteristics of their waste streams.

<b>TABLE 6.2</b> <b>DEFAULT MAXIMUM CH<sub>4</sub> PRODUCING CAPACITY (B<sub>o</sub>) FOR DOMESTIC WASTEWATER</b>
0.6 kg CH <sub>4</sub> /kg BOD
0.25 kg CH <sub>4</sub> /kg COD
Based on expert judgment by lead authors and on Doorn <i>et al.</i> (1997)

Because the B<sub>o</sub> and MCF values must be used together, updated Table 6.3 now also includes the resultant default CH<sub>4</sub> emission factors for each wastewater treatment and discharge pathway. In addition, the MCFs in Table 6.3 of the *2006 IPCC Guidelines* have been updated to reflect revisions to the following specific wastewater treatment and discharge pathways and systems (see also new Annex 6A.3).

### DISCHARGE FROM TREATED OR UNTREATED SYSTEMS

Updated Table 6.3 presents updated default MCFs associated with the discharge of wastewater to a water body and it is *good practice* to apply the Tier 1 MCF to discharges of both treated and untreated wastewater. The BOD of treated wastewater is typically 5–25 mg/L (Hammer & Hammer Jr. 2012; Tchobanoglous *et al.* 2014), which provides a substrate for the formation of CH<sub>4</sub> in a receiving water body. Furthermore, much of the dissolved CH<sub>4</sub> that is generated in sewers is released either in the treatment plant headworks or to the receiving water body in the case of untreated or primary treated discharges (Short *et al.* 2014; Short *et al.* 2017). Recent evidence points to the operation of both microbial and non-microbial methanogenic pathways in nature (e.g., Jugold *et al.* 2012) and strong relationships between the nutrient status of a receiving water body and the rate of generation of CH<sub>4</sub> have been observed (e.g., Smith *et al.* 2017). Despite this relationship, most rivers, estuaries and coastal waters are considerably supersaturated with CH<sub>4</sub>, irrespective of their nutrient status (Patra *et al.* 1998; Grunwald *et al.* 2009; Ward *et al.* 2017), while open oceans are slightly supersaturated (Tilbrook & Karl 1995; Oudot *et al.* 2002; Castro-Morales *et al.* 2014). Supersaturated conditions occur when the rate of methanogenesis exceeds the rate at which the CH<sub>4</sub> is oxidised and/or transferred to the atmosphere and is important as it governs the driving force

(mass transfer coefficient) and likely water-to-air CH<sub>4</sub> emission from a receiving environment. So, while the conditions of the receiving water body play a modulating role in relation to the rate of methanogenesis, the addition of organic matter from sewer discharges is generally expected to increase CH<sub>4</sub> emissions in freshwater and coastal environments. Recent reviews of measurements of CH<sub>4</sub> generation indicate that a significant proportion of the CH<sub>4</sub> emitted from freshwater systems has its origins in carbon deposited on sediments (Deemer *et al.* 2016) which is one reason why methanogenesis is more intense in lakes and reservoirs than fast-flowing rivers.

Using the same stoichiometric relationship as was used to calculate the default B<sub>0</sub> value (see new Annex 6A.2), a ratio of 0.938 kg C per kg COD is obtained. Deemer *et al.* (2016) performed an extensive review of measurements of CH<sub>4</sub> and CO<sub>2</sub> originating in aquatic systems, and independent measurements of both CH<sub>4</sub> and CO<sub>2</sub> emission fluxes around the world. Using these data in combination with information on the partitioning of global carbon flows in freshwater systems Tranvik *et al.* (2009) and a default B<sub>0</sub> of 0.25 kg CH<sub>4</sub>/kg COD, a Tier 2 MCF of 0.035 is calculated for rivers. Where it is possible to separately identify discharges to slow-flowing systems such as lakes and reservoirs, a Tier 2 MCF of 0.19 is presented (see updated Table 6.3 and new Annex 6A.4).

If countries are not able to collect activity data regarding the distribution of discharge to reservoirs, lakes, and estuaries as compared to discharges to other aquatic environments, they should use the default Tier 1 factors. The default Tier 1 MCF for CH<sub>4</sub> generation for discharges to all aquatic environments is presented as the mean of the two Tier 2 MCFs, or 0.11.

Concerning decentralised treatment systems for domestic wastewater, CH<sub>4</sub> and N<sub>2</sub>O emissions from effluent infiltration into soil must be considered.

### **CENTRALISED, AEROBIC TREATMENT PLANTS**

The MCF for centralised aerobic treatment plants has been updated in Table 6.3 to reflect the potential for generation of CH<sub>4</sub> from these systems. In addition, there are no longer separate MCFs for “well managed” and “not well managed” systems and it is *good practice* to estimate CH<sub>4</sub> from all centralised, aerobic treatment plants. If country-specific data are available to differentiate whether systems are overloaded or not well managed, these situations should be reflected in the calculation of TOW (for inflow overload) or S<sub>mass</sub> (for systems that are not well managed and therefore not achieving the expected removal of sludge).

### **IMPACT OF TEMPERATURE ON DECENTRALISED TREATMENT SYSTEMS OF DOMESTIC WASTEWATER**

Temperature affects wastewater treatment processes, in particular decentralised systems where no external supplemental heat is provided (uncontrolled temperature) and anaerobic digestion for which the optimal temperature is 30–38°C. At lower temperatures, the rate of anaerobic digestion decreases and CH<sub>4</sub> production becomes unlikely below 12°C. Inside septic tanks, the temperature is uncontrolled and is related to atmospheric temperature as well as volumes of household hot and cold water used and discharged. There may also be a gradient of temperature inside the septic tank, with warmer conditions at the bottom (sludge layer) and colder at the top (Leverenz *et al.* 2010). Therefore, in countries having seasonal temperature variability, when the temperature in septic tanks cools, the rate of digestion slows, the SRT increases, sludge accumulates, and CH<sub>4</sub> emissions decrease. When the liquid temperature warms, the rate of digestion increases, sludge accumulated during the cold season decomposes, gas solubility in the liquid decreases and CH<sub>4</sub> emissions increase. This situation can produce a ‘spring boil’ phenomenon, wherein warmer weather conditions give rise to increased anaerobic microbial activity, increased gas production, and decreased solids removal efficiency due to the resuspension of settled and incoming solids. Accordingly, there is a seasonal variability of CH<sub>4</sub> emissions (Leverenz *et al.* 2010); however, at this time, insufficient data exist to establish a temperature-dependent emission factor associated with these systems. Countries that experience significant seasonal temperature variations may wish to consider the development of a country-specific emission factor.

<b>TABLE 6.3 (UPDATED)</b> <b>DEFAULT MCF VALUES AND RESULTANT EF<sup>2</sup> FOR DOMESTIC WASTEWATER BY TYPE OF TREATMENT SYSTEM AND DISCHARGE PATHWAY, J<sup>1</sup></b>				
<b>Type of treatment and discharge pathway or system</b>	<b>Comments</b>	<b>MCF<sup>1</sup> (Range)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg BOD)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg COD)</b>
<b>Discharge from treated or untreated system</b>				
Discharge to aquatic environments (Tier 1)	Most aquatic environments including rivers are supersaturated in CH <sub>4</sub> . Nutrient oversupply will increase CH <sub>4</sub> emissions. Environments where carbon accumulates in sediments have higher potential for methane generation.	0.11 (0.004 – 0.27)	0.068	0.028
Discharge to aquatic environments other than reservoirs, lakes, and estuaries (Tier 2)	Most aquatic environments including rivers are supersaturated in CH <sub>4</sub> . Nutrient oversupply will increase CH <sub>4</sub> emissions.	0.035 <sup>3</sup> (0.004 – 0.06)	0.021	0.009
Discharge to reservoirs, lakes, and estuaries (Tier 2)	Environments where carbon accumulates in sediments have higher potential for methane generation.	0.19 <sup>3</sup> (0.08 – 0.27)	0.114	0.048
Discharge to soil	Sludge and/or wastewater discharge to soil may be a source of CH <sub>4</sub> for fertilisation	Emissions reported in Volume 4		
Stagnant sewer	Open and warm	0.5 (0.4 – 0.8)	0.3	0.125
Flowing sewer (open or closed)	Fast moving, clean. (Insignificant amounts of CH <sub>4</sub> from pump stations, etc.)	0	0	0
<b>Wastewater treatment system</b>				
Centralised, aerobic treatment plant	Some CH <sub>4</sub> can be emitted from settling basins and other anaerobic pockets. May also emit CH <sub>4</sub> generated in upstream sewer networks during turbulent and/or aerobic treatment processes. For treatment plants that are receiving wastewater beyond the design capacity, inventory compilers should judge the amount of organic material removed in sludge accordingly.	0.03 <sup>4</sup> (0.003 – 0.09)	0.018	0.0075
Anaerobic reactor (e.g., upflow anaerobic sludge blanket digestion (UASB))	CH <sub>4</sub> recovery is not considered here.	0.8 (0.8 – 1.0)	0.48	0.2
Anaerobic shallow lagoon and facultative lagoons	Depth less than 2 metres, use expert judgment.	0.2 (0 – 0.3)	0.12	0.05
Anaerobic deep lagoon	Depth more than 2 metres	0.8 (0.8 – 1.0)	0.48	0.2
Constructed wetlands	<i>See 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2014)</i>			
Septic tank	Septic tanks emit CH <sub>4</sub>	0.5 <sup>5</sup> (0.4 – 0.72)	0.3	0.125
Septic tank + land dispersal field	Septic tanks emit CH <sub>4</sub> ; negligible emissions come from land dispersal field	0.5 <sup>5</sup> (0.4 – 0.72)	0.3	0.125

<b>TABLE 6.3 (UPDATED) (CONTINUED)</b> <b>DEFAULT MCF VALUES AND RESULTANT EF<sup>2</sup> FOR DOMESTIC WASTEWATER BY TYPE OF TREATMENT SYSTEM AND DISCHARGE PATHWAY, J<sup>1</sup></b>				
Type of treatment and discharge pathway or system	Comments	MCF <sup>1</sup> (Range)	EF <sup>2</sup> (kg CH <sub>4</sub> /kg BOD)	EF <sup>2</sup> (kg CH <sub>4</sub> /kg COD)
Latrine	Dry climate, ground water table lower than latrine, small family (3–5 persons)	0.1 (0.05 – 0.15)	0.06	0.025
Latrine	Dry climate, ground water table lower than latrine, communal (many users)	0.5 (0.4 – 0.6)	0.3	0.125
Latrine	Wet climate/flush water use, ground water table higher than latrine	0.7 (0.7 – 1.0)	0.42	0.175
<b>Sludge treatment system</b>				
Anaerobic digester for sludge	See Chapter 4 for emissions methodology	See Chapter 4, Table 4.1		
Composting	Emissions reported in Volume 5, Chapter 4	See Chapter 4, Table 4.1		
Incineration and open burning	Emissions reported in Volume 5, Chapter 5	See Chapter 5		
Sources:				
<sup>1</sup> Based on expert judgment by Lead Authors of this section.				
<sup>2</sup> Emission factors calculated using default B <sub>0</sub> and default MCF.				
<sup>3</sup> See Annex 6A.4.				
<sup>4</sup> See Annex 6A.3 (Czepiel <i>et al.</i> 1993; Kozak <i>et al.</i> 2009; Bellucci <i>et al.</i> 2010; Wang <i>et al.</i> 2011; Daelman <i>et al.</i> 2013; Kyung <i>et al.</i> 2015; Delre <i>et al.</i> 2017).				
<sup>5</sup> Leverenz <i>et al.</i> 2010; Diaz-Valbuena <i>et al.</i> 2011; Truhlar <i>et al.</i> 2016.				

### 6.2.2.3 CHOICE OF ACTIVITY DATA

The activity data for this source category is the total amount of organically degradable material in the wastewater (TOW). This parameter is a function of human population and BOD generation per person. It is expressed in terms of biochemical oxygen demand (kg BOD/year). The equation for TOW is:

<p><b>EQUATION 6.3 (UPDATED)</b></p> <p><b>TOTAL ORGANICALLY DEGRADABLE MATERIAL IN DOMESTIC WASTEWATER</b></p> $TOW = P \bullet BOD \bullet 0.001 \bullet 365$
---

Where:

- TOW = total organics in wastewater in inventory year, kg BOD/yr
- P = country population in inventory year, (person)
- BOD = country-specific per capita BOD<sub>5</sub> in inventory year, g/person/day. See Table 6.4.
- 0.001 = conversion from grams BOD to kg BOD

Total population statistics should be readily available from national statistics agencies or international agencies (e.g., United Nations Statistics, see <https://population.un.org/wpp/>). Table 6.4 includes BOD default values for selected countries. It is *good practice* to select a BOD default value from a nearby comparable country when country-specific data are not available. The degree of urbanisation for a country can be retrieved from various sources, (e.g., Global Environment Outlook, United Nations Environment Programme and World Development Indicators, World Health Organization). The urban high-income and urban-low income fractions can be determined by expert judgment when statistical or other comparable information is not available.

<b>TABLE 6.4</b>			
<b>ESTIMATED BOD<sub>5</sub> VALUES IN DOMESTIC WASTEWATER FOR SELECTED REGIONS AND COUNTRIES</b>			
<b>Country/Region</b>	<b>BOD<sub>5</sub> (g/person/day)</b>	<b>Range</b>	<b>Reference</b>
Africa	37	35 – 45	1
Egypt	34	27 – 41	1
Asia, Middle East, Latin America	40	35 – 45	1
India	34	27 – 41	1
West Bank and Gaza Strip (Palestine)	50	32 – 68	1
Japan	42	40 – 45	1
Brazil	50	45 – 55	2
Canada, Europe, Russia, Oceania	60	50 – 70	1
Denmark	62	55 – 68	1
Germany	62	55 – 68	1
Greece	57	55 – 60	1
Italy	60	49 – 60	3
Sweden	75	68 – 82	1
Turkey	38	27 – 50	1
United States	85	50 – 120	4
<p>Note: These values are based on an assessment of the literature. Please use national values, if available.</p> <p>Reference:</p> <ol style="list-style-type: none"> <li>1. Doorn and Liles (1999).</li> <li>2. Feachem <i>et al.</i> (1983).</li> <li>3. Masotti (1996).</li> <li>4. Metcalf and Eddy (2003).</li> </ol>			

This section is updated to include a new equation for the calculation of total organics in wastewater (TOW<sub>j</sub>) by treatment/discharge pathway or system (see new Equation 6.3a).

<p><b>EQUATION 6.3A (NEW)</b></p> <p><b>TOTAL ORGANICS IN DOMESTIC WASTEWATER BY TREATMENT/DISCHARGE PATHWAY OR SYSTEM</b></p> $TOW_j = \sum_i [TOW \cdot U_i \cdot T_{ij} \cdot I_j]$
--

Where:

TOW<sub>j</sub> = total organics in wastewater in inventory year, kg BOD/yr, for income group *i* and treatment/discharge pathway or system, *j*.

TOW = total organics in wastewater in inventory year, kg BOD/yr. See updated Equation 6.3 for TOW in wastewater prior to treatment or wastewater that is discharged without treatment and new Equation 6.3d for TOW in treated wastewater effluent.

U<sub>i</sub> = fraction of population in income group *i* in inventory year. See Table 6.5.

T<sub>ij</sub> = degree of utilisation of treatment/discharge pathway or system, *j*, for each income group fraction

I<sub>j</sub> = correction factor for additional industrial BOD discharged into treatment/discharge pathway or system *j* (for collected the default is 1.25, for uncollected the default is 1.00)

The factor *I* values in new Equation 6.3a are from the 2006 IPCC Guidelines. It expresses the BOD from industries and establishments (e.g., restaurants, butchers or grocery stores) that is co-discharged with

domestic wastewater. In some countries, information from industrial discharge permits may be available to improve *I*. Otherwise, expert judgment is recommended.

Table 6.5 includes default values of  $U_i$  and  $T_{i,j}$  for selected countries.

Country	Urbanisation(U) <sup>1</sup>			Degree of utilisation of treatment or discharge pathway or method for each income group (T <sub>i,j</sub> ) <sup>3</sup>															
	Fraction of Population			U=rural					U= urban high income					U=urban low income					
	Rural	urban-high <sup>2</sup>	urban-low <sup>2</sup>	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None	
<b>Africa</b>																			
Nigeria	0.52	0.10	0.38	0.02	0.28	0.04	0.10	0.56	0.32	0.31	0.00	0.37	0.00	0.17	0.24	0.05	0.34	0.20	
Egypt	0.57	0.09	0.34	0.02	0.28	0.04	0.10	0.56	0.15	0.05	0.10	0.70	0.00	0.17	0.24	0.05	0.34	0.20	
Kenya	0.62	0.08	0.30	0.02	0.28	0.04	0.10	0.56	0.32	0.31	0.00	0.37	0.00	0.17	0.24	0.05	0.34	0.20	
South Africa	0.39	0.12	0.49	0.10	0.28	0.04	0.10	0.48	0.15	0.15	0.00	0.70	0.00	0.17	0.24	0.05	0.34	0.20	
<b>Asia</b>																			
China	0.59	0.12	0.29	0.00	0.47	0.50	0.00	0.3	0.18	0.08	0.07	0.67	0.00	0.14	0.10	0.03	0.68	0.05	
India	0.71	0.06	0.23	0.00	0.47	0.10	0.10	0.33	0.18	0.08	0.07	0.67	0.00	0.14	0.10	0.03	0.53	0.20	
Indonesia	0.54	0.12	0.34	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20	
Pakistan	0.65	0.07	0.28	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20	
Bangladesh	0.72	0.06	0.22	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20	
Japan	0.20	0.80	0.00	0.20	0.00	0.50	0.30	0.00	0.00	0.00	0.10	0.90	0.00	0.10	0	0	0.90	0	
<b>Europe</b>																			
Russia	0.27	0.73	0.00	0.30	0.10	0.00	0.60	0.00	0.10	0.00	0.00	0.90	0.00	NA	NA	NA	NA	NA	
Germany <sup>5</sup>	0.06	0.94	0.00	0.20	0.00	0.00	0.80	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA	
United Kingdom	0.10	0.90	0.00	0.11	0.00	0.00	0.89	0.00	0.00	0.00	0.00	1.00	0.00	NA	NA	NA	NA	NA	
France	0.24	0.76	0.00	0.37	0.00	0.00	0.63	0.00	0.00	0.00	0.00	1.00	0.00	NA	NA	NA	NA	NA	
Italy	0.32	0.68	0.00	0.42	0.00	0.00	0.58	0.00	0.04	0.00	0.00	0.96	0.00	NA	NA	NA	NA	NA	
<b>North America</b>																			
United States	0.22	0.78	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA	
Canada	0.20	0.80	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA	
<b>Latin America and Caribbean</b>																			
Brazil	0.16	0.25	0.59	0.00	0.45	0.00	0.10	0.45	0.00	0.20	0.00	0.80	0.00	0.00	0.40	0.00	0.40	0.20	
Mexico	0.25	0.19	0.56	0.00	0.45	0.00	0.10	0.45	0.00	0.20	0.00	0.80	0.00	0.00	0.40	0.00	0.40	0.20	
<b>Oceania</b>																			
Australia and New Zealand	0.08	0.92	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA	

**TABLE 6.5 (CONTINUED)****SUGGESTED VALUES FOR URBANISATION (U) AND DEGREE OF UTILISATION OF TREATMENT, DISCHARGE PATHWAY OR METHOD (T<sub>i,j</sub>) FOR EACH INCOME GROUP FOR SELECTED COUNTRIES**

Notes:

1. Urbanization projections for 2005 (United Nations, 2002).
2. Suggested urban-high income and urban low income division. Countries are encouraged to use their own data or best judgment.
3. T<sub>i,j</sub> values based on expert judgment, (Doorn and Liles, 1999).
4. Sewers may be open or closed, which will govern the choice of MCF, see Table 3.3
5. Destatis, 2001.

Note: These values are from the literature or based on expert judgment. Please use national values, if available.

### Example

Table 6.6 includes an example. Categories with negligible contributions are not shown. Note that the table can easily be expanded with a column for MCF for each category. The degree of urbanization for this country is 65 percent.

Treatment or discharge system or pathway		T (%)	Notes
Urban high-income	To sea	10	No CH <sub>4</sub>
	To aerobic plant <sup>1</sup>	20	Add industrial component
	To septic systems	10	Uncollected
Urban low-income	To sea	10	Collected
	To pit latrines	15	Uncollected
Rural	To rivers, lakes, sea	15	Uncollected
	To pit latrines	15	
	To septic tanks	5	
Total		100%	Must add up to 100%
<sup>1</sup> The degree of treatment utilisation (T) does not take into account emissions associated with the discharge of treated effluent. Reference: Doorn and Liles (1999)			

This section is updated to also include new equations for the calculation of organic components removed as sludge from aerobic treatment plants and from septic systems (see Equations 6.3b and 6.3c, respectively). Note that the estimate of TOW<sub>ij</sub> in Equation 6.3a is specific to the wastewater treatment system or pathway. Inventory compilers should consider that sludge recovered from septic tanks may be transferred to centralised WWTPs. In these cases, it is *good practice* to include this additional organic load when estimating TOW in influent to the centralised WWTP.

The organic component removed from wastewater as sludge,  $S$ , in Equations 6.1 and 6.4, is not explained in detail in the *2006 IPCC Guidelines*. This section provides an update through the introduction of new Equations 6.3b and 6.3c, which provide default calculations of  $S$  for aerobic treatment plants and septic systems, respectively. The default value of  $S$  for all other systems is zero. For aerobic treatment systems, some inventory compilers incorrectly defined the variable “ $S$ ” in Equation 6.1 as the mass of sludge removed rather than the organic component removed from wastewater as sludge. It is important to note that the organic component removed from wastewater as sludge is not equivalent to the mass (tonnes) of sludge produced from wastewater treatment. Instead, the organic component removed as sludge is a function of sludge produced from wastewater treatment ( $S_{\text{mass}}$ ) and a sludge factor ( $K_{\text{rem}}$ ) which indicates how much organic matter is removed from the treatment process in sludge per kilogram of sludge produced.

**EQUATION 6.3B (NEW)**  
**ORGANIC COMPONENT REMOVED AS SLUDGE FROM AEROBIC TREATMENT PLANTS**

$$S_{aerobic} = (S_{mass} \cdot K_{rem} \cdot 1000)$$

Where:

$S_{aerobic}$  = organic component removed from wastewater (in the form of sludge) in aerobic treatment plants, kg BOD/yr

$S_{mass}$  = amount of raw sludge removed from wastewater treatment as dry mass, tonnes/year

$K_{rem}$  = sludge factor, kg BOD/kg sludge. See Table 6.6a.

1000 = conversion factor for tonnes to kilograms

New Table 6.6a provides factors associated with the amount of organics in wastewater removed in sludge. Aerobic WWTPs with primary treatment only remove about 0.5 kg of influent BOD per kg of primary sludge by sedimentation. The aerobic stage of treatment removes 1.5 kg BOD per kg of secondary sludge. The sludge produced in aerobic WWTPs with primary sedimentation contains approximately 70 percent of primary sludge and 30 percent of secondary sludge by weight. Aerobic WWTPs without primary treatment remove about 1.16 kg BOD per kg of sludge, depending on process type. Countries where data are available should estimate a country-specific  $K_{rem}$  as a ratio between BOD removed and sludge generated for each process listed in Table 6.6a. Country-specific  $K_{rem}$  should be estimated as a weighted average by individual processes.

<b>TABLE 6.6A (NEW)</b> <b>REMOVAL OF ORGANIC COMPONENT FROM WASTEWATER AS SLUDGE (<math>K_{rem}</math>) ACCORDING TO TREATMENT TYPE<sup>1,2</sup></b>		
<b>Treatment Type</b>	<b>Default</b>	<b>Range</b>
	<b>(kg BOD/kg dry mass sludge)</b>	
Mechanical treatment plants (primary sedimentation sludge)	0.5	0.4 – 0.6
Aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically)	0.8	0.65 – 0.95
Aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically)	1.0	0.8 – 1.2
Aerobic wastewater treatment plants without separate primary treatment	1.16	1.0 – 1.5
Sources:		
<sup>1</sup> BOD, or biochemical oxygen demand, is a proxy indicator of the quality (or organic content) of the waste, but it is not a direct mass measurement of the organic content. Just as the mass of oxygen in carbon dioxide is greater than the mass of carbon, it is feasible for the BOD of a carbon-containing molecule to exceed 1 when the molecule is metabolised to carbon dioxide.		
<sup>2</sup> Based on expert judgment by Lead Authors of this section using the following references: Pescod (1992); Davies (2005); Foladori <i>et al.</i> (2010); WEF (2010); Wisconsin Department of Natural Resources (2010); Serón <i>et al.</i> (2011).		

Concerning septic systems, emissions depend on the fraction of the population managing their septic tank in accordance with the sludge removal instructions of their septic tank/system ( $F$  in new Equation 6.3c). The default value for  $F$  is 0.5 and corresponds to the situation where 50 percent of the population managing their septic system are complying with the sludge removal instructions. This default value is for countries where there is no effective regulation or administrative requirements for sludge removal in septic systems. In countries with such regulations or requirements, some evidence of maintenance controls should be provided (for instance the existence of a local public service responsible for onsite sanitation). It is *good practice* to assess the  $F$  value using available data on sludge removal practices among the population using septic systems.

**EQUATION 6.3C (NEW)**  
**ORGANIC COMPONENT REMOVED AS SLUDGE FROM SEPTIC SYSTEMS**

$$S_{septic} = TOW_{septic} \cdot F \cdot 0.5$$

Where:

- $S_{septic}$  = organic component removed from wastewater (in the form of sludge) in septic systems, kg BOD/yr
- $TOW_{septic}$  = total organics in wastewater in septic systems inventory year, kg BOD/yr
- $F$  = fraction of the population managing their septic tank in compliance with the sludge removal instruction of their septic system
- $0.5$  = fraction of organics in wastewater removed in sludge when septic tank is managed in accordance with sludge removal instructions

For discharges of treated wastewater, inventory compilers should estimate the amount of TOW in effluent ( $TOW_{EFFluent}$ ) as shown in new Equation 6.3d.

**EQUATION 6.3D (NEW)**  
**TOTAL ORGANICS IN TREATED DOMESTIC WASTEWATER EFFLUENT**

$$TOW_{EFFtreat} = \sum_j \left[ TOW \cdot T_j \cdot (1 - TOW_{REM,j}) \right]$$

Where:

- $TOW_{EFFtreat}$  = total organics in the treated wastewater effluent discharged to aquatic environments in inventory year, kg BOD/yr
- $TOW$  = total organically degradable material in domestic wastewater in inventory year, kg BOD/yr. See Equation 6.3 (Updated).
- $T_j$  = degree of utilisation of treatment system  $j$  in inventory year ( $\sum_i T_{ij}$ ). See Table 6.5.
- $j$  = each wastewater treatment type used in inventory year
- $TOW_{REM,j}$  = fraction of total wastewater organics removed during wastewater treatment per treatment type  $j$ . See new Table 6.6b. Pathways for organics removal include loss to sludge and biological decomposition.

**TABLE 6.6B (NEW)**  
**WASTEWATER TREATMENT ORGANICS REMOVAL FRACTIONS ( $TOW_{REM}$ ) ACCORDING TO TREATMENT TYPE**

Treatment Type	Default	Range
Untreated systems	0	0 – 0.1
Primary (mechanical treatment plants)	0.40	0.25 – 0.50
Primary + Secondary (biological treatment plants)	0.85	0.80 – 0.90
Primary + Secondary + Tertiary (advanced biological treatment plants)	0.90	0.80 – 0.95
Septic tank/septic system	0.625	0.50 – 0.60
Latrines – Dry climate, groundwater table lower than latrine, small family (3–5 persons)	0.1	0.05 – 0.15
Latrines – Dry climate, groundwater table lower than latrine, communal (many users)	0.5	0.4 – 0.6
Latrines – Wet climate/flush water use, groundwater table higher than latrine	0.7	0.7 – 1.0

**TABLE 6.6B (NEW) (CONTINUED)**  
**WASTEWATER TREATMENT ORGANICS REMOVAL FRACTIONS (TOW<sub>REM</sub>) ACCORDING TO TREATMENT TYPE**

Sources:

<sup>1</sup> Based on expert judgment by Lead Authors of this section using the following references: Pescod (1992); WEF (2009); Schaidler *et al.* (2017).

### 6.2.2.4 TIME SERIES CONSISTENCY

No refinement.

### 6.2.2.5 UNCERTAINTIES

Chapter 3, Uncertainties, in Volume 1 provides advice on quantifying uncertainties in practice. It includes guidance on eliciting and using expert judgments which in combination with empirical data can provide overall uncertainty estimates. This section provides an update to Table 6.7 to provide default uncertainty ranges for new or updated emission factor and activity data of domestic wastewater. The following parameters are believed to be very uncertain:

- The degrees to which wastewater in developing countries is treated in latrines, septic tanks, or removed by sewer, for urban high, urban low income groups and rural population (T<sub>ij</sub>).
- The fraction of sewers that are ‘open’, as well as the degree to which open sewers in developing countries are anaerobic and will emit CH<sub>4</sub>. This will depend on retention time and temperature, and on other factors including the presence of a facultative layer and possibly components that are toxic to anaerobic bacteria (e.g., certain industrial wastewater discharges).
- The amount of industrial TOW that is discharged into open or closed domestic sewers for each country is very difficult to quantify.

<b>TABLE 6.7 (UPDATED)</b> <b>DEFAULT UNCERTAINTY RANGES FOR DOMESTIC WASTEWATER</b>	
<b>Parameter</b>	<b>Uncertainty Range</b>
<b>Emission Factor</b>	
Maximum CH <sub>4</sub> producing capacity (B <sub>o</sub> )	± 30%
Fraction treated anaerobically (MCF)	The MCF is technology dependent. See Table 6.3. Thus, the uncertainty range is also technology dependent. The uncertainty range should be determined by expert judgment, bearing in mind that MCF is a fraction and must be between 0 and 1. Suggested ranges are provided below. Untreated systems, ± 50% Lagoons ± 30% Centralised plant, digester, reactor, ± 10%
<b>Activity Data</b>	
Human population (P)	± 5%
Biochemical oxygen demand (BOD)	± 30%
Fraction of population income group (U)	Good data on urbanisation are available, however, the distinction between urban high income and urban low income may have to be based on expert judgment. ± 15%
Degree of utilisation of treatment/ discharge pathway or system for each income group (T <sub>ij</sub> )	Can be as low as ± 3% for countries that have good records and only one or two systems. Can be ± 50% for an individual method/pathway. Verify that total T <sub>ij</sub> = 100%
Correction factor for additional industrial BOD discharged into sewers (I)	For uncollected, the uncertainty is zero %. For collected the uncertainty is ± 20%

<b>TABLE 6.7 (UPDATED) (CONTINUED)</b> <b>DEFAULT UNCERTAINTY RANGES FOR DOMESTIC WASTEWATER</b>	
<b>Parameter</b>	<b>Uncertainty Range</b>
Amount of sludge removed from wastewater treatment ( $S_{\text{mass}}$ )	$\pm 30\%$
Sludge factor ( $K_{\text{rem}}$ )	$\pm 25\%$
Fraction of the population managing their septic system complying with the sludge removal instruction (F)	Can be as low as $\pm 3\%$ for countries that have good records on implementation. Can be $\pm 50\%$ if based on expert judgment.
Amount of CH <sub>4</sub> recovered or flared (R)	For systems with measured data, the uncertainty is equal to the uncertainty of the measurement system.
Source: Based on expert judgment by Lead Authors of this section.	

### 6.2.2.6 QA/QC, COMPLETENESS, REPORTING AND DOCUMENTATION

No refinement.

## 6.2.3 Industrial wastewater

Industrial wastewater may be treated on site or released into domestic sewer systems. If it is released into the domestic sewer system, the emissions are to be included with the domestic wastewater emissions. This section deals with estimating CH<sub>4</sub> emissions from on-site industrial wastewater treatment. Only industrial wastewater with significant carbon loading that is treated under intended or unintended anaerobic conditions will produce CH<sub>4</sub>. Organics in industrial wastewater are often expressed in terms of COD, which is used here.

### 6.2.3.1 CHOICE OF METHOD

Assessment of CH<sub>4</sub> production potential from industrial wastewater streams is based on the concentration of degradable organic matter in the wastewater, the volume of wastewater, and the propensity of the industrial sector to treat their wastewater in anaerobic systems. Using these criteria, major industrial wastewater sources with high CH<sub>4</sub> gas production potential can be identified as follows:

- pulp and paper manufacture;
- meat and poultry processing (slaughterhouses);
- alcohol, beer, starch production;
- organic chemicals production;
- other food and drink processing (dairy products, vegetable oil, fruits and vegetables, canneries, juice making, etc.).

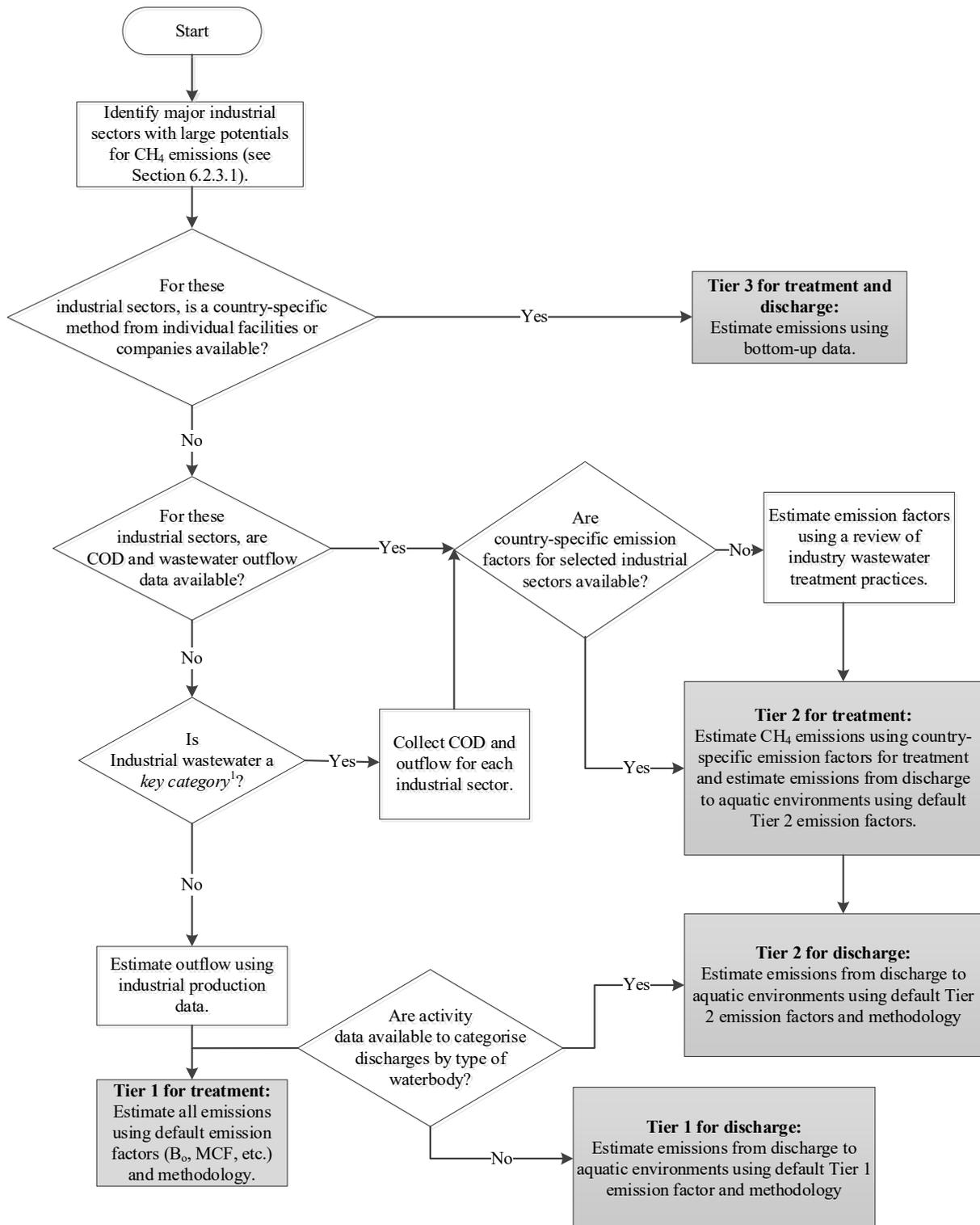
Both the pulp and paper industry and the meat and poultry processing industries produce large volumes of wastewater that contain high levels of degradable organics. The meat and poultry processing facilities typically employ anaerobic lagoons to treat their wastewater, while the paper and pulp industry also use lagoons and anaerobic reactors. The non-animal food and beverage industries produce considerable amounts of wastewater with significant organic carbon levels and are also known to use anaerobic processes such as lagoons and anaerobic reactors. Anaerobic reactors treating industrial effluents with biogas facilities are usually linked with recovery of the generated CH<sub>4</sub> for energy. Emissions from the combustion process for energy should be reported in the Energy Sector.

The method for estimating emissions from industrial wastewater is similar to the one used for domestic wastewater. An updated decision tree for industrial wastewater is included as updated Figure 6.3 and should be used to determine the tier approach that is applicable to the country.

The development of emission factors and activity data is more complex because there are many types of wastewater, and many different industries to track. The most accurate estimates of emissions for this source category would be based on measured data from point sources. Due to the high costs of measurements and the

potentially large number of point sources, collecting comprehensive measurement data is very difficult. It is suggested that inventory compilers use a top-down approach that includes the following general steps:

- Step 1:** Use Equation 6.6 to estimate total organically degradable carbon in wastewater (TOW) for industrial sector *i*
- Step 2:** Select the pathway and systems (updated Figure 6.1) according to country activity data. Use Equation 6.5 to obtain emission factor. For each industrial sector estimate the emission factor using maximum methane producing capacity and the average industry-specific MCF.
- Step 3:** Use Equation 6.4 to estimate emissions, adjust for possible sludge removal and or CH<sub>4</sub> recovery and sum the results.

Figure 6.3 (Updated) Decision tree for CH<sub>4</sub> emissions from industrial wastewater treatment

<sup>1</sup> See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

The general equation to estimate CH<sub>4</sub> emissions from industrial wastewater is as follows:

**EQUATION 6.4**  
**TOTAL CH<sub>4</sub> EMISSIONS FROM INDUSTRIAL WASTEWATER**

$$CH_4 \text{ Emissions} = \sum_i [(TOW_i - S_i) \cdot EF_i - R_i] \cdot 10^{-6}$$

Where:

- CH<sub>4</sub> Emissions = CH<sub>4</sub> emissions in inventory year, Gg CH<sub>4</sub>/yr
- TOW<sub>*i*</sub> = total organically degradable material in wastewater from industry *i* in inventory year, kg COD/yr
- i* = industrial sector
- S<sub>*i*</sub> = organic component removed from wastewater (in the form of sludge) in inventory year, kg COD/yr
- EF<sub>*i*</sub> = emission factor for industry *i*, kg CH<sub>4</sub>/kg COD for treatment/discharge pathway or system(s) used in inventory year
- If more than one treatment practice is used in an industry this factor would need to be a weighted average.
- R<sub>*i*</sub> = amount of CH<sub>4</sub> recovered or flared in inventory year, kg CH<sub>4</sub>/yr
- 10<sup>-6</sup> = conversion of kg to Gg

The amount of CH<sub>4</sub> which is recovered or flared is expressed as R in Equation 6.4.

### 6.2.3.2 CHOICE OF EMISSION FACTORS

This section represents an update to Section 6.2.3.2 of the *2006 IPCC Guidelines*.

As stated in the *2006 IPCC Guidelines*, there are significant differences in the CH<sub>4</sub> emitting potential of different types of industrial wastewater dependent on the type and form of constituents present in the wastewater. To the extent possible, data should be collected to determine the maximum CH<sub>4</sub> producing capacity (B<sub>o</sub>) in each industry.

As mentioned before, the MCF indicates the extent to which the CH<sub>4</sub> producing potential (B<sub>o</sub>) is realised in each type of treatment method. Thus, it is an indication of the degree to which the system is anaerobic. See Equation 6.5.

**EQUATION 6.5**  
**CH<sub>4</sub> EMISSION FACTOR FOR INDUSTRIAL WASTEWATER**

$$EF_j = B_o \cdot MCF_j$$

Where:

- EF<sub>*j*</sub> = emission factor for each treatment/discharge pathway or system, kg CH<sub>4</sub>/kg COD, (See Table 6.8.)
- j* = each treatment/discharge pathway or system
- B<sub>o</sub> = maximum CH<sub>4</sub> producing capacity, kg CH<sub>4</sub>/kg COD
- MCF<sub>*j*</sub> = methane correction factor (fraction). See Table 6.8.

*Good practice* is to use country- and industry-sector specific data that may be available from government authorities, industrial organisations, or industrial experts. If country-specific data are available to determine the B<sub>o</sub> for a particular industry, industry-specific MCFs must be developed for the calculation of CH<sub>4</sub> emissions. However, if country-specific data are not available, it is *good practice* to use the IPCC default factors listed in Table 6.2.

In determining the MCF, which is the fraction of waste treated anaerobically, expert judgment is recommended. A peer-reviewed survey of industry wastewater treatment practices is one useful technique for estimating these data. Surveys should be conducted frequently enough to account for major trends in industry practices (i.e., every 3-5 years). Chapter 2, Approaches to Data Collection, in Volume 1, describes how to elicit expert judgment for

uncertainty ranges. Similar expert elicitation protocols can be used to obtain the necessary information for other types of data if published data and statistics are not available. Table 6.8 includes default MCF values, which are based on expert judgment.

In addition, the MCFs in Table 6.8 have been updated to reflect revisions to certain wastewater treatment and discharge pathways and systems, as described in Section 6.2.2.2.

<b>TABLE 6.8 (UPDATED)</b> <b>DEFAULT MCF VALUES AND RESULTANT EF<sup>2</sup> FOR INDUSTRIAL WASTEWATER</b>				
<b>Type of treatment and discharge pathway or system</b>	<b>Comments</b>	<b>MCF<sup>1</sup> (Range)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg BOD)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg COD)</b>
<b>Discharge from treated or untreated system</b>				
Discharge to aquatic environments (Tier 1)	Most aquatic environments including rivers are supersaturated in CH <sub>4</sub> . Nutrient oversupply will increase CH <sub>4</sub> emissions. Environments where carbon accumulates in sediments have higher potential for methane generation.	0.11 (0.004 – 0.27)	0.068	0.028
Discharge to aquatic environments other than reservoirs, lakes, and estuaries (Tier 2)	Most aquatic environments including rivers are supersaturated in CH <sub>4</sub> . Nutrient oversupply will increase CH <sub>4</sub> emissions.	0.035 <sup>3</sup> (0.004 – 0.06)	0.021	0.009
Discharge to reservoirs, lakes, and estuaries (Tier 2)	Environments where carbon accumulates in sediments have higher potential for methane generation.	0.19 <sup>3</sup> (0.08 – 0.27)	0.114	0.048
Discharge to soil	Sludge and/or wastewater discharge to soil may be a source of CH <sub>4</sub> for fertilisation	Emissions reported in Volume 4		
<b>Wastewater treatment system</b>				
Centralised, aerobic treatment plant	Some CH <sub>4</sub> can be emitted from settling basins and other anaerobic pockets. For treatment plants that are receiving wastewater beyond the design capacity, inventory compilers should judge the amount of organic material removed in sludge accordingly.	0 (0 – 0.1)	0	0
Anaerobic reactor (e.g., upflow anaerobic sludge blanket digestion (UASB))	CH <sub>4</sub> recovery is not considered here.	0.8 (0.8 – 1.0)	0.48	0.2
Anaerobic shallow lagoon and facultative lagoons	Depth less than 2 metres, use expert judgment.	0.2 (0 – 0.3)	0.12	0.05
Anaerobic deep lagoon	Depth more than 2 metres.	0.8 (0.8 – 1.0)	0.48	0.2
Constructed wetlands	<i>See 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2014)</i>			

<b>TABLE 6.8 (UPDATED) (CONTINUED)</b> <b>DEFAULT MCF VALUES AND RESULTANT EF<sup>2</sup> FOR INDUSTRIAL WASTEWATER</b>				
<b>Type of treatment and discharge pathway or system</b>	<b>Comments</b>	<b>MCF<sup>1</sup> (Range)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg BOD)</b>	<b>EF<sup>2</sup> (kg CH<sub>4</sub>/kg COD)</b>
<b>Sludge treatment system</b>				
Anaerobic digester for sludge	See Chapter 4 for emissions methodology	See Chapter 4, Table 4.1		
Composting	Emissions reported in Volume 5, Chapter 4	See Chapter 4, Table 4.1		
Incineration and open burning	Emissions reported in Volume 5, Chapter 5	See Chapter 5		
Sources:				
<sup>1</sup> Based on expert judgment by Lead Authors of this section.				
<sup>2</sup> Emission factors calculated using default B <sub>0</sub> and default MCF.				
<sup>3</sup> See Annex 6A.4.				

### 6.2.3.3 CHOICE OF ACTIVITY DATA

No refinement.

### 6.2.3.4 TIME SERIES CONSISTENCY

No refinement.

### 6.2.3.5 UNCERTAINTIES

No refinement.

### 6.2.3.6 QA/QC, COMPLETENESS, REPORTING AND DOCUMENTATION

No refinement.

## 6.3 NITROUS OXIDE EMISSIONS FROM DOMESTIC WASTEWATER

This section refines Section 6.3 of the *2006 IPCC Guidelines* by providing update and new guidance for estimating domestic N<sub>2</sub>O emissions from WWTPs and provides new guidance on the estimation of N<sub>2</sub>O emissions from wastewater after disposal of untreated wastewater or treated wastewater effluent into aquatic environments by accounting for losses of nitrogen prior to disposal.

### 6.3.1 Methodological issues

Nitrous oxide emissions can occur as emissions from WWTPs or as emissions from receiving aquatic environments following the disposal of untreated or treated wastewater effluent. This section describes how to estimate the N<sub>2</sub>O produced during wastewater treatment, sludge treatment that occurs within the wastewater treatment system, and disposal of the wastewater. More recent research and field surveys have revealed that emissions in sewer networks and from nitrification or nitrification-denitrification processes at WWTPs, previously judged to be a minor source, may in fact result in more substantial emissions. N<sub>2</sub>O is generated as a by-product of nitrification, or as an intermediate product of denitrification. There are many factors affecting N<sub>2</sub>O

emissions from wastewater treatment systems such as the temperature and dissolved oxygen concentration of the wastewater, and the specific operational conditions.

Emissions also result from untreated wastewater or wastewater treatment effluent that is discharged into aquatic environments. It is important to note that emissions are dependent on the nutrient-impacted status and oxygenation level of the aquatic environment receiving the wastewater discharge. The current methodology in the *2006 IPCC Guidelines* appropriately captures discharge to relatively clean and/or well-oxygenated environments. However, in the case of discharge to nutrient-impacted waters such as eutrophic lakes, estuaries and rivers, or locations where stagnant conditions occur, emissions can be significantly higher.

Three tiers of methods for estimating N<sub>2</sub>O emissions from this category are summarised below:

The Tier 1 method applies default values for the emission factor and activity parameters. This method is considered *good practice* for countries with limited data.

The Tier 2 method follows the same method as Tier 1 but allows for incorporation of a country-specific emission factor and country-specific activity data. For example, a specific emission factor for a prominent treatment system based on field measurements could be incorporated under this method. Use of country-specific emission factor in the same region or climate area is also *good practice*. The amount of sludge removed for incineration, landfills, and agricultural land should be taken into consideration.

For a country with good data and advanced methodologies, a country-specific method could be applied as a Tier 3 method. For example, a more advanced country-specific method could be based on plant-specific emissions data from large wastewater treatment facilities or using country-specific measurements of nitrogen discharged to aquatic environments of varying nutrient-impacted status. Direct measurement methods would provide a more accurate measurement of N<sub>2</sub>O production from each treatment plant.

### 6.3.1.1 CHOICE OF METHOD

A decision tree for domestic wastewater is included in new Figure 6.4.

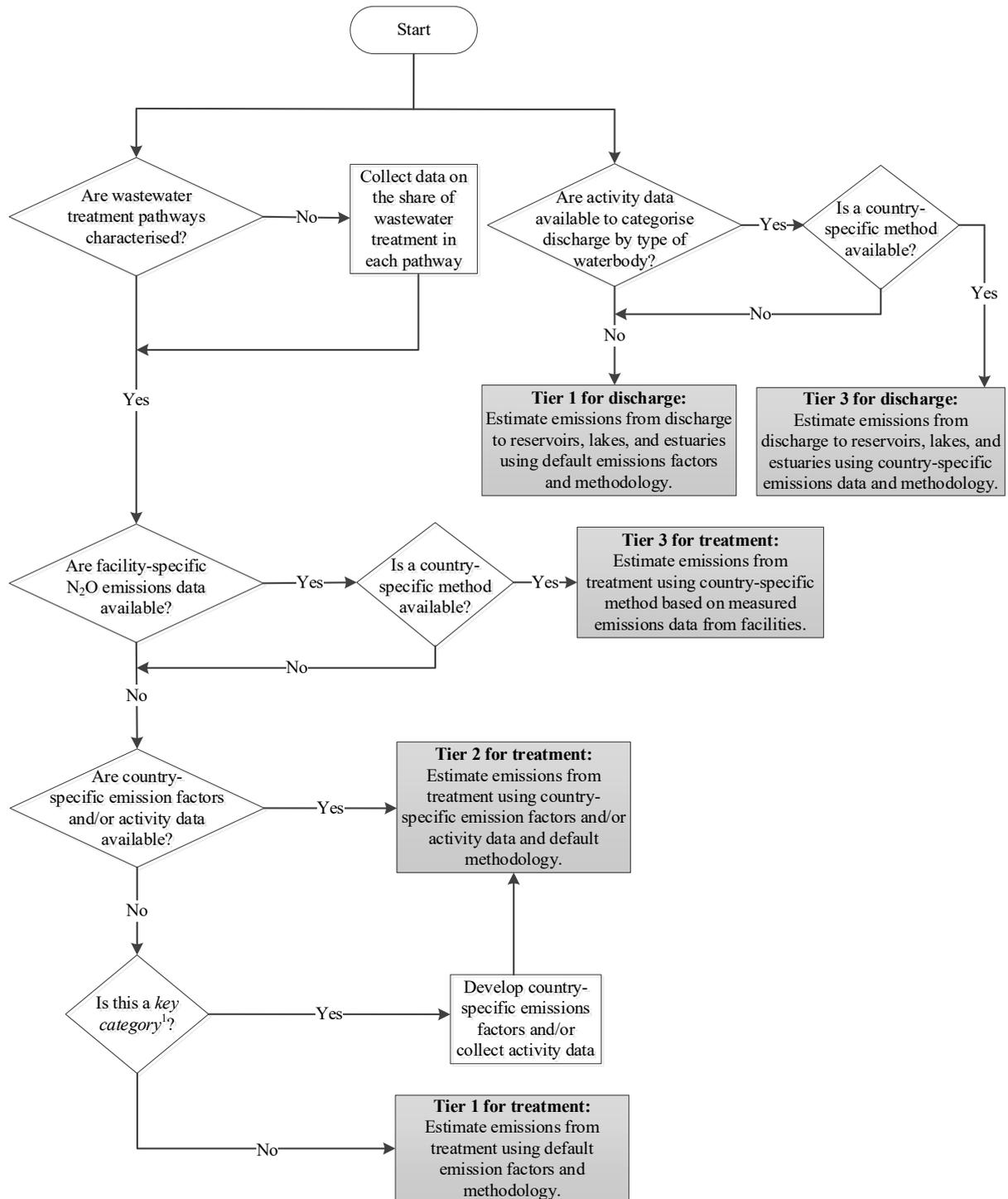
The steps for *good practice* in inventory preparation for N<sub>2</sub>O from domestic wastewater are as follows:

- Step 1:** Use new Equation 6.10 to estimate total nitrogen in wastewater and updated Equation 6.8 to estimate total nitrogen in wastewater effluent.
- Step 2:** Select the pathway and systems (see updated Figure 6.1) according to country activity data. Select the emission factor for each domestic wastewater treatment/discharge pathway or system.
- Step 3:** Use updated Equation 6.9 to estimate emissions from wastewater treatment and sum the results for each treatment pathway/system.
- Step 4:** Use updated Equation 6.7 to estimate emissions from effluent, accounting for losses of nitrogen that occur within the wastewater treatment process including sludge removal and sum the results for each pathway/system. Emissions should also be calculated for nitrogen discharged as untreated wastewater.

As described earlier, the wastewater characterisation will determine the fraction of wastewater treated or disposed of by a particular system. To determine the use of each type of treatment or discharge system, it is *good practice* to refer to national statistics (e.g., from regulatory authorities). If these data are not available, wastewater associations or international organisations such as the WHO may have data on the system usage.

Otherwise, consultation with sanitation experts can help, and expert judgment can also be applied (see Chapter 2, *Approaches to Data Collection*, in Volume 1). Urbanisation statistics may provide a useful tool, e.g., city sizes and income distribution.

If activity data are available to categorize discharges to nutrient-impacted environments, these refinements introduce a new Tier 3 emission factor for those discharges.

Figure 6.4 (New) Decision tree for N<sub>2</sub>O emissions from domestic wastewater

<sup>1</sup> See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

**EQUATION 6.9 (UPDATED)**  
**N<sub>2</sub>O EMISSIONS FROM DOMESTIC WASTEWATER TREATMENT PLANTS**

$$N_2O\ Plants_{DOM} = \left[ \sum_{i,j} (U_i \cdot T_{ij} \cdot EF_j) \right] \cdot TN_{DOM} \cdot \frac{44}{28}$$

Where:

- $N_2O_{Plants_{DOM}}$  =  $N_2O$  emissions from domestic wastewater treatment plants in inventory year, kg  $N_2O$ /yr
- $TN_{DOM}$  = total nitrogen in domestic wastewater in inventory year, kg N/yr. See new Equation 6.10.
- $U_i$  = fraction of population in income group  $i$  in inventory year. See Table 6.5.
- $T_{ij}$  = degree of utilisation of treatment/discharge pathway or system  $j$ , for each income group fraction  $i$  in inventory year. See Table 6.5.
- $i$  = income group: rural, urban high income and urban low income
- $j$  = each treatment/discharge pathway or system
- $EF_j$  = emission factor for treatment/discharge pathway or system  $j$ , kg  $N_2O$ -N/kg N

The factor 44/28 is for the conversion of kg  $N_2O$ -N into kg  $N_2O$ .

It is also required to estimate direct  $N_2O$  emissions arising from the discharge of wastewater (treated or untreated) into aquatic receiving environments. The methodology for emissions from effluent is similar to that of  $N_2O$  emissions explained in Volume 4, Section 11.2.2 in Chapter 11  $N_2O$  Emissions from Managed Soils, and  $CO_2$  Emissions from Lime and Urea Application. The simplified general equation is as follows:

**EQUATION 6.7 (UPDATED)**

**$N_2O$  EMISSIONS FROM DOMESTIC WASTEWATER EFFLUENT**

$$N_2O_{EFFLUENT,DOM} = N_{EFFLUENT,DOM} \cdot EF_{EFFLUENT} \cdot \frac{44}{28}$$

Where:

- $N_2O_{EFFLUENT,DOM}$  =  $N_2O$  emissions from domestic wastewater effluent in inventory year, kg  $N_2O$ /yr
- $N_{EFFLUENT,DOM}$  = nitrogen in the effluent discharged to aquatic environments, kg N/yr. See updated Equation 6.8.
- $EF_{EFFLUENT}$  = emission factor for  $N_2O$  emissions from wastewater discharged to aquatic systems, kg  $N_2O$ -N/kg N

The factor 44/28 is the conversion of kg  $N_2O$ -N into kg  $N_2O$ .

### 6.3.1.2 CHOICE OF EMISSION FACTORS

New Table 6.8a includes default Tier 1 EF values for use in estimation of  $N_2O$  emissions from waters receiving treated or untreated effluent (see Annex 6A.5). These refinements to the emission factors build on the current default value for  $EF_{EFFLUENT}$  provided in Table 6.11 of the *2006 IPCC Guidelines*. This existing emission factor is adequate for all discharges when using the Tier 1 methodology. However, it is expected to generate an underestimate of  $N_2O$  emissions in the case of discharge to nutrient-impacted waters such as eutrophic lakes, estuaries and rivers, or locations where stagnant conditions occur. Research published between 1978 and 2017 provide data indicating that higher  $N_2O$  emissions occur when wastewater is discharged to nutrient-impacted (eutrophic) or hypoxic aquatic receiving environments. Accordingly, Table 6.8a provides a new  $EF_{EFFLUENT}$  of 0.019 g  $N_2O$ -N/g N (95percent confidence limits 0.0041–0.091) for use with a Tier 3 method (see Annex 6A.6 for a discussion of information used to develop this new emission factor). The compiler can make use of many different indications of whether this higher EF value should be employed. Harmful algal blooms and hypoxia are the two most common symptoms of waterway nutrient over-enrichment (eutrophication). One possibility is to consider the dissolved oxygen status of the receiving waters. Waterway hypoxia is becoming increasingly common globally and definitions of hypoxia can vary depending on temperature, salinity, and the particular biota of interest. Dissolved oxygen concentrations of between 0.1–3.0 mg/L (or <30percent of the oxygen saturation concentration) are typically classified as hypoxic (Vaquer-Sunyer & Duarte 2008; Naqvi *et al.* 2010; Rabalais *et al.* 2010) and are likely to result in increased  $N_2O$  yields from microbial metabolism of discharged wastewater nitrogen.

Oxygen status can be a highly dynamic indicator in practice, and compilers may have better access to information regarding the nutrient (trophic) status of receiving waters. Various thresholds for the boundary between mesotrophic and eutrophic conditions have been proposed, such as Secchi depth (suggestions range from 2 to 3.6 m), total phosphorus (20–75  $\mu\text{g/L}$ ), total nitrogen (0.3–5 mg/L), benthic chlorophyll (70 mg/m<sup>2</sup>) and suspended chlorophyll concentration (5–30  $\mu\text{g/L}$ ) (Dodds *et al.* 1998; Burns *et al.* 2009; Mateo-Sagasta & Burke 2010). Compilers may also consider whether there have been reports of algal blooms, sulphurous odours,

fish kills or other indications of eutrophic and/or hypoxic conditions in the discharge environment. Global datasets exist which may assist compilers in assessing the risk of nutrient impacts in different regions (Diaz *et al.* 2011; Xie & Ringler 2017). It is important to note that the context for application of this new Tier 3  $EF_{\text{EFFLUENT}}$  factor is not necessarily the same as for nitrogen runoff from agriculture, due to the combination of reducing conditions and high organic loading in many wastewaters which are unlikely to exist in agricultural runoff systems.

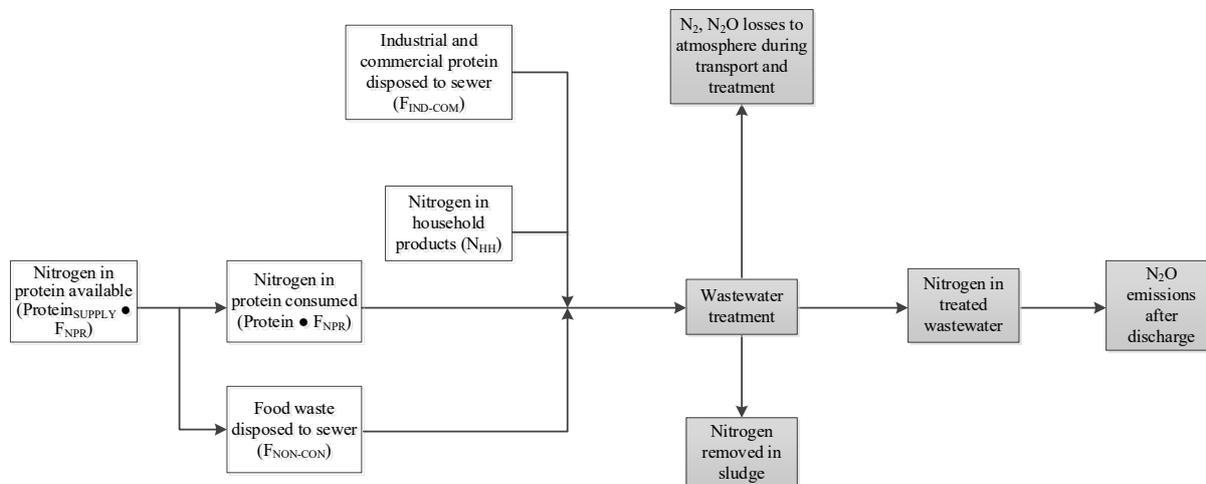
Type of treatment and discharge pathway or system	Comments	$EF^1$ (kg $N_2O$ -N/kg N)	Range
<b>Discharge from treated or untreated system, <math>EF_{\text{EFFLUENT}}</math></b>			
Freshwater, estuarine, and marine discharge (Tier 1)	Based on limited field data and on specific assumptions regarding the occurrence of nitrification and denitrification in rivers and in estuaries	0.005 <sup>2</sup>	0.0005 – 0.075
Nutrient-impacted and/or hypoxic freshwater, estuarine, and marine environments (Tier 3, if needed)	Higher emissions are associated with nutrient-impacted/hypoxic water such as eutrophic lakes, estuaries and rivers, or locations where stagnant conditions occur. See section 6.3.1.2 for more information.	0.019 <sup>2</sup>	0.0041 – 0.091
Discharge to soil	Emissions reported in Volume 4		
<b>Wastewater treatment system, <math>EF_{\text{plants}}</math></b>			
Centralised, aerobic treatment plant	$N_2O$ is variable and can be significant	0.016 <sup>1</sup>	0.00016 – 0.045
Anaerobic reactor	$N_2O$ is not significant	0	0 – 0.001
Anaerobic lagoons	$N_2O$ is not significant	0	0 – 0.001
Constructed wetlands	<i>See 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2014)</i>		
Septic tank	$N_2O$ is not significant	0	0 – 0.001
Septic tank + land dispersal field	$N_2O$ is emitted by the soil dispersal system	0.0045	0 – 0.005
Latrine	$N_2O$ is not significant	0	0 – 0.001
<b>Sludge treatment system</b>			
Anaerobic digester for sludge	$N_2O$ is not significant	0	0
Composting	See Chapter 4 for emissions methodology	See Chapter 4, Table 4.1	
Incineration and open burning	See Chapter 5 for emissions methodology	See Chapter 5	
Sources: Based on scientific literature and expert judgment by Lead Authors of this section.			
<sup>1</sup> See Annex 6A.5.			
<sup>2</sup> See Annex 6A.6.			

### 6.3.1.3 CHOICE OF ACTIVITY DATA

The methodology to calculate the amount of N content in wastewater effluent ( $N_{\text{EFFLUENT,DOM}}$ ) presented in Equation 6.8 of the *2006 IPCC Guidelines* currently does not account for the removal of ammonia-N via nitrification-denitrification processes in the sewer and the WWTP, or the removal of N in sludge, which can result in a significant overestimate of N discharged to aquatic receiving environments. Typical total N concentration in raw urban sewage is about 40 mg/L (range 20–70 mg/L) (Tchobanoglous *et al.* 2014), whereas effluent treated in conventional activated sludge facilities (with nitrification) has a total of about 25 mg/L. Plants with biological nutrient removal (with denitrification) regularly achieve an effluent total N of 5 mg/L or less. The difference is due both to N removed in sludge (see Table 2.4A (New), Chapter 2 of Volume 5 regarding the N content of sewage sludge) versus N loss to the atmosphere (see new Figure 6.5).

This section updates the methodology presented in the 2006 IPCC Guidelines to estimate the amount of N content in wastewater entering treatment ( $TN_{DOM}$ ), the loss or removal of N through the treatment process (either through biological conversion or removal with sludge) ( $N_{REM}$ ), and the N content in wastewater discharged to aquatic systems ( $N_{EFFLUENT,DOM}$ ).

**Figure 6.5 (New) Nitrogen in domestic wastewater treatment**



### NITROGEN IN DOMESTIC WASTEWATER ( $TN_{DOM}$ )

The activity data that are needed for estimating  $TN_{DOM}$  in domestic wastewater include the population associated with the wastewater, the average annual per capita protein consumed (kg/person/yr), and factors to account for N in non-consumed protein entering the wastewater and other N from household, industrial, and commercial sources co-discharged into the sewer system. The total N in wastewater for each treatment pathway is estimated as follows:

**EQUATION 6.10 (NEW)**  
**TOTAL NITROGEN IN DOMESTIC WASTEWATER BY TREATMENT PATHWAY**

$$TN_{DOM\_j} = \left( P_{treatment\_j} \cdot Protein \cdot F_{NPR} \cdot N_{HH} \cdot F_{NON-CON} \cdot F_{IND-COM} \right)$$

Where:

- $TN_{DOM\_j}$  = total annual amount of nitrogen in domestic wastewater for treatment pathway j, kg N/yr
- $P_{treatment\_j}$  = human population who are served by the treatment pathway j, person/yr
- Protein = annual per capita protein consumption, kg protein/person/yr
- $F_{NPR}$  = fraction of nitrogen in protein, default = 0.16 kg N/kg protein
- $F_{NON-CON}$  = factor for nitrogen in non-consumed protein disposed in sewer system, kg N/kg N. See new Table 6.10a.
- $F_{IND-COM}$  = factor for industrial and commercial co-discharged protein into the sewer system, kg N/kg N
- $N_{HH}$  = additional nitrogen from household products added to the wastewater, default is 1.1 (some country data are in new Table 6.10a).

If national statistics on protein consumed or protein supply are not available, Food Balance Sheets of FAOSTAT can be used as activity data on per capita “protein supply quantity.” This information represents the total amount of protein available to the population but must be adjusted to reflect the fraction of protein consumed (FPC), according to the new Equation 6.10a.

**EQUATION 6.10A (NEW)**  
**ESTIMATION OF PROTEIN CONSUMED**

$$Protein = Protein_{SUPPLY} \cdot FPC$$

Where:

$Protein_{SUPPLY}$  = annual per capita protein supply, kg protein/person/yr

FPC = Fraction of protein consumed. Default regional values are listed in the new Table 6.10a

Food that is not consumed may be disposed to the sewer (e.g., as result of the use of food waste disposals in some countries) and a factor for non-consumed protein ( $F_{NON-CON}$ ) should be used to reflect this additional N entering wastewater (see new Table 6.10a). If food waste is disposed with solid waste, it is assumed that no additional N is entering wastewater and  $F_{NON-CON} = 1$ .

Bath and laundry water may contain household chemicals (detergents, shampoos, softeners, dishwashing agents, WC fresheners, cosmetics, etc.) and a factor for N from household products ( $N_{HH}$ ) should be used. The default factor for  $N_{HH}$  is 1.1 (Henze *et al.* 2008; Tjandraatmadja *et al.* 2008), but additional regional factors are provided in Table 6.10a.

Region <sup>1</sup>	Protein consumed <sup>2</sup> as fraction of protein supply	$F_{NON-CON}$ <sup>2</sup> in case food waste is disposed in sewer	Additional N from households' chemicals
Europe	0.85	1.09	1.08
North America and Oceania	0.80	1.13	1.17 (USA) 1.07 (Australia)
Industrialised Asia	0.86	1.08	No data
Sub-Saharan Africa	0.98	1.01	No data
North Africa, West and central Asia	0.90	1.06	No data
South and Southeast Asia	0.96	1.02	1.13 (India)
Latin America	0.92	1.04	No data

<sup>1</sup> See Annex 6A.7 for a list of countries by region  
<sup>2</sup> Based on FAO (2011)

<b>TABLE 6.10B (NEW)</b> <b>ESTIMATE ON USE OF FOOD WASTE DISPOSAL IN SEWER<sup>1</sup></b>	
<b>Country</b>	<b>Share of households disposing food waste in sewer</b>
USA	50%
Canada	10%
Australia	12%
New Zealand	30%
UK	5%
Ireland	1 – 2%
Italy	Supported
Czech Republic	<1% / not allowed
Denmark	Rare
Belgium	Restricted / not allowed
The Netherlands	Not allowed
Germany	Not allowed
<sup>1</sup> Based on EPA (2008) and expert judgment by Lead Authors	

Wastewater from industrial or commercial sources that is discharged into the sewer may contain protein (e.g., from grocery stores and butchers). The default for this fraction is 1.25 for centralised treatment and 1 for decentralised treatment systems (septic system, latrines, discharge).

### **NITROGEN IN WASTEWATER EFFLUENT ( $N_{EFFLUENT,DOM}$ )**

The total nitrogen in wastewater effluent is estimated as follows:

<b>EQUATION 6.8 (UPDATED)</b>	
<b>TOTAL NITROGEN IN DOMESTIC WASTEWATER EFFLUENT</b>	
$N_{EFFLUENT,DOM} = \sum_j \left[ (TN_{DOM} \cdot T_j) \cdot (1 - N_{REM,j}) \right]$	

Where:

- $N_{EFFLUENT,DOM}$  = total nitrogen in the wastewater effluent discharged to aquatic environments in inventory year, kg N/yr
- $TN_{DOM}$  = total nitrogen in domestic wastewater in inventory year, kg N/yr. See new Equation 6.10.
- $T_j$  = degree of utilisation of treatment system  $j$  in inventory year ( $\sum_i T_{ij}$ ). See Table 6.5
- $j$  = each wastewater treatment type used in inventory year
- $N_{REM}$  = fraction of total wastewater nitrogen removed during wastewater treatment per treatment type  $j$ . See new Table 6.10c. Pathways for N removal include transfer to sludge and nitrification–denitrification with concomitant N loss to the atmosphere.

Treatment Type	Default	Range
No treatment	0 <sup>1-3</sup>	0 <sup>1-3</sup>
Primary (mechanical)	0.10 <sup>1-3</sup>	0.05 – 0.20 <sup>1-3</sup>
Secondary (biological)	0.40 <sup>1-3</sup>	0.35 – 0.55 <sup>1-3</sup>
Tertiary (advanced biological)	0.80 <sup>1-4</sup>	0.45 – 0.85 <sup>1-4</sup>
Septic tank	0.15 <sup>1-3</sup>	0.10 – 0.25 <sup>1-3</sup>
Septic tank + land dispersal field	0.68 <sup>5</sup>	0.62 – 0.73 <sup>5</sup>
Latrine	0.12 <sup>6</sup>	0.07 – 0.21 <sup>6</sup>
Sources: <sup>1</sup> Kristensen <i>et al.</i> (2004) <sup>2</sup> Van Drecht <i>et al.</i> (2009) <sup>3</sup> Based on expert judgment by Lead Authors of this section. <sup>4</sup> Ekama and Wentzel (2008) <sup>5</sup> Andreoli <i>et al.</i> (1979) <sup>6</sup> EMEP/EAA (2016)		

### 6.3.2 Time series consistency

No refinement.

### 6.3.3 Uncertainties

Large uncertainties are associated with the IPCC default factors for N<sub>2</sub>O. Updated Table 6.11 below includes uncertainty ranges based on expert judgment.

	Definition	Default Value	Range
<b>Emission Factor</b>			
EF	N <sub>2</sub> O emission factor	See Table 6.8a	See Table 6.8a
<b>Activity Data</b>			
P	Number of people in country	Country-specific	± 10 %
Protein	Annual per capita protein consumption	Country-specific	± 10 %
F <sub>NPR</sub>	Fraction of nitrogen in protein (kg N/kg protein)	0.16	0.15 – 0.17
T <sub>plant</sub>	Degree of utilisation of large WWT plants	Country-specific	± 20 %
F <sub>NON-COM</sub>	Factor to adjust for non-consumed protein, based on available protein	1.0 for countries with no in-sink disposals, 1.1 for countries with in-sink disposals	0.9 – 1.2
	Factor to adjust for non-consumed protein, based on consumed protein	1.1 for countries with no in-sink disposals, 1.25 for countries with in-sink disposals	1.0 – 1.4
F <sub>IND-COM</sub>	Factor to allow for co-discharge of industrial nitrogen into sewers. For countries with significant fish processing plants, this factor may be higher. Expert judgment is recommended.	1.25	1.0 – 1.5

TABLE 6.11 (UPDATED) (CONTINUED) N <sub>2</sub> O METHODOLOGY DEFAULT DATA			
	Definition	Default Value	Range
N <sub>REM</sub>	Factor to account for losses of nitrogen prior to discharge	See Table 6.10c	See Table 6.10c

### 6.3.4 QA/QC, Completeness, Reporting and Documentation

No refinement.

## 6.4 NITROUS OXIDE EMISSIONS FROM INDUSTRIAL WASTEWATER

### 6.4.1 Methodological issues

This section refines the *2006 IPCC Guidelines* by adding new guidance for estimating N<sub>2</sub>O emissions from industrial WWTPs and refines the estimation of N<sub>2</sub>O emissions from wastewater after disposal of untreated wastewater or wastewater treatment effluent into aquatic environments by accounting for losses of nitrogen prior to disposal.

#### 6.4.1.1 CHOICE OF METHOD

A decision tree for industrial wastewater is included in new Figure 6.6.

The steps for *good practice* in inventory preparation for N<sub>2</sub>O from industrial wastewater are as follows:

- Step 1:** Use new Equation 6.13 to estimate total nitrogen in wastewater.
- Step 2:** Select the pathway and systems (see updated Figure 6.1) according to country activity data. Select the emission factor for each industrial wastewater treatment/discharge pathway or system.
- Step 3:** Use new Equation 6.11 to estimate emissions from wastewater treatment and sum the results for each pathway/system.
- Step 4:** Use new Equation 6.12 to estimate emissions from effluent, accounting for losses of nitrogen that occur within the wastewater treatment process, including sludge removal, and sum the results for each pathway/system.

As described earlier, the wastewater characterisation will determine the fraction of wastewater treated or disposed of by a particular system. To determine the use of each type of treatment or discharge system, it is *good practice* to refer to national statistics (e.g., from regulatory authorities). If these data are not available, industry associations may have data on the system usage. Otherwise, consultation with industry experts can help, and expert judgment can also be applied (see Chapter 2 Approaches to Data Collection, Volume 1).

EQUATION 6.11 (NEW)	
N <sub>2</sub> O EMISSIONS FROM INDUSTRIAL WASTEWATER TREATMENT PLANTS	
$N_2O\ Plants_{IND} = \left[ \sum_i (T_{i,j} \cdot EF_j \cdot TN_{IND,i}) \right] \cdot \frac{44}{28}$	

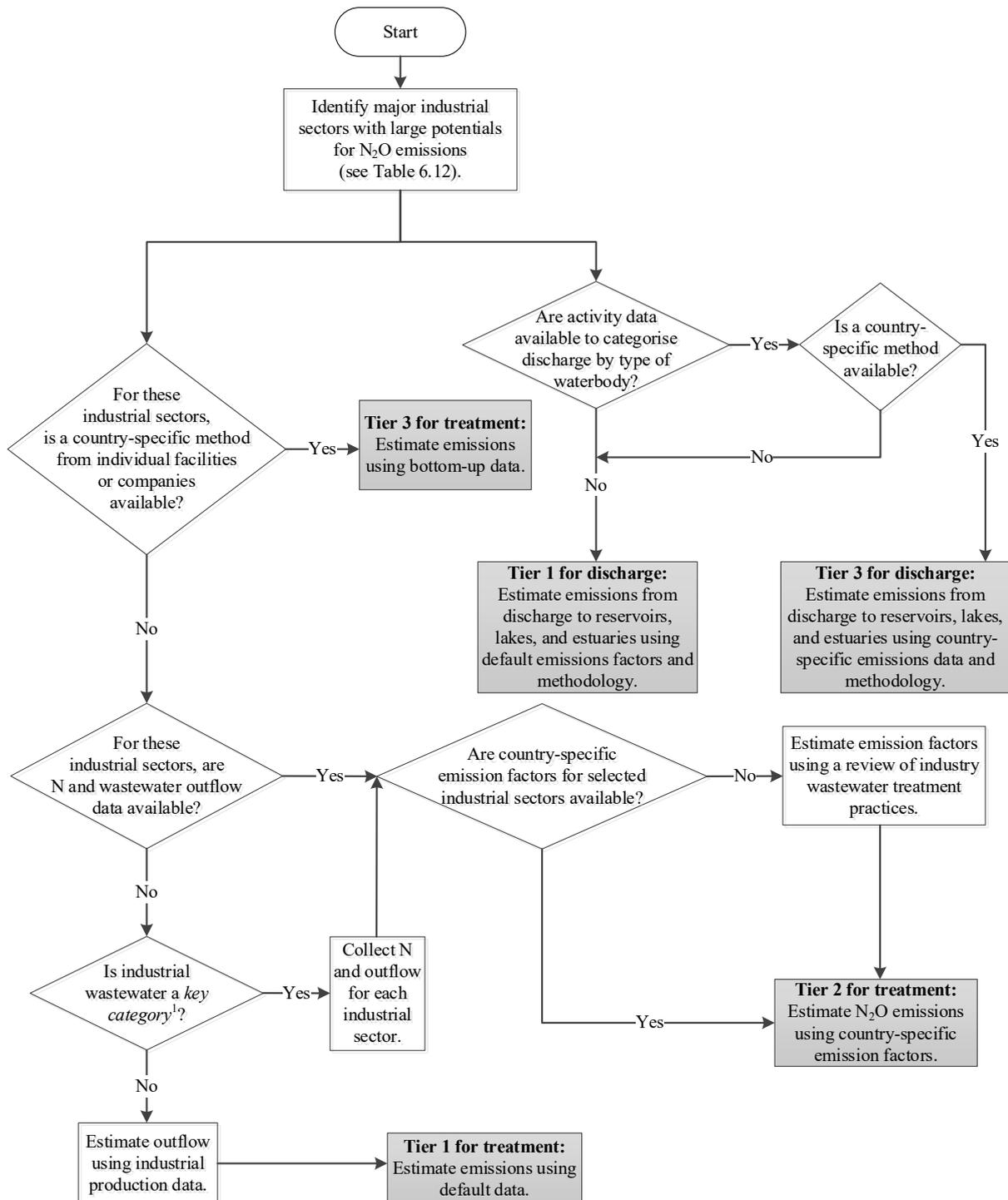
Where:

- N<sub>2</sub>O Plants<sub>IND</sub> = N<sub>2</sub>O emissions from industrial wastewater treatment plants in inventory year, kg N<sub>2</sub>O/yr
- TN<sub>IND*i*</sub> = total nitrogen in wastewater from industry *i* in inventory year, kg N/yr. See new Equation 6.13.
- T<sub>*i,j*</sub> = degree of utilisation of treatment/discharge pathway or system *j*, for each industry *i* in inventory year
- i* = industry

$j$  = each treatment/discharge pathway or system

$EF_j$  = emission factor for treatment/discharge pathway or system  $j$ , kg N<sub>2</sub>O-N/kg N. See Table 6.8a (New).

The factor 44/28 is for the conversion of kg N<sub>2</sub>O-N into kg N<sub>2</sub>O.

Figure 6.6 (New) Decision tree for N<sub>2</sub>O emissions from industrial wastewater

<sup>1</sup> See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

It is also required to estimate N<sub>2</sub>O emissions from wastewater treatment effluent that is discharged into aquatic environments. The methodology for emissions from effluent is like that of N<sub>2</sub>O emissions explained in Volume 4, Section 11.2.2, Chapter 11, N<sub>2</sub>O Emissions from Managed Soils, and CO<sub>2</sub> Emissions from Lime and Urea Application. The simplified general equation is as follows:

**EQUATION 6.12 (NEW)**  
**N<sub>2</sub>O EMISSIONS FROM INDUSTRIAL WASTEWATER EFFLUENT**

$$N_2O_{Effluent_{IND}} = N_{EFFLUENT,IND} \cdot EF_{EFFLUENT} \cdot \frac{44}{28}$$

Where:

$N_2O_{Effluent_{IND}}$  = N<sub>2</sub>O emissions from industrial wastewater effluent in inventory year, kg N<sub>2</sub>O/yr

$N_{EFFLUENT,IND}$  = nitrogen in the industrial wastewater effluent discharged to aquatic environments, kg N/yr. See new Equation 6.14.

$EF_{EFFLUENT}$  = emission factor for N<sub>2</sub>O emissions from wastewater discharged to aquatic systems, kg N<sub>2</sub>O-N/kg N

The factor 44/28 is for the conversion of kg N<sub>2</sub>O-N into kg N<sub>2</sub>O.

### 6.4.1.2 CHOICE OF EMISSION FACTORS

New Table 6.8a includes default EF values for N<sub>2</sub>O emissions.

### 6.4.1.3 CHOICE OF ACTIVITY DATA

#### TOTAL NITROGEN IN INDUSTRIAL WASTEWATER (TN<sub>IND</sub>)

The activity data for this source category is the amount of total nitrogen (TN) in the industrial wastewater entering treatment (TN<sub>IND</sub>). This parameter is a function of industrial output (product) P (tonnes/yr), wastewater generation W (m<sup>3</sup>/ton of product), and total N concentration in the untreated wastewater (kg TN/m<sup>3</sup>). See new Equation 6.13. The following steps are required for determination of TN<sub>IND</sub>:

- (i) Identify the industrial sectors that generate wastewater with large quantities of N, by evaluating total industrial product, N in the wastewater, and wastewater produced.
- (ii) Identify industrial sectors that use treatment systems with N<sub>2</sub>O emissions factors (see new Table 6.8a). Experience has shown that usually three or four industrial sectors are *key*.

For each selected sector estimate total N in the industrial wastewater (TN<sub>IND</sub>).

**EQUATION 6.13 (NEW)**  
**TOTAL NITROGEN IN INDUSTRIAL WASTEWATER**

$$TN_{IND_i} = P_i \cdot W_i \cdot TN_i$$

Where:

$TN_{IND_i}$  = total nitrogen in wastewater entering treatment for industry *i*, kg TN/yr

*i* = industrial sector

$P_i$  = total industrial product for industrial sector *i*, t/yr

$W_i$  = wastewater generated for industrial sector *i*, m<sup>3</sup>/t<sub>product</sub>

$TN_i$  = total nitrogen in untreated wastewater for industrial sector *i*, kg TN/m<sup>3</sup>

Industrial production data and wastewater generation rates may be obtained from national statistics, regulatory agencies, wastewater treatment associations or industry associations. In some cases, quantification of the N loading in the wastewater may require expert judgment. In some countries, N content and total water usage per sector data may be available directly from a regulatory agency. New Table 6.12 provides examples that could be used as default values for industries that may be considered key sources of N<sub>2</sub>O. These values should be used with caution, because they are industry-, process-, and country-specific.

**TABLE 6.12 (NEW)**  
**EXAMPLES OF INDUSTRIAL WASTEWATER DATA**

Industry Type	Wastewater Generation W (m <sup>3</sup> /tonne)	Range for W (m <sup>3</sup> /tonne)	Total Nitrogen (TN) (kg/m <sup>3</sup> )	TN Range (kg/m <sup>3</sup> )
Alcohol refining	24 <sup>2</sup>	16 – 32 <sup>2</sup>	2.4 <sup>2</sup>	0.94 – 3.86 <sup>2</sup>
Beer & malt	6.3 <sup>2</sup>	5.0 – 9.0 <sup>2</sup>	0.055 <sup>3</sup>	0.025 – 0.08 <sup>3</sup>
Fish processing	5 <sup>2</sup>	2 – 8 <sup>2</sup>	0.60 <sup>2</sup>	0.21 – 0.98 <sup>2</sup>
Iron and steel manufacturing	5 <sup>1</sup>	0.004 – 10.4 <sup>4</sup>	0.25 <sup>1</sup>	0.0004 – 0.524 <sup>4</sup>
Meat & poultry	13 <sup>2</sup>	8 – 18 <sup>2</sup>	0.19 <sup>2</sup>	0.17 – 0.20 <sup>2</sup>
Nitrogen fertiliser	2.89 <sup>2</sup>	0.46 – 8.3 <sup>2</sup>	0.5 <sup>2</sup>	0.1 – 0.8 <sup>2</sup>
Plastics & resins	0.6 <sup>5</sup>	0.3 – 1.2 <sup>5</sup>	0.25 <sup>6</sup>	No range provided
Starch production	9 <sup>2</sup>	4 – 18 <sup>2</sup>	0.9 <sup>2</sup>	0.8 – 1.10 <sup>2</sup>

<sup>1</sup> Based on expert judgment by Lead Authors of this section.

<sup>2</sup> IPCC (2014)

<sup>3</sup> Simate *et al.* (2011)

<sup>4</sup> US EPA (2002a)

<sup>5</sup> Doorn *et al.* (1997)

<sup>6</sup> Li *et al.* (2016)

## NITROGEN REMOVED FROM WASTEWATER (N<sub>REM</sub>)

Nitrogen removal by different treatment facilities can range from 10–85 percent. Default values for the fraction of nitrogen removed by type of wastewater treatment system are presented in Table 6.10c.

## NITROGEN IN WASTEWATER EFFLUENT (N<sub>EFFLUENT,IND</sub>)

The total nitrogen in the industrial wastewater effluent is estimated as follows:

**EQUATION 6.14 (NEW)**  
**TOTAL NITROGEN IN INDUSTRIAL WASTEWATER EFFLUENT**

$$N_{EFFLUENT,IND} = \sum_j \left[ TN_{IND,i} \cdot T_j \cdot (1 - N_{REM,j}) \right]$$

Where:

N<sub>EFFLUENT,IND</sub> = total annual amount of nitrogen in the industrial wastewater effluent, kg N/yr

TN<sub>IND,i</sub> = total nitrogen in wastewater entering treatment for industry *i*, kg TN/yr

T<sub>*j*</sub> = degree of utilisation of treatment system *j* in inventory year ( $\sum_i T_{ij}$ ). See Table 6.5.

*j* = each wastewater treatment type used in inventory year

N<sub>REM,j</sub> = fraction of total wastewater nitrogen removed during wastewater treatment per treatment type *j*. See new Table 6.10c.

## 6.4.2 Time series consistency

Once an industrial sector is included in the inventory calculation, it should be included for each subsequent year. If the inventory compiler adds a new industrial sector to the calculation, then he or she should re-calculate the entire time series so that the method is consistent from year to year. General guidance on recalculation of estimates through time series is provided in Volume 1, Chapter 5, Time Series Consistency.

If a country decides to incorporate plant emissions into the estimate, this change must be made for the entire time series. Potential sludge removal should be treated consistently across years in the time series.

### 6.4.3 Uncertainties

Uncertainty estimates for EF, P, W and TN are provided in new Table 6.13. The estimates are based on expert judgment.

Parameter	Uncertainty Range
<b>Emission Factor</b>	
N <sub>2</sub> O emission factor	± 30%
<b>Activity Data</b>	
Industrial production (P)	± 25% Use expert judgment regarding the quality of data source to assign more accurate uncertainty range.
Wastewater/unit production (W)	These data can be very uncertain as the same sector might use different waste handling procedures at different plants and in different countries. The product of the parameters (W•TN) is expected to have less uncertainty. An uncertainty value can be attributed directly to TN concentration. –50 %, +100% is suggested (i.e., a factor of 2).
TN/unit wastewater (TN)	
Source: Expert Judgment by Lead Authors of this section.	

### 6.4.4 QA/QC, Completeness, Reporting and Documentation

#### QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

It is *good practice* to conduct quality control checks and quality assurance procedures as outlined in Chapter 6, QA/QC and Verification, of Volume 1. Below, some fundamental QA/QC procedures include:

- For industrial wastewater, inventory compilers may review the secondary data sets (e.g., from national statistics, regulatory agencies, wastewater treatment associations or industry associations) that are used to estimate and rank industrial TN waste output. Some countries may have regulatory control over industrial discharges, in which cases significant QA/QC protocols may already be in place for the development of the wastewater characteristics on an industry basis.
- For industrial wastewater, inventory compilers should cross-check values for EFs against those from other national inventories with similar wastewater characteristics.
- If sludge removal is reported in the wastewater inventory, check for consistency with the estimates for sludge applied to agriculture soils, sludge incinerated, and sludge deposited in solid waste disposal.
- For countries that use country-specific parameters or higher tier methods, inventory compilers should cross-check the national estimates with emissions using the IPCC default method and parameters.

#### COMPLETENESS

Completeness for estimating emissions from industrial wastewater depends on an accurate characterisation of industrial sectors that produce nitrogen-laden wastewater. In most countries, approximately 3–4 industrial sectors will account for the majority of the nitrogenous wastewater volume, so the inventory compilers should ensure that these sectors are covered. Periodically, the inventory compilers should re-survey industrial sources, particularly if some industries are growing rapidly.

This category should only cover industrial wastewater treated onsite. Emissions from industrial wastewater released into domestic sewer systems should be addressed and included with domestic wastewater.

Some sludge from industrial wastewater treatment may be incinerated or deposited in landfills or on agricultural lands. This constitutes an amount of N that should be subtracted from effluent N. It is *good practice* to be consistent across sectors: the amount of N that is removed as sludge should be equal to the amount of sludge disposed at landfills, applied to agricultural soils, incinerated, or treated elsewhere.

## **REPORTING AND DOCUMENTATION**

It is *good practice* to document and report a summary of the methods used, activity data and emission factors. When country-specific methods and/or emission factors are used, the reasoning for the choices as well as references to how the country-specific data (measurements, literature, expert judgment, etc.) have been derived (measurements, literature, expert judgment, etc.) should be documented and included in the reporting.

If sludge is incinerated, landfilled, or spread on agricultural lands, the quantities of sludge and associated emissions should be reported in the waste incineration, solid waste disposal systems, or agricultural categories, respectively.

More information on reporting and documentation can be found in Volume 1, Chapter 6, Section 6.11 Documentation, archiving and reporting.

## Appendix 6A.1 Non-biogenic (fossil) CO<sub>2</sub> emissions from wastewater treatment and discharge: Basis for Future Methodological Development

The *2006 IPCC Guidelines* assume that organic carbon present in wastewater derives from modern (biogenic) organic matter in human excreta or food waste (Doorn *et al.* 2006). Consequently, CO<sub>2</sub> emissions from wastewater treatment according to those Guidelines are also considered wholly biogenic and are discounted from international greenhouse gas accounting inventories, since they do not represent a transfer of carbon from the lithosphere to the atmosphere. In comparison, fossil organic carbon (that with turnover timescales exceeding 10<sup>6</sup> years) is considered to have a role in climate change and is accounted for in international greenhouse gas emissions inventories. In the *2006 IPCC Guidelines*, it is assumed that emissions from biogas flaring are not significant because the CO<sub>2</sub> emissions are of biogenic origin and the CH<sub>4</sub> and N<sub>2</sub>O emissions are very small so *good practice* in the Waste Sector does not require their estimation. If countries wish to report such emissions, they should be reported under the Waste Sector. A discussion of emissions from flares and more detailed information are given in Volume 2, Energy, Chapter 4.2. However, the presence of fossil organic carbon in sewage also implies the emission of additional fossil CO<sub>2</sub> from wastewater treatment facilities, sludge management, and environmental recipients of treated or untreated wastewater.

Data emerging since the *2006 IPCC Guidelines* indicate that wastewater contains an appreciable amount of non-biogenic (fossil) organic carbon, with this fossil carbon thought to be derived from the use of petroleum-based products (domestically and commercially). These products include: cosmetics; pharmaceuticals; surfactants; detergents and food additives (Law *et al.* 2013). Additionally, direct dosing of synthetic, fossil-derived organic substrates (e.g., methanol) can occur at wastewater treatment plants to enhance denitrification performance (Schneider *et al.* 2015). Despite early indications of the potential for significant fossil organic carbon fractions in sewage sludge (Turekian & Benoit 1981), fossil carbon in wastewater was first detailed by Griffith *et al.* (2009) following the sampling of treated effluent from 12 predominantly domestic wastewater treatment plants within the Hudson and Connecticut River watersheds, USA. Since then, several studies have surveyed fossil organic carbon in wastewater from Japan (Nara *et al.* 2010; Toyoda *et al.* 2011), Australia (Law *et al.* 2013), Denmark (Yoshida *et al.* 2014) and North America (Schneider *et al.* 2015).

Research published since the *2006 IPCC Guidelines* (Griffith *et al.* 2009; Law *et al.* 2013; Yoshida *et al.* 2014; Schneider *et al.* 2015; Tseng *et al.* 2016) gives an emerging consensus figure for the fossil wastewater organic carbon fraction at some 4–14percent; although more recent work suggests this can be as high as 28percent (Tseng *et al.*, 2016) or 51percent (Nara *et al.* 2010; recalculated by Tseng *et al.* 2016) in some influents. Schneider *et al.* (2015) put the fossil content of activated sludge process off-gases at 10–15percent. Law *et al.* (2013) put the subsequent fossil carbon fraction in anaerobic digester biogas CO<sub>2</sub> at 2.1±0.2percent due to greater recalcitrance of fossil carbon during anaerobic digestion, and total additional scope 1 wastewater treatment plant emission load from previously unaccounted fossil carbon somewhere between 2–12percent. Tseng *et al.* (2016) put this figure at some 13 to 24percent higher without and with energy recovery respectively.

Based on the above data, countries are encouraged to evaluate if such emissions should be reported, particularly those countries that have higher levels of fossil carbon in wastewater. In addition, future improvements to the *IPCC Guidelines* should include a method for estimating these non-biogenic emissions associated with wastewater treatment operations and wastewater discharges.

**TABLE 6AP.1 (NEW)**  
**SUMMARY OF LITERATURE INVESTIGATING FOSSIL ORGANIC CARBON IN WASTEWATER**

<b>Wastewater treatment system</b>	<b>Detection/measurement approach</b>	<b>Fossil C fraction in various wastewater streams</b>	<b>Reference</b>	<b>Comments</b>
Effluent from 12 WWTPs (using conventional activated sludge) sampled, USA	Effluent grab samples; <sup>14</sup> C analysed via isotope ratio mass spectrometry	25% of treated wastewater dissolved organic carbon (DOC) and 14% of treated wastewater particulate organic carbon (POC)	Griffith <i>et al.</i> (2009)	WWTPs handle predominantly domestic wastewater. Secondary treated effluent sampled only (i.e. not raw influent), so results may overestimate true fossil carbon fraction in raw sewage, since heterotrophic bacteria are known to preferentially utilize young ( <sup>14</sup> C-enriched) carbon for assimilation (Raymond & Bauer 2001). Average reported effluent DOC concentration was 8.7 mg/L.
Four large activated sludge WWTPs in Brisbane, Australia (two receiving domestic sewage and two receiving 15% industrial load)	Range of sampling locations (influent, primary- and secondary-treated effluent, waste activated sludge (WAS), digested biosolids)	Fossil fraction of total organic carbon (TOC) in domestic WWTP influent 4–7% and 8–14% for WWTPs receiving 15% industrial load (5–14% overall range); ≈29–50% of this influent fossil C is transformed to CO <sub>2</sub> during secondary activated sludge treatment (1.4–6.3% of influent TOC). Higher fossil C fraction in WAS from WWTPs receiving industrial load (8–14%) versus domestic WWTPs (6–7%). 2.1(±0.2)% of biogas CO <sub>2</sub> is fossil in origin.	Law <i>et al.</i> (2013)	Higher fossil C fractions in WWTPs receiving industrial wastewater load. Equivalent concentrations of fossil organic carbon in raw wastewater were between 6–35 mg/L. Majority of fossil organic carbon in raw wastewater is present in particulate form (>80%; 5 to 29 mg/L), whereas dissolved fossil carbon levels are relatively small (1–6 mg/L).
Influent to Avedøre WWTP, Denmark	Single 24-hour flow proportionate composite influent sample collected in February 2013. Radiocarbon isotope ratio method (ASTM-D6866-12).	14(±3)% in influent wastewater	Yoshida <i>et al.</i> (2014)	Avedøre WWTP receives 15% industrial load from adjacent pharmaceuticals industry. Figure of 14% is corrected for cellulosic biogenic carbon from toilet paper which may contain elevated levels of <sup>14</sup> C due to historical atomic bomb detonations and underestimate fossil C fraction.
Modified Ludzack–Ettinger (MLE) activated sludge process with biological nitrification–denitrification, USA	<sup>14</sup> C content of emitted CO <sub>2</sub> measured twice a day for five days in early spring using floating chambers	11.4–15.1% (mean 12.83%) based on measured CO <sub>2</sub> emissions from secondary treatment reactor	Schneider <i>et al.</i> (2015)	
Three municipal WWTPs and waste stabilisation ponds, two industrial WWTPs	Raw and partially treated wastewater, gas and sludge samples taken during 2010–2013	2–28% in the primary influent	Tseng <i>et al.</i> (2016)	Article provides a tabulation of results from 6 separate research papers.

**TABLE 6AP.1 (NEW) (CONTINUED)**  
**SUMMARY OF LITERATURE INVESTIGATING FOSSIL ORGANIC CARBON IN WASTEWATER**

<b>Wastewater treatment system</b>	<b>Detection/measurement approach</b>	<b>Fossil C fraction in various wastewater streams</b>	<b>Reference</b>	<b>Comments</b>
Assumed conventional activated sludge-based WWTP with primary gravity sedimentation, Japan	Fresh domestic sewage, primary-treated and secondary-treated wastewater sampled	$\Delta^{14}\text{C}$ values (‰) of sewage DOC was more negative ( $^{14}\text{C}$ ages in the order of $\approx 1000$ – $5000$ years) than nearby lake and river water; no fossil C fraction given.	Nara <i>et al.</i> (2010)	No information on relative fossil C fraction given.
A2O WWTP, Japan	13 wastewater samples collected along the treatment train during March, 2008	$\delta^{13}\text{C}$ signature of $-50.7$ ‰ (depleted with respect to background air)	Toyoda <i>et al.</i> (2011)	WWTP received municipal wastewater

## Annex 6A.1 Summary data for pit latrine use, no sanitation facility, and groundwater use by country

Country	Data Source <sup>1</sup>	Report Year	Pit Latrine Use for Sanitation (%)	No Sanitation Facility (%)	Groundwater Use for Drinking (%)
Afghanistan	MICS	2010–2011	42.5	17.7	62.9
Albania	DHS	2008–2009	24.0	0.0	20.8
Algeria	MICS	2006	2.2	4.9	13.4
Angola	MICS	2001	31.0	38.7	37.5
Armenia	DHS	2010	30.4	0.0	2.5
Azerbaijan	DHS	2006	58.8	0.3	25.7
Bangladesh	DHS	2007	60.1	7.5	90.8
Belarus	MICS	2005	27.5	0.0	12.5
Belize	MICS	2006	40.7	2.1	7.5
Benin	DHS	2006	11.7	69.5	38.6
Bhutan	MICS	2010	52.7	3.4	1.5
Bolivia	DHS	2008	25.7	28.4	7.9
Bosnia and Herzegovina	MICS	2006	2.5	0.1	15.7
Botswana	MICS	2000	57.2	16.2	2.9
Brazil	DHS	1996	42.2		21.3
Burkina Faso	MICS	2006	1.0	62.6	68.9
Burundi	MICS	2005	92.7	3.0	69.0
Cambodia	DHS	2010	5.7	55.3	50.0
Cameroon	MICS	2006	82.6	7.5	49.9
Central African Republic	MICS	2006	75.4	22.3	69.1
Chad	DHS	2004	24.3	74.1	77.2
China	CHS04	2004	49.9	2.3	20.1
Colombia	DHS	2010	0.7	4.8	3.2
Comoros	MICS	2000	95.0	0.7	7.9
Congo	DHS	2005	84.4	10.2	30.6
Côte d'Ivoire	MICS	2006	42.7	34.0	51.8
Cuba	MICS	2010–2011	25.7	1.0	18.2
Democratic People's Republic of Korea	MICS	2009	37.4	0.0	10.8
Democratic Republic of the Congo	MICS	2010	80.0	14.5	59.1
Djibouti	MICS	2006	73.4	3.9	2.7
Dominican Republic	DHS	2007	47.6	36.0	9.7
Egypt	DHS	2008		0.4	4.0
Eritrea	DHS	2002	9.0	74.3	45.2

<b>Country</b>	<b>Data Source<sup>1</sup></b>	<b>Report Year</b>	<b>Pit Latrine Use for Sanitation (%)</b>	<b>No Sanitation Facility (%)</b>	<b>Groundwater Use for Drinking (%)</b>
Ethiopia	DHS	2011	56.0	38.2	50.6
Gabon	DHS	2000	92.8	3.0	40.0
Gambia	MICS	2005–2006	80.6	4.4	41.0
Georgia	MICS	2005	57.8	0.0	25.7
Ghana	MICS	2010–2011	56.6	0.5	0.1
Guatemala	DHS	1998–1999	40.9	13.2	14.9
Guinea	DHS	2005	67.2	30.3	60.7
Guinea-Bissau	MICS	2006	4.0	31.1	79.1
Guyana	DHS	2009	43.3	1.0	3.5
Haiti	DHS	2005–2006	32.0	0.0	45.0
Honduras	DHS	2005–2006	39.8	16.7	15.8
India	DHS	2005–2006	12.9	56.2	58.6
Indonesia	DHS	2007	3.8	8.1	52.3
Iraq	MICS	2006	28.9	2.5	3.4
Jamaica	MICS	2005	77.2	0.6	3.3
Jordan	DHS	2009	43.5	0.0	0.0
Kazakhstan	MICS	2006	62.3	0.0	22.5
Kenya	DHS	2008–2009	67.3	14.5	41.4
Kyrgyzstan	MICS	2005–2006	82.0	0.1	10.1
Lao People's Democratic Republic	MICS	2006	31.7	50.1	48.7
Lesotho	DHS	2009	66.8	35.6	36.2
Liberia	DHS	2007	20.1	54.7	76.2
Madagascar	DHS	2008–2009	35.1	43.7	53.3
Malawi	DHS	2010	84.9	9.9	75.3
Maldives	DHS	2009	27.8	1.0	1.3
Mali	DHS	2006	60.2	19.6	69.9
Mauritania	MICS	2007	35.1	45.5	37.7
Mongolia	MICS	2005	67.1	13.4	60.7
Montenegro	MICS	2005–2006	7.7	0.3	9.2
Morocco	DHS	2003–2004	1.7	15.9	16.3
Mozambique	MICS	2008	52.7	41.8	55.9
Myanmar	MICS	2009–2010	74.9	7.0	73.6
Namibia	DHS	2006–2007	11.7	53.4	16.6
Nepal	DHS	2011	21.0	38.4	46.9
Nicaragua	DHS	2001	59.1	13.9	25.3
Niger	DHS	2006	21.5	78.0	74.3
Nigeria	MICS	2007	58.9	27.7	47.6
Pakistan	DHS	2006–2007	13.7	28.4	55.6

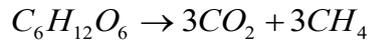
**TABLE 6A.1 (NEW) (CONTINUED)**  
**SUMMARY DATA FOR PIT LATRINE USE, NO SANITATION FACILITY, AND GROUNDWATER USE BY COUNTRY**

Country	Data Source <sup>1</sup>	Report Year	Pit Latrine Use for Sanitation (%)	No Sanitation Facility (%)	Groundwater Use for Drinking (%)
Peru	DHS	2011	1.9	12.0	6.6
Philippines	DHS	2008	11.7	9.6	39.0
Republic of Moldova	DHS	2005	62.5	0.0	56.0
Rwanda	DHS	2010	96.6	1.1	59.0
Samoa	DHS	2009	10.0	0.1	3.8
Sao Tome and Principe	DHS	2008–2009	23.1	57.7	5.9
Senegal	DHS	2010–2011	57.1	16.5	27.6
Serbia	MICS	2010	4.5	0.0	8.5
Sierra Leone	MICS	2010	63.4	28.9	54.1
Somalia	MICS	2006	37.2	53.8	25.6
South Africa	DHS	2003	36.7	8.1	3.8
Sudan	MICS	2000	55.2	32.4	40.7
Suriname	MICS	2006	19.6	6.3	3.1
Swaziland	MICS	2010	69.7	15.4	19.3
Syrian Arab Republic	MICS	2006	18.2	1.0	7.7
Tajikistan	MICS	2005	85.5	0.4	14.2
TFYR Macedonia	MICS	2005	6.9	3.1	7.0
Thailand	MICS	2005–2006	1.4	0.8	12.3
Timor-Leste	DHS	2009–2010	28.0	35.8	48.7
Togo	MICS	2010	31.5	55.7	55.2
Trinidad and Tobago	MICS	2006	15.0	0.1	1.2
Turkey	DHS	2003	22.8	0.5	7.3
Turkmenistan	DHS	2000	71.3	0.6	22.9
Uganda	DHS	2006	66.4	11.8	73.5
Ukraine	DHS	2007	47.2	0.0	28.0
United Republic of Tanzania	DHS	2010	78.8	15.9	48.3
Uzbekistan	MICS	2006	87.4	0.0	20.1
Vanuatu	MICS	2007	77.3	3.2	22.7
Venezuela	MICS	2000	6.7	4.4	2.1
Viet Nam	MICS	2010–2011	18.2	6.4	43.7
Yemen	MICS	2006	42.1	21.4	35.9
Zambia	DHS	2007	57.1	23.5	47.1
Zimbabwe	DHS	2010–2011	42.6	28.3	64.0

Sources:  
<sup>1</sup>MICS: Multiple Indicator Cluster Surveys, UNICEF (<http://www.childinfo.org/mics.html>); DHS: Demographic and Health Surveys, USAID (<http://www.measuredhs.com>); CHS04: Economic, Population, Nutrition, and Health Survey, data accessed from WHO/UNICEF Joint Monitoring Programme reports (<http://wssinfo.org>)

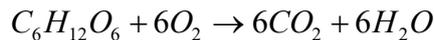
## Annex 6A.2 Derivation of the maximum CH<sub>4</sub> producing potential (B<sub>0</sub>) for domestic wastewater

The maximum CH<sub>4</sub> producing potential (B<sub>0</sub>) for domestic wastewater is calculated theoretically by the anaerobic decomposition of glucose considering the total degradation of organic matter:



One mole of glucose weighs 180 g and produces 3 moles of methane which weighs  $3 \times 16 = 48$  g. Therefore, the methane production rate per gram of glucose is  $48 \text{ g} / 180 \text{ g} = 0.27 \text{ g methane} / \text{g glucose}$ .

The complete oxidation of one mole of glucose (180 g) requires six moles of oxygen ( $6 \times 32 \text{ g} = 192 \text{ g}$ )



Then, the oxygen demand rate per gram of glucose is  $192 \text{ g} / 180 \text{ g} = 1.067 \text{ g oxygen} / \text{g glucose}$

Finally, the maximum CH<sub>4</sub> producing potential (B<sub>0</sub>) for domestic wastewater based of COD content is  $48 \text{ g CH}_4 / 192 \text{ g oxygen} = 0.25 \text{ kg CH}_4 / \text{kg COD}$ .

The COD/BOD ratio of a specific wastewater indicates the amount of organic matter difficult to degrade. For domestic wastewater, a typical COD/BOD ratio is 2.4 based on empirical tests. However, the ratio between the components in any given domestic wastewater stream may vary due to contributions from other sources, particularly wastewater contributions from commercial or industrial sources. The expected range of COD/BOD ratios is between 1.5 and 3.5 (Henze *et al.* 2008).

Inventory compilers should compare country-specific data on COD/BOD ratio in domestic wastewater to IPCC default values of 2.4. If inventory compilers use country-specific COD/BOD ratio, they should provide documented justification why their country-specific values are more appropriate for their national circumstances.

It should be noted that the emission factors are made up of a) the maximum CH<sub>4</sub> producing capacity (B<sub>0</sub>) and b) MCF which indicates the extent to which the B<sub>0</sub> is released in each wastewater treatment/discharge pathways or systems. If a country chooses to introduce country-specific data for B<sub>0</sub> based on measured composition of wastewater, they must also update the MCF because the MCFs were developed using the default B<sub>0</sub> values.

## Annex 6A.3 Estimation of default methane conversion factors for CH<sub>4</sub> in centralised wastewater treatment plants treating domestic wastewater

We reviewed scientific literature to find measured CH<sub>4</sub> emissions from full-scale domestic wastewater treatment plants (excluding anaerobic sludge digestion). Although much literature exists, relatively few studies relate to full-scale treatment plants and provide key information such as influent organics in wastewater or organics removed in sludge. We reviewed and accepted data from 14 wastewater treatment plants. MCFs were calculated from data presented in studies, including measured CH<sub>4</sub> emissions from wastewater treatment plant (not including sludge digesters), influent organics in wastewater, estimates of organics removed in sludge, and the IPCC default B<sub>0</sub> value. Some data were not accepted for use because the treatment system co-treated a significant percentage of non-domestic wastewater, such as food waste. The references used, along with the type of treatment system studied and the resulting MCF, are listed in Table 6A.2. Although CH<sub>4</sub> emissions vary by the type of wastewater treatment system used, more on-site exhaustive monitoring data are required to develop different MCFs for different treatment processes. Overall, an MCF of 0.03 was calculated for aerobic wastewater treatment systems with a standard deviation of 0.024 and a range of 0.003–0.09.

<b>Type of treatment process (Name of plant)</b>	<b>Reference</b>	<b>MCF<sup>1</sup></b>
Activated sludge (Stickney)	Bellucci <i>et al.</i> (2010)	0.017
Activated sludge (Northside)	Bellucci <i>et al.</i> (2010)	0.004
Activated sludge (Egan)	Bellucci <i>et al.</i> (2010)	0.014
Activated sludge	Czepiel <i>et al.</i> (1993)	0.013
Biological nutrient removal (Kralingseveer)	Daelman <i>et al.</i> (2013)	0.03
Biological nutrient removal (Kortenoord)	Daelman <i>et al.</i> (2013)	0.02
Biological nutrient removal (Papendrecht)	Daelman <i>et al.</i> (2013)	0.04
Sequencing batch reactor (Holbæk)	Delre <i>et al.</i> (2017)	0.038
Activated sludge (Källby)	Delre <i>et al.</i> (2017)	0.048
Biological nutrient removal (Lundtofte)	Delre <i>et al.</i> (2017)	0.014
Biological nutrient removal (Lynetten)	Delre <i>et al.</i> (2017)	0.015
Activated sludge	Kozak <i>et al.</i> (2009)	0.09
5-stage Bardenpho	Kyung <i>et al.</i> (2015)	0.07
Anaerobic/anoxic/oxic (A2O) process	Wang <i>et al.</i> (2011)	0.003

<sup>1</sup> MCF shown was calculated from data presented in studies, including measured CH<sub>4</sub> emissions from wastewater treatment plant (not including sludge digesters), influent organics in wastewater, estimates of organics removed in sludge, and the IPCC default B<sub>0</sub> value.

## Annex 6A.4 Calculation of MCF for methane emissions from sewage discharges

Data were obtained from a recent global review article by Deemer *et al.* (2016) for CO<sub>2</sub> and CH<sub>4</sub> emissions from different environments. At equilibrium with current atmospheric conditions, CO<sub>2</sub> is relatively soluble (over 500 µg/L) compared with CH<sub>4</sub> (about 40 ng/L) at 25 degrees Celsius. Therefore, a reliance on studies that only measure diffusive flux will underestimate the relative emission of CH<sub>4</sub>. Deemer *et al.* (2016) raised previous estimates of CH<sub>4</sub> emissions by excluding data from sources that did not include assessment of ebullition. Regarding emissions from all kinds of reservoirs, this exclusion had the effect of increasing the relative CH<sub>4</sub> flux (CH<sub>4</sub>-C/(CH<sub>4</sub>-C + CO<sub>2</sub>-C)) to 27 percent (first data row in Table 6A.3) which is higher than previously thought. For an estimate of this effect on the other data, it is noted that about 52 percent of the data listed by Deemer and colleagues included ebullition, and for this about 40–60 percent of the total ebullitive and diffusive flux was due to ebullition. To illustrate the potential effect of adding ebullition to the *reservoir* studies a scaling factor of  $1.48 = 0.52/1 + 0.48/0.5$  is applied for *reservoirs* and *hydroelectric reservoirs* in the table. Deemer *et al.* (2016) used (Bastviken *et al.* 2011) for an estimate of methane emissions from *lakes* and the original data (Table 1 in Bastviken and colleagues) suggests a smaller correction factor for that *lake* data of 1.23. For rivers, Stanley *et al.* (2016) reports a relationship similar to Deemer *et al.*'s observation – that of total flux, 46 percent is ebullitive among those studies reporting both kinds of fluxes (see Table 1 in Stanley *et al.* 2016). Correcting the average of the larger dataset in Stanley *et al.* (2016) with this figure, suggests a range of riverine yields of 0.4–6 percent. Note that the riverine CO<sub>2</sub> figure in Deemer *et al.* (2016) of 7,954 mg C/m<sup>2</sup>/day was based on original 1,800 Tg C/y datum in Raymond *et al.* (2013), which has been reduced using the Lauerwald *et al.* (2015) updated estimate of 659 Tg C/y figure and is thus 2,872 mg C/m<sup>2</sup>/day.

Considering the data in Table 6A.3, the average yield for reservoirs and lakes is 19percent (8–27 percent) while the average for rivers is much lower at 3.5 percent (0.4–6 percent). Data ranges rather than standard deviations are given owing to the potential for overlap between the underlying datasets. These CH<sub>4</sub> yield data are used to estimate the MCF. On the same basis as the B<sub>0</sub> calculation, 1.067 kg of O<sub>2</sub> are required to oxidise one kg of glucose. Considering that 40 percent of glucose is carbon, this implies the COD of glucose on a carbon basis is 2.67 kg COD/kg C. So 0.19 kg CH<sub>4</sub>-C/kg (CH<sub>4</sub>-C + CO<sub>2</sub>-C) corresponds to 0.071 kg CH<sub>4</sub>-C/kg COD. Taking a global perspective, Tranvik *et al.* (2009) state that approximately 1.4 Pg of carbon is emitted from inland waters at CO<sub>2</sub> and a further 0.1 Pg as CH<sub>4</sub>, the remainder being sequestered in sediments or lost to the ocean. Thus of 3.0 Pg of carbon inputs, 50 percent is emitted to the atmosphere. Correcting the previous figure for this yield and converting to kg CH<sub>4</sub> suggests  $0.071 \text{ [kg CH}_4\text{-C/kg COD]} \times (12.01 + 1.00797 \times 4) / 12.01 \text{ [kg CH}_4\text{/kg CH}_4\text{-C]} \times 0.5 = 0.048 \text{ kg CH}_4\text{/kg COD}$ . For use in conjunction with B<sub>0</sub> then  $\text{MCF} = 0.048 / 0.25 = 0.19$  (0.08–0.27) for lakes and reservoirs. In the same way,  $\text{MCF} = 0.035$  (0.004–0.06) for rivers and streams.

**TABLE 6A.3 (NEW)**  
**SUMMARY OF LITERATURE INVESTIGATING METHANE EMISSIONS FROM WASTEWATER DISCHARGE**

Type of Waterbody	CH <sub>4</sub> flux (mg C/m <sup>2</sup> /day)	<i>n</i> (reservoirs, lakes or rivers)	CH <sub>4</sub> flux corrected for ebullition (mg C/m <sup>2</sup> /day)	CO <sub>2</sub> flux (mg C/m <sup>2</sup> /day)	Yield	Approx. revised yield	Reference
Reservoirs	120	75	120	330	27%	27%	Deemer <i>et al.</i> (2016)
Reservoirs	82–96	161	121–142	498	14–16%	20–22%	CH <sub>4</sub> : Bastviken <i>et al.</i> (2011), St. Louis <i>et al.</i> (2000); CO <sub>2</sub> : St Louis <i>et al.</i> (2000)
Hydroelectric reservoirs	24–112	85, 104	48–224	386–660	6–15%	8–20%	Barros <i>et al.</i> (2011); Li and Zhang (2014)
Lakes	40	66	80	216	16%	19%	CH <sub>4</sub> : Bastviken <i>et al.</i> (2011); CO <sub>2</sub> Raymond <i>et al.</i> (2013)
Rivers	6–98	21, 26	11–183	2872	0.21–3.3%	0.39–6.0%	CH <sub>4</sub> : Bastviken <i>et al.</i> (2011), Stanley <i>et al.</i> 2016; CO <sub>2</sub> : Lauerwald <i>et al.</i> (2015)

## Annex 6A.5 Estimation of default emission factors for N<sub>2</sub>O in domestic wastewater treatment plants

We reviewed scientific literature to find emission factors from full-scale domestic wastewater treatment plants. Although much literature exists regarding N<sub>2</sub>O emission from wastewater treatment processes, relatively few studies relate to full-scale treatment plants and provide key information such as influent nitrogen load. We collected 30 data and found that N<sub>2</sub>O emission correlated with influent nitrogen load (Figure 6A.1). Emission factors and references are listed in Table 6A.4 and Table 6A.5. Specific and relatively new/uncommon treatment processes such as membrane bioreactors were intentionally excluded from this list in order to develop emission factors for the most typical and widely used treatment processes globally. Although N<sub>2</sub>O emissions vary by the type of nitrogen removal process used, more on-site exhaustive monitoring data are required to develop different N<sub>2</sub>O emission factors for different treatment processes.

**Figure 6A.1 (New) Correlation between influent total nitrogen (TN) loading and N<sub>2</sub>O emissions**

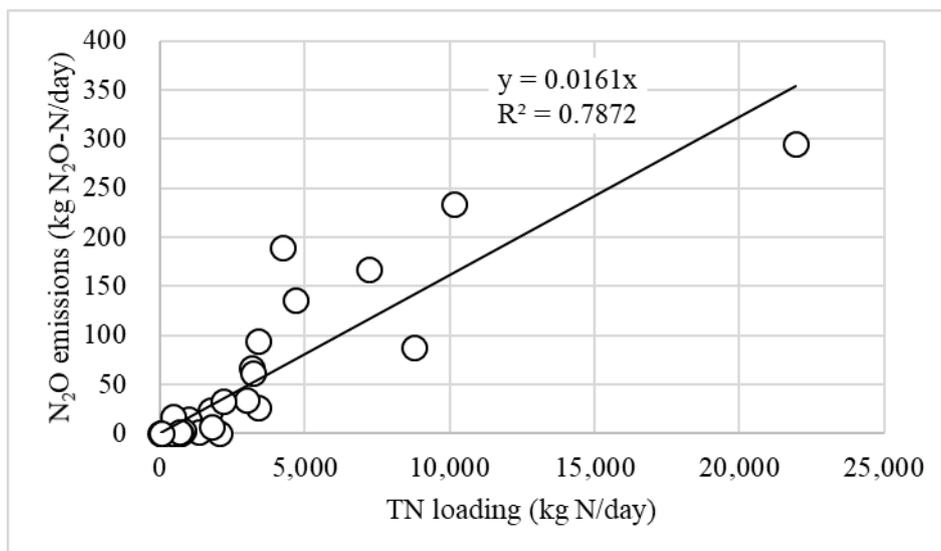


TABLE 6A.4 (NEW)			
DEFAULT N <sub>2</sub> O EMISSION FACTORS FOR DOMESTIC WASTEWATER TREATMENT PLANTS			
N <sub>2</sub> O emission factor (kg N <sub>2</sub> O-N/kg N)	SD	Maximum	Minimum
0.016	0.012	0.045	0.00016

**TABLE 6A.5 (NEW)**  
**N<sub>2</sub>O EMISSION FACTORS IN FULL-SCALE DOMESTIC WASTEWATER TREATMENT PLANTS**

Type of treatment process <sup>1</sup>	Categories	References	N <sub>2</sub> O emission factor (kg N <sub>2</sub> O-N/kg N)
AO	Biological Nitrogen Removal (BNR)	Daelman <i>et al.</i> (2015)	0.028
AO	BNR	Foley <i>et al.</i> (2010)	0.021
AO	BNR	Foley <i>et al.</i> (2010)	0.045
A2O	BNR	Foley <i>et al.</i> (2010)	0.013
SBR	BNR	Foley <i>et al.</i> (2010)	0.023
OD	BNR	Foley <i>et al.</i> (2010)	0.0080
IA	BNR	Kimochi <i>et al.</i> (1998)	0.0005
EA	BNR	Foley <i>et al.</i> (2010)	0.015
A2O	BNR	Wang <i>et al.</i> (2016)	0.013
CAS	BNR	Aboobakar <i>et al.</i> (2013)	0.00036
AO	BNR	Rodriguez-Caballero <i>et al.</i> (2014)	0.00116
OD	BNR	Masuda <i>et al.</i> (2018)	0.00016
AO	BNR	Masuda <i>et al.</i> (2018)	0.0013
AO	BNR	Masuda <i>et al.</i> (2018)	0.0049
Separate-stage BNR	BNR	Ahn <i>et al.</i> (2010)	0.00019
Bardenpho	BNR	Ahn <i>et al.</i> (2010)	0.0036
Step-feed BNR	BNR	Ahn <i>et al.</i> (2010)	0.011
MLE	BNR	Ahn <i>et al.</i> (2010)	0.0007
MLE	BNR	Ahn <i>et al.</i> (2010)	0.0006
OD	BNR	Ahn <i>et al.</i> (2010)	0.0003
Step-feed BNR	BNR	Ahn <i>et al.</i> (2010)	0.015
Step feed, plug flow	BNR	Ni <i>et al.</i> (2015); Pan <i>et al.</i> (2016)	0.019
SBR	BNR	Bao <i>et al.</i> (2016)	0.029
SBR	BNR	Rodriguez-Caballero <i>et al.</i> (2015)	0.038
Plug flow	Non-BNR	Ahn <i>et al.</i> (2010)	0.0041
Plug flow	Non-BNR	Ahn <i>et al.</i> (2010)	0.0036
Step-feed non-BNR	Non-BNR	Ahn <i>et al.</i> (2010)	0.010
Plug flow	Non-BNR	Masuda <i>et al.</i> (2015)	0.023
AO	Non-BNR	Bao <i>et al.</i> (2016)	0.013
IA	Non-BNR	de Mello <i>et al.</i> (2013)	0.0016

<sup>1</sup> AO; Anaerobic-oxic activated sludge process, A2O; Anaerobic-anoxic-oxic activated sludge process, SBR; Sequencing batch reactor, OD; Oxidation ditch, IA; Intermittent aeration process, EA; Extended aeration process, CAS; Conventional activated sludge process, MLE; Modified Ludzack-Ettinger.

## Annex 6A.6 Estimation of default emission factors for N<sub>2</sub>O in effluent

Table 6.11 in the 2006 IPCC Guidelines was based on expert judgment. For the refinement of these guidelines, literature was reviewed for reported yields of N<sub>2</sub>O from environments with known oxygen saturation conditions. A total of 62 data points for well-oxygenated environments and 59 for low-oxygen environments were obtained from the following literature: Kaplan *et al.* (1978); McElroy *et al.* (1978); Goreau *et al.* (1980); McCarthy *et al.* (1984); Seitzinger *et al.* (1984); Kaplan and Wofsy (1985); Seitzinger (1988); Yoshida (1988); Mantoura *et al.* (1993); Kester *et al.* (1997); Seitzinger and Kroeze (1998); Punshon and Moore (2004); Frame and Casciotti (2010); Beaulieu *et al.* (2011); Yan *et al.* (2012); Zhu *et al.* (2013); Ji *et al.* (2015); Wang *et al.* (2015); He *et al.* (2017).

These data suggested a mean yield of 0.019 kg N<sub>2</sub>O-N/kg-N for low oxygen environments (for use in Tier 3 methodologies, if needed) and 0.005 kg N<sub>2</sub>O-N/kg-N for well-oxygenated environments (default Tier 1 factor). Calculation of a simple standard deviation is inappropriate for this data, since it is a proportion. Therefore, confidence intervals for these averages were calculated using the adjusted Wald method for small proportions (Bonett & Price 2012). The resulting 95percent (two tailed) limits are 0.0041–0.0912 and 0.0–0.0753 respectively.

## Annex 6A.7 List of countries by region included in Table 6.10a

Table 6.10a in Section 6.3.1.3 presents default factors for protein consumed as a fraction of protein supplied, fraction of food not consumed and disposed in sewer, and a fraction to represent additional nitrogen introduced to the sewer from household chemicals. The information is provided by geographic region. The list of countries by region can be found in Table 6A.6.

<b>TABLE 6A.6 (NEW)</b> <b>LIST OF COUNTRIES BY REGION INCLUDED IN TABLE 6.10A</b>	
<b>Region</b>	<b>Country</b>
<b>Europe</b>	Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxemburg, Macedonia, Moldova, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
<b>North America and Oceania</b>	Australia, Canada, New Zealand, United States of America
<b>Industrialized Asia</b>	Japan, China, South Korea
<b>Sub-Saharan Africa</b>	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Rep., Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
<b>North Africa, West and Central Asia</b>	Algeria, Egypt, Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Libya, Mongolia, Morocco, Oman, Saudi Arabia, Syria, Tajikistan, Tunisia, Turkey, Turkmenistan, Utd Arab Emirates, Uzbekistan, Yemen
<b>South and Southeast Asia</b>	Afghanistan, Bangladesh, Bhutan, Cambodia, India, Indonesia, Iran, Laos, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Vietnam
<b>Latin America</b>	Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Rep., Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Uruguay, Venezuela

## References

### References newly cited in the 2019 Refinement

- Aboobakar, A., Cartmell, E., Stephenson, T., Jones, M., Vale, P. & Dotro, G. (2013) Nitrous oxide Emissions and Dissolved Oxygen Profiling in a Full-Scale Nitrifying Activated Sludge Treatment Plant. *Water Research* **47**(2): 524-534.
- Ahn, J.H., Kim, S., Park, H., Rahm, B., Pagilla, K. & Chandran, K. (2010) N<sub>2</sub>O Emissions from Activated Sludge Processes, 2008-2009: Results of a National Monitoring Survey in the United States. *Environ Sci Technol* **44**(12): 4505-4511.
- Andreoli, A., Bartilucci, N., Forgione, R. & Reynolds, R. (1979) Nitrogen Removal in a Subsurface Disposal System. *Journal (Water Pollution Control Federation)* **51**(4): 841-854.
- Bao, Z., Sun, S. & Sun, D. (2016) Assessment of Greenhouse Gas Emission from A/O and SBR Wastewater Treatment Plants in Beijing, China. *International Biodeterioration & Biodegradation* **108**: 108-114.
- Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., del Giorgio, P. & Roland, F. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience* **4**: 593.
- Bastviken, D., Tranvik, L.J., Downing, J.A., Crill, P.M. & Enrich-Prast, A. (2011) Freshwater Methane Emissions Offset the Continental Carbon Sink. *Science* **331**(6013): 50.
- Beaulieu, J.J., Tank, J.L., Hamilton, S.K., Wollheim, W.M., Hall, R.O., Mulholland, P.J., Peterson, B.J., Ashkenas, L.R., Cooper, L.W., Dahm, C.N., Dodds, W.K., Grimm, N.B., Johnson, S.L., McDowell, W.H., Poole, G.C., Valett, H.M., Arango, C.P., Bernot, M.J., Burgin, A.J., Crenshaw, C.L., Helton, A.M., Johnson, L.T., O'Brien, J.M., Potter, J.D., Sheibley, R.W., Sobota, D.J. & Thomas, S.M. (2011) Nitrous oxide emission from denitrification in stream and river networks. *Proc. Natl. Acad. Sci. USA* **108**(1): 214-219.
- Bellucci, F., Kozak, J.A., Heraty, L., Carbone, J., Sturchio, N.C., Connor, C., Kollias, L. & Lanyon, R. (2010) Greenhouse Gas Emissions from Three Chicago Wastewater Treatment Plants. In: *Proceedings of the Water Environment Federation, WEFTEC 2010*, pp. 4179-4199. Proceedings of the Water Environment Federation, WEFTEC 2010.
- Bonett, D.G. & Price, R.M. (2012) Adjusted Wald Confidence Interval for a Difference of Binomial Proportions Based on Paired Data. *Journal of Educational and Behavioral Statistics* **37**(4): 479-488.
- Burns, N., McIntosh, J. & Scholes, P. (2009) Strategies for Managing the lakes of the Rotorua District, New Zealand. *Lake and Reservoir Management* **25**(3): 284-296.
- Castro-Morales, K., Macías-Zamora, J.V., Canino-Herrera, S.R. & Burke, R.A. (2014) Dissolved Methane Concentration and Flux in the Coastal Zone of the Southern California Bight-Mexican Sector: Possible Influence of Wastewater. *Estuarine, Coastal and Shelf Science* **144**: 65-74.
- Conrad, R. & Seiler, W. (1988) Methane and hydrogen in seawater (Atlantic Ocean). *Deep Sea Research Part A. Oceanographic Research Papers* **35**(12): 1903-1917.
- Czepiel, P.M., Crill, P.M. & Harriss, R.C. (1993) Methane emissions from municipal wastewater treatment processes. *Environmental Science & Technology* **27**(12): 2472-2477.
- Daelman, M.R., van Voorthuizen, E.M., van Dongen, U.G., Volcke, E.I. & van Loosdrecht, M.C. (2012) Methane Emission During Municipal Wastewater Treatment. *Water Research* **46**(11): 3657-3670.
- Daelman, M.R., van Voorthuizen, E.M., van Dongen, U.G., Volcke, E.I. & van Loosdrecht, M.C. (2015) Seasonal and Diurnal Variability of N<sub>2</sub>O Emissions from a Full-Scale Municipal Wastewater Treatment Plant. *Sci Total Environ* **536**: 1-11.
- Daelman, M.R.J., Voorthuizen, E.M.v., Dongen, L.G.J.M.v., Volcke, E.I.P. & Loosdrecht, M.C.M.v. (2013) Methane and Nitrous Oxide Emissions from Municipal Wastewater Treatment – Results from a Long-Term Study. *Water Science and Technology* **67**(10): 2350-2355.

- Davies, P.S. (2005) The Biological Basis of Wastewater Treatment. In: Strathkelvin Instruments Ltd, Glasgow UK. Available at <<http://www.s-can.nl/media/1000154/thebiologicalbasisofwastewatertreatment.pdf>>.
- de Mello, W.Z., Ribeiro, R.P., Brotto, A.C., Kligerman, D.C., Piccoli, A.d.S. & Oliveira, J.L.M. (2013) Nitrous oxide emissions from an intermittent aeration activated sludge system of an urban wastewater treatment plant. *Química Nova* **36**: 16-20.
- Deemer, B.R., Harrison, J.A., Li, S.Y., Beaulieu, J.J., Delsontro, T., Barros, N., Bezerra-Neto, J.F., Powers, S.M., dos Santos, M.A. & Vonk, J.A. (2016) Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. *Bioscience* **66**(11): 949-964.
- Delre, A., Mønster, J. & Scheutz, C. (2017) Greenhouse gas emission quantification from wastewater treatment plants, using a tracer gas dispersion method. *Science of The Total Environment* **605-606**: 258-268.
- Diaz, R., Selman, M. & Chique, C. (2011) Global Eutrophic and Hypoxic Coastal Systems. World Resources Institute. Eutrophication and Hypoxia: Nutrient Pollution in Coastal Waters. In: World Resources Institute, <<https://www.wri.org/resources/data-sets/eutrophication-hypoxia-map-data-set>>.
- Diaz-Valbuena, L.R., Leverenz, H.L., Cappa, C.D., Tchobanoglous, G., Horwath, W.R. & Darby, J.L. (2011) Methane, Carbon dioxide, and Nitrous Oxide Emissions from Septic Tank Systems. *Environ Sci Technol* **45**(7): 2741-2747.
- Dodds, W.K., Jones, J.R. & Welch, E.B. (1998) Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. *Water Research* **32**(5): 1455-1462.
- Doorn, M.R.J., Strait, R.P., Barnard, W. & Eklund, B. (1997) Estimate of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. In: U.S. EPA Office of Research and Development, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-97-091, September 1997.
- Doorn, M.R.J., Towprayoon, S., Vieira, S.M.M., Irving, W., Palmer, C., Pipatti, R. & Wang, C. (2006) Chapter 6: Wastewater Treatment and Discharge. In: *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 5 - Waste*, eds. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe, The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.
- Ekama, G.A. & Wentzel, M.C. (2008) *Organic Matter Removal. In: Biological Wastewater Treatment: Principles, Modelling and Design*. Henze, M., van Loosdrecht, M.C.M., Ekama, G.A. and Brdjanovic, D. (Eds), pp. 53-86. IWA Publishing.
- EMEP/EAA. (2016) 2016 EMEP/EEA air pollutant emission inventory guidebook: 5.D Wastewater handling. In: European Environment Agency, Publications Office of the European Union, Luxembourg. Available at <<https://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/5-waste/5-d-wastewater-handling-2016/view>>.
- EPA. (2008) Examining the Use of Food Waste Disposers. In: Environmental Protection Agency (EPA), Ireland.
- FAO. (2011) Global food losses and food waste – Extent, causes and prevention. In: Food and Agriculture Organization of the United Nations, Rome.
- Foladori, P., Andreottola, G. & Ziglio, G. (2010) Sludge composition and production in full-plants. In: *Sludge Reduction Technologies in Wastewater Treatment Plants*, pp. 6-19. IWA Publishing, London, UK.
- Foley, J., de Haas, D., Yuan, Z. & Lant, P. (2010) Nitrous Oxide Generation in Full-Scale Biological Nutrient Removal Wastewater Treatment Plants. *Water Research* **44**(3): 831-844.
- Foley, J., Yuan, Z., Keller, J., Senante, E., Chandran, K., Willis, J., Shah, A., Loosdrecht, M.v. & Voorthuizen, E.v., eds. (2015) *N<sub>2</sub>O and CH<sub>4</sub> Emission from Wastewater Collection and Treatment Systems: State of the Science Report and Technical Report*. GWRC Report Series. IWA Publishing, London, UK.

- Frame, C.H. & Casciotti, K.L. (2010) Biogeochemical Controls and Isotopic Signatures of Nitrous Oxide Production by a Marine Ammonia-Oxidizing Bacterium. *Biogeosciences* **7**(9): 2695-2709.
- Goreau, T.J., Kaplan, W.A., Wofsy, S.C., McElroy, M.B., Valois, F.W. & Watson, S.W. (1980) Production of  $\text{NO}_2^-$  and  $\text{N}_2\text{O}$  by nitrifying bacteria at reduced concentrations of oxygen. *Applied and Environmental Microbiology* **40**(3): 526-532.
- Graham, J.P. & Polizzotto, M.L. (2013) Pit Latrines and their Impacts on Groundwater Quality: A Systematic Review. *Environ Health Perspect* **121**(5): 521-530.
- Griffith, D.R., Barnes, R.T. & Raymond, P.A. (2009) Inputs of Fossil Carbon from Wastewater Treatment Plants to U.S. Rivers and Oceans. *Environmental Science & Technology* **43**(15): 5647-5651.
- Grunwald, M., Dellwig, O., Beck, M., Dippner, J.W., Freund, J.A., Kohlmeier, C., Schnetger, B. & Brumsack, H.J. (2009) Methane in the Southern North Sea: Sources, Spatial Distribution and Budgets. *Estuarine Coastal and Shelf Science* **81**(4): 445-456.
- Guisasola, A., de Haas, D., Keller, J. & Yuan, Z. (2008) Methane formation in sewer systems. *Water Research* **42**(6-7): 1421-1430.
- Hammer, M.J. & Hammer Jr., M.J. (2012) *Water and wastewater technology* Pearson Prentice Hall, Upper Saddle River, N.J.
- He, Y., Wang, X., Chen, H., Yuan, X., Wu, N., Zhang, Y., Yue, J., Zhang, Q., Diao, Y. & Zhou, L. (2017) Effect of Watershed Urbanization on  $\text{N}_2\text{O}$  Emissions from the Chongqing Metropolitan River Network, China. *Atmospheric Environment* **171**: 70-81.
- Henze, M., Loosdrecht, M.C.M.v., Ekama, G.A. & Brdjanovic, D. (2008) *Biological Wastewater Treatment: Principles Modelling and Design*. London, UK: IWA Publishing.
- IPCC. (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. In: eds. T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda & T. Troxler, p. 354. The Intergovernmental Panel on Climate Change (IPCC), Switzerland.
- Ji, Q., Babbin, A.R., Jayakumar, A., Oleynik, S. & Ward, B.B. (2015) Nitrous Oxide Production by Nitrification and Denitrification in the Eastern Tropical South Pacific Oxygen Minimum Zone. *Geophysical Research Letters* **42**(24): 10,755-710,764.
- Jugold, A., Althoff, F., Hurkuck, M., Greule, M., Lenhart, K., Lelieveld, J. & Keppler, F. (2012) Non-microbial methane formation in oxic soils. *Biogeosciences* **9**(12): 5291-5301.
- Kaplan, W.A., Elkins, J.W., Kolb, C.E., McElroy, M.B., Wofsy, S.C. & Durán, A.P. (1978) Nitrous oxide in fresh water systems: An estimate for the yield of atmospheric  $\text{N}_2\text{O}$  associated with disposal of human waste. *Pure and Applied Geophysics* **116**(2): 423-438.
- Kaplan, W.A. & Wofsy, S.C. (1985) The Biogeochemistry of Nitrous Oxide: a Review. *Advances in Aquatic Microbiology* **3**: 181-202.
- Kester, R.A., de Boer, W. & Laanbroek, H.J. (1997) Production of  $\text{NO}$  and  $\text{N}_2\text{O}$  by pure cultures of nitrifying and denitrifying bacteria during changes in aeration. *Applied and Environmental Microbiology* **63**(10): 3872-3877.
- Kimochi, Y., Inamori, Y., Mizuochi, M., Xu, K.-Q. & Matsumura, M. (1998) Nitrogen Removal and  $\text{N}_2\text{O}$  Emission in a Full-Scale Domestic Wastewater Treatment Plant with Intermittent Aeration. *Journal of Fermentation and Bioengineering* **86**(2): 202-206.
- Kozak, J.A., O'Connor, C., Granato, T., Kollias, L., Belluci, F. & Sturchio, N. (2009) Methane and Nitrous Oxide Emissions from Wastewater Treatment Plant Processes. In: *Proceedings of the Water Environment Federation, WEFTEC 2009*, pp. 5347-5361.

- Kristensen, P., Fribourg-Blanc & Nixon, S. (2004) Outlook on Nutrient Discharges in Europe from Urban Waste Water Treatment Plants (final draft). In: European Environment Agency. EEA European Topic Centre on Water, Copenhagen, 33 p.
- Kyung, D., Kim, M., Chang, J. & Lee, W. (2015) Estimation of Greenhouse Gas Emissions from a Hybrid Wastewater Treatment Plant. *Journal of Cleaner Production* **95**: 117-123.
- Lauerwald, R., Laruelle, G.G., Hartmann, J., Ciais, P. & Regnier, P.A.G. (2015) Spatial patterns in CO<sub>2</sub> evasion from the global river network. *Global Biogeochemical Cycles* **29**(5): 534-554.
- Law, Y., Jacobsen, G.E., Smith, A.M., Yuan, Z. & Lant, P. (2013) Fossil organic carbon in wastewater and its fate in treatment plants. *Water Research* **47**(14): 5270-5281.
- Leverenz, H.L., Tchobanoglous, G. & Darby, J.L. (2010) Evaluation of Greenhouse Gas Emissions from Septic Systems, Water Environment Research Foundation Final Report. . In: Co-published by IWA Publishing, London, UK.
- Li, E., Chao, P. & Chow, B. (2016) British Petroleum/Shanghai SECCO Acrylonitrile Plant Wastewater Reuse Project. *Proceedings of the Water Environment Federation* **2016**(7): 3119-3128.
- Li, S. & Zhang, Q. (2014) Carbon emission from global hydroelectric reservoirs revisited. *Environmental Science and Pollution Research* **21**(23): 13636-13641.
- Mantoura, R.F.C., Law, C.S., Owens, N.J.P., Peter, Burkill, H., Woodward, E.M.S., Howland, R.J.M. & Llewellyn, C.A. (1993) Nitrogen Biogeochemical Cycling in the Northwestern Indian Ocean. *Deep-Sea Research II* **40**: 651-671.
- Masuda, S., Sano, I., Hojo, T., Li, Y.Y. & Nishimura, O. (2018) The Comparison of Greenhouse Gas Emissions in Sewage Treatment Plants with Different Treatment Processes. *Chemosphere* **193**: 581-590.
- Masuda, S., Suzuki, S., Sano, I., Li, Y.Y. & Nishimura, O. (2015) The Seasonal Variation of Emission of Greenhouse Gases from a Full-Scale Sewage Treatment Plant. *Chemosphere* **140**: 167-173.
- Mateo-Sagasta, J. & Burke, J. (2010) Agriculture and Water Quality Interactions: A Global Review. In: SOLAW Background Thematic Report - TR08. Food and Agriculture Organisation of the United Nations. Available at <<http://www.fao.org/3/a-bl092e.pdf>>.
- McCarthy, J.J., Kaplan, W. & Nevins, J.L. (1984) Chesapeake Bay Nutrient and Plankton Dynamics. 2. Sources and Sinks of Nitrite. *Limnology and Oceanography* **29**: 84-98.
- McElroy, M.B., Elkins, J.W., Wofsy, S.C., Kolb, C.E., Dura'n, A.P. & Kaplan, W.A. (1978) Production and Release of N<sub>2</sub>O from the Potomac Estuary. *Limnology and Oceanography* **23**(6): 1168-1182.
- Naqvi, S.W.A., Bange, H.W., Farias, L., Monteiro, P.M.S., Scranton, M.I. & Zhang, J. (2010) Marine hypoxia/anoxia as a source of CH<sub>4</sub> and N<sub>2</sub>O. *Biogeosciences* **7**(7): 2159-2190.
- Nara, F.W., Imai, A., Matsushige, K., Komatsu, K., Kawasaki, N. & Shibata, Y. (2010) Radiocarbon measurements of dissolved organic carbon in sewage-treatment-plant effluent and domestic sewage. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **268**(7): 1142-1145.
- Ni, B.J., Pan, Y., van den Akker, B., Ye, L. & Yuan, Z. (2015) Full-Scale Modeling Explaining Large Spatial Variations of Nitrous Oxide Fluxes in a Step-Feed Plug-Flow Wastewater Treatment Reactor. *Environ Sci Technol* **49**(15): 9176-9184.
- Oudot, C., Jean-Baptiste, P., Fourré, E., Mormiche, C., Guevel, M., Ternon, J.-F.-c. & Corre, P.L. (2002) Transatlantic Equatorial Distribution of Nitrous Oxide and Methane. *Deep-Sea Research Part I: Oceanographic Research Papers* **49**(7): 1175-1193.

- Pan, Y., van den Akker, B., Ye, L., Ni, B.J., Watts, S., Reid, K. & Yuan, Z. (2016) Unravelling the Spatial Variation of Nitrous Oxide Emissions from a Step-Feed Plug-Flow Full Scale Wastewater Treatment Plant. *Scientific Report* **6**: 20792.
- Patra, P.K., Lal, S., Venkataramani, S., Gauns, M. & Sarma, V.V.S.S. (1998) Seasonal Variability in Distribution and Fluxes of Methane in the Arabian Sea. *Journal of Geophysical Research-Oceans* **103**(C1): 1167-1176.
- Pescod, M.B. (1992) *Wastewater treatment and use in agriculture - FAO irrigation and drainage paper 47*. Rome, Italy: Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla.
- Punshon, S. & Moore, R.M. (2004) Nitrous oxide production and consumption in a eutrophic coastal embayment. *Marine Chemistry* **91**(1-4): 37-51.
- Rabalais, N.N., Díaz, R.J., Levin, L.A., Turner, R.E., Gilbert, D. & Zhang, J. (2010) Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences* **7**(2): 585-619.
- Raymond, P.A. & Bauer, J.E. (2001) Use of  $^{14}\text{C}$  and  $^{13}\text{C}$  Natural Abundances for Evaluating Riverine, Estuarine, and Coastal DOC and POC Sources and Cycling: A Review and Synthesis. *Organic Geochemistry* **32**: 469-485.
- Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P. & Guth, P. (2013) Global carbon dioxide emissions from inland waters. *Nature* **503**: 355.
- Rodriguez-Caballero, A., Aymerich, I., Marques, R., Poch, M. & Pijuan, M. (2015) Minimizing  $\text{N}_2\text{O}$  Emissions and Carbon Footprint on a Full-Scale Activated Sludge Sequencing Batch Reactor. *Water Res* **71**: 1-10.
- Rodriguez-Caballero, A., Aymerich, I., Poch, M. & Pijuan, M. (2014) Evaluation of process conditions triggering emissions of green-house gases from a biological wastewater treatment system. *Sci Total Environ* **493**: 384-391.
- Schaidt, L.A., Rodgers, K.M. & Rudel, R.A. (2017) Review of Organic Wastewater Compound Concentrations and Removal in Onsite Wastewater Treatment Systems. *Environ Sci Technol* **51**(13): 7304-7317.
- Schneider, A.G., Townsend-Small, A. & Rosso, D. (2015) Impact of direct greenhouse gas emissions on the carbon footprint of water reclamation processes employing nitrification–denitrification. *Science of the Total Environment* **505**: 1166-1173.
- Seitzinger, S.P. (1988) Denitrification in Freshwater and Coastal Marine Ecosystems: Ecological and Geochemical Significance. *Limnol. Oceanogr.* **33**(4, part 2): 702-724.
- Seitzinger, S.P. & Kroeze, C. (1998) Global Distribution of Nitrous Oxide Production and N Inputs in Freshwater and Coastal Marine Ecosystems. *Global Biogeochemical Cycles* **12**(1): 911-917.
- Seitzinger, S.P., Nixon, S.W. & Pilson, M.E.Q. (1984) Denitrification and Nitrous Oxide Production in a Coastal Marine Ecosystem. *Limnology and Oceanography* **29**(1): 73-83
- Serón, N., Puig, S., Meijer, S.C.F., Balaguer, M.D. & Colprim, J. (2011) Sludge production based on organic matter and nitrogen removal performances. *Water Practice and Technology* **6**(2): wpt2011029.
- Short, M.D., Daikeler, A., Peters, G.M., Mann, K., Ashbolt, N.J., Stuetz, R.M. & Peirson, W.L. (2014) Municipal Gravity Sewers: an Unrecognised Source of Nitrous Oxide. *Sci Total Environ* **468-469**: 211-218.
- Short, M.D., Daikeler, A., Wallis, K., Peirson, W.L. & Peters, G.M. (2017) Dissolved Methane in the Influent of Three Australian Wastewater Treatment Plants Fed by Gravity Sewers. *Sci Total Environ* **599-600**: 85-93.
- Simate, G.S., Cluett, J., Iyuke, S.E., Musapatika, E.T., Ndlovu, S., Walubita, L.F. & Alvarez, A.E. (2011) The treatment of brewery wastewater for reuse: State of the art. *Desalination* **273**(2): 235-247.

- Smith, R.M., Kaushal, S.S., Beaulieu, J.J., Pennino, M.J. & Welty, C. (2017) Influence of infrastructure on water quality and greenhouse gas dynamics in urban streams. *Biogeosciences* **14**(11): 2831-2849.
- St. Louis, V.L., Kelly, C.A., Duchemin, É., Rudd, J.W.M. & Rosenberg, D.M. (2000) Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate. *Bioscience* **50**(9): 766-775.
- Stanley, E.H., Casson, N.J., Christel, S.T., Crawford, J.T., Loken, L.C. & Oliver, S.K. (2016) The ecology of methane in streams and rivers: patterns, controls, and global significance. *Ecological Monographs* **86**(2): 146-171.
- Tchobanoglous, G., Stensel, H., Tsuchihashi, R., Burton, F., Abu-Orf, M., Bowden, G. & Pfrang, W. (2014) *Wastewater Engineering: Treatment and Resource Recovery*. New York: McGraw Hill.
- Tilbrook, B.D. & Karl, D.M. (1995) Methane Sources, Distributions and Sinks from California Coastal Waters to the Oligotrophic North Pacific Gyre. *Marine Chemistry* **49**(1): 51-64.
- Tjandraatmadja, G., Diaper, C., Gozukara, Y., Burch, L., Sheedy, C. & Price, G. (2008) Sources of critical contaminants in domestic wastewater: contaminant contribution from household products. In: CSIRO: Water for a Healthy Country National Research Flagship Report.
- Toyoda, S., Suzuki, Y., Hattori, S., Yamada, K., Fujii, A., Yoshida, N., Kouno, R., Murayama, K. & Shiomi, H. (2011) Isotopomer Analysis of Production and Consumption Mechanisms of N<sub>2</sub>O and CH<sub>4</sub> in an Advanced Wastewater Treatment System. *Environmental Science & Technology* **45**(3): 917-922.
- Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larsen, S., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Prairie, Y., Renwick, W.H., Roland, F., Sherman, B.S., Schindler, D.W., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E. & Weyhenmeyer, G.A. (2009) Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography* **54**(6part2): 2298-2314.
- Truhlar, A.M., Rahm, B.G., Brooks, R.A., Nadeau, S.A., Makarsky, E.T. & Walter, M.T. (2016) Greenhouse Gas Emissions from Septic Systems in New York State. *J Environ Qual* **45**(4): 1153-1160.
- Tseng, L.Y., Robinson, A.K., Zhang, X., Xu, X., Southon, J., Hamilton, A.J., Sobhani, R., Stenstrom, M.K. & Rosso, D. (2016) Identification of Preferential Paths of Fossil Carbon within Water Resource Recovery Facilities via Radiocarbon Analysis. *Environ Sci Technol* **50**(22): 12166-12178.
- Turekian, K.K. & Benoit, G.J. (1981) Radiocarbon in New York Bight sediments and the use of carbon isotopes in delineating carbon sources. In: *Proceedings of Flux of Organic Carbon by Rivers to the Oceans, Woods Hole, MA, USA, 21-25 September*, pp. 314-330. Carbon Dioxide Effects Research and Assessment Program. United States Department of Energy, Springfield.
- US EPA. (2002a) Development Document for Final Effluent Limitations Guidelines and Standards for the Iron and Steel Manufacturing Point Source Category. In: U.S. Environmental Protection Agency, Office of Water (4303T), Washington, DC 20460. EPA-821-R-02-004.
- US EPA. (2002b) Wastewater Technology Fact Sheet: Facultative Lagoons. In: United States Environmental Protection Agency, Office of Water, EPA 832-F-02-014.
- Van Drecht, G., Bouwman, A.F., Harrison, J. & Knoop, J.M. (2009) Global Nitrogen and Phosphate in Urban Wastewater for the Period 1970 to 2050. *Global Biogeochemical Cycles* **23**, GB0A03.(4).
- Vaquer-Sunyer, R. & Duarte, C.M. (2008) Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences* **105**(40): 15452.
- Wang, J., Chen, N., Yan, W., Wang, B. & Yang, L. (2015) Effect of Dissolved Oxygen and Nitrogen on Emission of N<sub>2</sub>O from Rivers in China. *Atmospheric Environment* **103**: 347-356.
- Wang, J., Zhang, J., Xie, H., Qi, P., Ren, Y. & Hu, Z. (2011) Methane Emissions from a Full-Scale A/A/O Wastewater Treatment Plant. *Bioresour Technol* **102**(9): 5479-5485.

- Wang, Y., Lin, X., Zhou, D., Ye, L., Han, H. & Song, C. (2016) Nitric Oxide and Nitrous Oxide Emissions from a Full-Scale Activated Sludge Anaerobic/Anoxic/Oxic Process. *Chemical Engineering Journal* **289**: 330-340.
- Ward, B.B., Kilpatrick, K.A., Novelli, P.C. & Scranton, M.I. (1987) Methane oxidation and methane fluxes in the ocean surface layer and deep anoxic waters. *Nature* **327**(6119): 226-229.
- Ward, N.D., Bianchi, T.S., Medeiros, P.M., Seidel, M., Richey, J.E., Keil, R.G. & Sawakuchi, H.O. (2017) Where Carbon Goes When Water Flows: Carbon Cycling across the Aquatic Continuum. *Frontiers in Marine Science* **4**: 1-27.
- WEF. (2009) Following the Flow- An Inside Look at Wastewater Treatment. In: Water Environment Federation (WEF), Alexandria, Virginia, USA.
- WEF. (2010) Wastewater Treatment Operator Training Manual: Fundamentals of Utility Management. In: Water Environment Federation (WEF), Alexandria, Virginia, USA.
- Willis, J.L. (2017) GHG Methodologies for Sewer CH<sub>4</sub>, Methanol-Use CO<sub>2</sub> and Biogas-Combustion CH<sub>4</sub> and their Significance for Centralized Wastewater Treatment. In: School of Chemical Engineering, The University of Queensland. PhD Thesis. Available at [https://espace.library.uq.edu.au/view/UQ:705938/S42830878\\_final\\_thesis.pdf](https://espace.library.uq.edu.au/view/UQ:705938/S42830878_final_thesis.pdf).
- Wisconsin Department of Natural Resources. (2010) Advanced Activated Sludge Study Guide: December 2010 Edition. In: Wisconsin Department of Natural Resources, Bureau of Science Services, Madison, WI 53707. Available at <http://dnr.wi.gov/regulations/opcert/documents/wwsgactsludgeadv.pdf>.
- Xie, H. & Ringler, C. (2017) Agricultural nutrient loadings to the freshwater environment: the role of climate change and socioeconomic change. *Environmental Research Letters* **12**(10): 104008.
- Yan, W., Yang, L., Wang, F., Wang, J. & Ma, P. (2012) Riverine N<sub>2</sub>O concentrations, exports to estuary and emissions to atmosphere from the Changjiang River in response to increasing nitrogen loads. *Global Biogeochemical Cycles* **26**(4): GB4006.
- Yoshida, H., Clavreul, J., Scheutz, C. & Christensen, T.H. (2014) Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant. *Water Research* **56**(0): 292-303.
- Yoshida, N. (1988) N-depleted N<sub>2</sub>O as a product of nitrification. *Nature* **335**: 528-529.
- Zhu, X., Burger, M., Doane, T.A. & Horwath, W.R. (2013) Ammonia Oxidation Pathways and Nitrifier Denitrification are Significant Sources of N<sub>2</sub>O and NO Under Low Oxygen Availability. *Proc Natl Acad Sci U S A* **110**(16): 6328-6333.

#### References copied from the 2006 IPCC Guidelines

- Destatis (2001). "Öffentliche Wasserversorgung und Abwasserbeseitigung 2001, Tabelle 1 "Übersichtstabelle Anschlussgrade" (Statistical Office Germany (<http://www.destatis.de/>))
- Doorn, M.R.J., Strait, R., Barnard, W. and Eklund, B. (1997). *Estimate of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*, Final Report, EPA-600/R-97-091, Prepared for United States Environmental Protection Agency, Research Triangle Park, NC, USA.
- Doorn, M.R.J. and Liles, D. (1999). Global Methane, Quantification of Methane Emissions and Discussion of Nitrous Oxide, and Ammonia Emissions from Septic Tanks, Latrines, and Stagnant Open Sewers in the World. EPA-600/R-99-089, Prepared for U.S. EPA, Research Triangle Park, NC, USA.
- Feachem, R.G., Bradley, D.J., Garelick H. and Mara D.D. (1983). *Sanitation and Disease – Health Aspects of Excreta and Wastewater Management*, World Bank, John Wiley & Sons, USA.
- Masotti, L. (1996). "Depurazione delle acque. Tecniche ed impianti per il trattamento delle acque di rifiuto". Eds Calderini. pp. 29-30
- Metcalf & Eddy, Inc. (2003) *Wastewater Engineering: Treatment, Disposal, Reuse*. McGraw-Hill: New York.

United Nations (2002). World Urbanization Prospects, The 2001 Revision Data Tables and Highlights. Population Division, Department of Economic and Social Affairs, United Nations Secretariat. ESA/P/WP.173. March 2002.