CHAPTER 6

CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

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6.1 INTRODUCTION

6.1.1 Constructed Wetlands for Wastewater Treatment

Wetland ecosystems can act as sources, sinks, or transformers of nutrients and carbon (C) (Mitsch and Gossenlink, 1993). This ability of wetlands has led to a widespread use of natural and constructed wetlands (CWs) for water quality improvement (Brix, 1997).

Constructed wetlands systems are fully human-made wetlands for wastewater treatment, which apply various technological designs, using natural wetland processes, associated with wetland hydrology, soils, microbes and plants. Thus, CWs are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater. Synonymous terms to “constructed” include “man-made”, “engineered” or “artificial” (Vymazal, 2007).

"Semi-natural treatment wetlands" (SNTWs) for wastewater treatment are natural wetland systems that have been modified for this purpose. The modifications made within these systems usually are based on increasing the volume of water reserved (i.e. dams) and constructing channels for targeting the influent and effluent. These systems can be found in both freshwater and coastal wetlands. The functioning of SNTWs is similar to that of surface flow CWs.

This chapter only provides guidance for CWs and SNTWs for wastewater treatment. Decision tree for finding the appropriate guidance chapter within this supplement or the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) is provided as Figure 1.1 in Chapter 1 of this supplement.

Emissions from CWs and SNTWs must be reported in waste sector. If freshwater and coastal wetlands are modified to SNTWs, inventory compilers should check with relevant land-use category in this supplement to avoid double-counting.

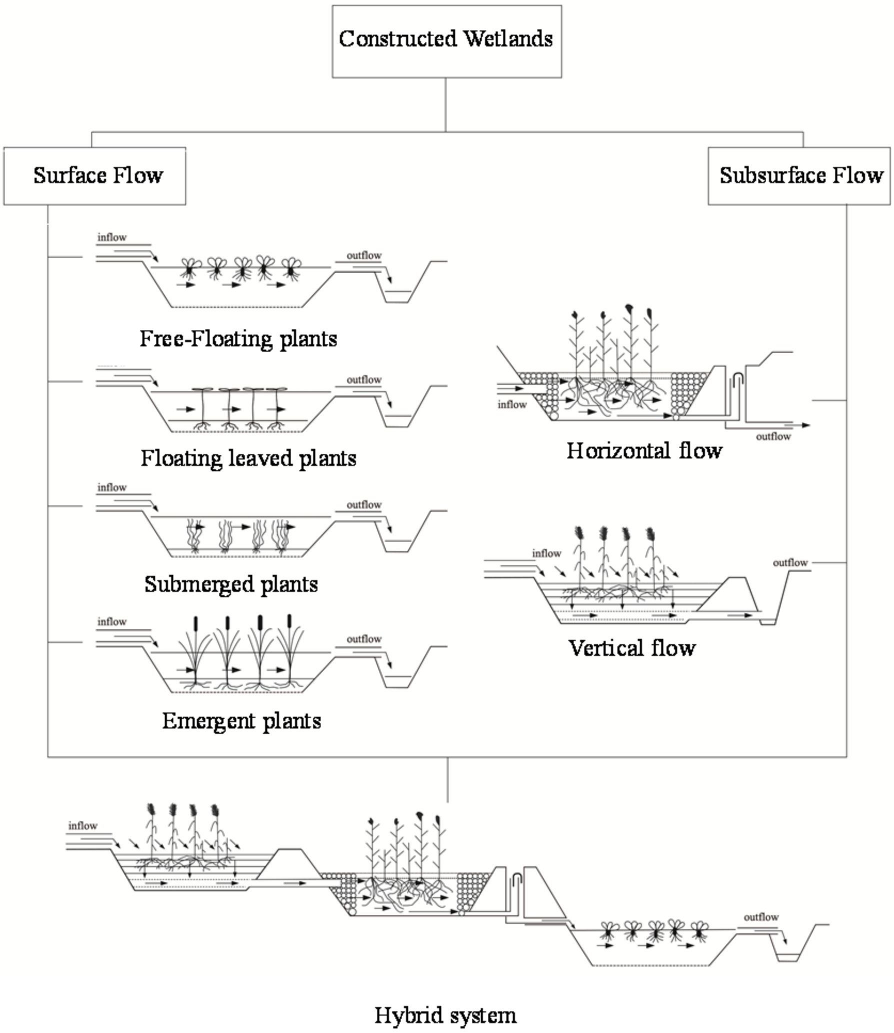
Constructed wetlands and SNTWs can be used to improve the quality of collected wastewater including domestic wastewater, industrial wastewater such as wastewater from processing factories of agricultural products and dairy farm, collected runoff from agricultural land and leachate from landfill. For some wastewaters, CWs are the sole treatment; for others, they are one component in a sequence of treatment processes (US EPA, 1995).

There are various types of CWs used for treatment of wastewater, and the following paragraphs highlight the main classification of CWs.

TYPE OF CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

Constructed wetlands may be categorized according to the various design parameters, but the three most important criteria are hydrology (water surface flow and subsurface flow), macrophyte growth form (emergent, submerged, free-floating, and floating leaved plants) and flow path (horizontal and vertical) (see Figure 6.1; Vymazal 2007, 2011). Different types of CWs may be combined (which are called hybrid or combined systems) to utilize the specific advantages of the different systems. For instance, to guarantee more effective removal of ammonia and total nitrogen (N), during the 1990s and 2000s an enhanced design approach combined vertical and horizontal flow CWs to achieve higher treatment efficiency (Vymazal, 2011).

Figure 6.1 Classification and configuration of constructed wetlands for wastewater treatment



Note: Adapted from Vymazal, 2007, 2011. Lower part is original. Most of SNTWs represent surface flow type wetlands.

Constructed Wetlands with Surface Flow

Constructed wetlands with *surface flow* (SF), known as *free water surface CWs*, contain areas of open water and floating, submerged, and emergent plants (Kadlec and Wallace 2008). The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels (Crites *et al*. 2005), ensure better water purification. The most common application for SF CWs is for tertiary treatment of municipal wastewater and also for stormwater runoff and mine drainage waters (Kadlec and Knight 1996; Kadlec and Wallace 2008). SF CWs are suitable in all climates, including the far north (Mander and Jenssen 2003).

Constructed Wetlands with Subsurface Flow

In *horizontal subsurface flow constructed wetlands* (HSSF CWs), the wastewater flows from the inlet and flows slowly through the porous medium under the surface of the bed planted with emergent vegetation to the outlet where it is collected before leaving via a water level control structure (Vymazal *et al*., 1998). During passage the wastewater comes into contact with a network of aerobic, anoxic, and anaerobic zones. Most of the bed is anoxic/anaerobic due to permanent saturation of the beds. The aerobic zones occur around roots and rhizomes that leak oxygen into the substrate (Brix 1987). HSSF CWs are commonly sealed with a liner to prevent seepage and to ensure the controllable outflow. HSSF CWs are commonly used for secondary treatment of municipal wastewater but many other applications have been reported in the literature (Vymazal and Kröpfelova 2008). The oxygen transport capacity in these systems is insufficient to ensure aerobic decomposition, thus, anaerobic processes play an important role in HSSF CWs (Vymazal and Kröpfelova 2008). Some HSSF CWs, having the ability to insulate the surface of the bed, are capable of operation under colder conditions than SF systems (Mander and Jenssen 2003).

Vertical subsurface flow constructed wetlands (VSSF CWs) comprise a flat bed of graded gravel topped with sand planted with macrophytes. VSSF CWs are fed with large intermittent wastewater flows, which flood the surface of the bed, then percolate down through the bed and are collected by a drainage network at the bottom. The bed drains completely which allows air to refill the bed. Thus, VSSF CWs provide greater oxygen transfer into the bed, producing a nitrified (high NO_3^-) effluent (Cooper *et al*., 1996; Cooper 2005). Consequently, VSSF CWs do not provide suitable conditions for denitrification to complete conversion to gaseous nitrogen forms, which then escape to the atmosphere.

In recently developed tidal ("fill and drain") flow systems better contact of wastewater with the microorganisms growing on the media is guaranteed. This significantly enhances the purification processes (Vymazal 2011).

Hybrid Constructed Wetlands

Various types of CWs can be combined to achieve higher removal efficiency, especially for nitrogen. The design consists of two stages, several parallel vertical flow (VF) beds followed by 2 or 3 horizontal flow (HF) beds in series (VSSF-HSSF system). The VSSF wetland is intended to remove organics and suspended solids and to promote nitrification, while in HSSF wetland denitrification and further removal of organics and suspended solids occur.

Another configuration is a HSSF-VSSF system. The large HSSF bed is placed first to remove organics and suspended solids and to promote denitrification. An intermittently loaded small VF bed is used for additional removal of organics and suspended solids and for nitrification of ammonia into nitrate. To maximize removal of total N, however, the nitrified effluent from the VF bed must be recycled to the sedimentation tank (Vymazal 2011).

The VSSF-HSSF and HSSF-VSSF CWs are the most common hybrid systems, but in general, any kind of CWs could be combined to achieve higher treatment effect (Vymazal 2007).

GREENHOUSE GASES EMISSIONS FROM VARIOUS TYPES OF CONSTRUCTED WETLANDS

Emissions of greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are a byproduct of CWs, the importance of which has been increasing recently. Methane is produced in methanogenesis whereas N_2O is a product of denitrification and/or nitrification of N compounds by microorganisms. Among several environmental factors controlling the greenhouse gases emissions, availability of C and nutrients (especially N) which directly depend on wastewater loading, temperature, hydrological regime (pulsing vs steady-state flow), groundwater depth, moisture of filter material (water filled soil pores (WFSP)), and presence of aerenchyma plants play a significant role (see Table 6.1).

Soil temperature, oxidation reduction potential and the soil moisture (WFSP, depth of ground water level) are the most significant factors affecting emissions of CH_4 from CWs (Mander *et al*., 2003; Van der Zaag *et al*., 2010). Several investigations show that a water table deeper than 20 cm from the surface of wetlands and/or water-logged soils oxidizes most CH_4 fluxes (Soosaar *et al*., 2011; Salm *et al*., 2012). Fluxes of N_2O, however do not show a clear correlation with soil/air temperature, and significant emissions of N_2O from CWs have been observed in winter (Søvik *et al*., 2006). Likewise, freezing and thawing cycles enhance N_2O emissions (Yu *et al*., 2011). Hydrological regime also plays a significant role in greenhouse gases emissions from CWs. Altor and Mitsch (2008) and Mander *et al*., (2011) demonstrated that the intermittent loading (pulsing) regime and fluctuating water table in CWs enhance CO_2 emissions and significantly decrease CH_4 emissions. N_2O emissions, in contrast, do not show a clear pattern regarding pulsing regime.

Table 6.2 shows CH_4 and N_2O conversion rates derived from the relationship between the initial (input) C and N loadings and respective CH_4 and N_2O emissions from the main types of CWs. There is a significant positive correlation ($p < 0.05$) between the initial loadings and CH_4 and N_2O emissions from both SF and VSSF CWs, whereas no correlation was found for HSSF types. Seemingly, high variability of conditions and combination of several factors in HSSF CWs may be the reason for that. The limited number of available data did not allow derivation of reliable relationships for HSSF CWs. These shares (%) can be used as a base for the calculation of emission factors for Tier 1 and Tier 2 methodologies. The high emission factor for CH_4 in SF CWs (Table 6.4) is thought to be due to the additional CH_4 from sediments accumulated at the bottom of SF CWs.

TABLE 6.1
SELECTED FACTORS IMPACTING CH_4 AND N_2O EMISSIONS IN CONSTRUCTED WETLANDS

Factors/processes	CH_4	N_2O
Higher water/soil/air temperature	Increase in almost all cases [1-6] with few exceptions [7]	No clear relationship [1-4, 7, 8]
Higher moisture of soil or filter material (higher value of WFSP)	Clear increase [9, 10]	Decrease [9, 10]
Higher wastewater loading	Increase [1-4, 11, 12]	Increase [1, 2, 4, 13]
Presence of aerenchymal plants	Increase [14-16] Decrease (depends on conditions) [17]	Increase [16, 18] Decrease [16, 19]
Pulsing hydrological regime (intermittent loading)	Clear decrease [9, 20]	Increase [9, 21, 22] Decrease in some SF CWs [23]
Deeper water table (from surface) in HSSF CWs	Decrease [9, 10]	Increase [9, 10]

Source:
[1] Mander and Jenssen 2003; [2] Mander *et al*., 2005; [3] Teiter and Mander 2005; [4] Søvik *et al*., 2006; [5] Kayranli et al., 2010; [6] Van der Zaag *et al*., 2010; [7] Søvik and Kløve 2007; [8] Fey *et al*., 1999; [9] Mander *et al*., 2011; [10] Yang *et al*., 2013; [11] Tanner *et al*., 1997; [12] Tai *et al*., 2002; [13] Hunt *et al*., 2009; [14] Inamori *et al*., 2007; [15] Inamori *et al*., 2008; [16] Wang *et al*., 2008; [17] Maltais-Landry *et al*., 2009; [18] Rückauf *et al*., 2004; [19] Silvan *et al*., 2005; [20] Altor and Mitsch 2008; [21] Jia *et al*., 2011; [22] Van de Riet *et al*., 2013; [23] Hernandez and Mitsch 2006

TABLE 6.2
INFLUENT TOTAL ORGANIC CARBON (TOC) AND TOTAL NITROGEN (TN) VALUES, RELEVANT CH_4-C AND N_2O-N EMISSIONS, AND SHARE (%) OF CH_4-C AND N_2O-N IN THE INITIAL LOADING OF TOC AND TN IN CONSTRUCTED WETLANDS

Type of CW	Influent TOC* (mg C m^{-2} h^{-1})	CH_4-C emission* (mg CH_4-C m^{-2} h^{-1})	CH_4-C/ TOC** (%)	Influent TN* (mg N m^{-2} h^{-1})	N_2O-N emission* (mg N_2O-N m^{-2} h^{-1})	N_2O-N/TN** (%)
SF	1.04-173.6 (10) [1-11]	0.15-181.0 (10.7) [1-11]	42 (20)	0.76-202.8 (12) [2, 3, 6-11, 21-23]	0.009-0.65 (0.03) [2, 6-11, 21-23]	0.13 (0.02)
HSSF	15.0-2190.2 (177) [8, 10-12, 15-20]	0.048-17.5 (1.7) [8, 10, 11, 15-20]	12 (6.9)	1.04-295.20 (40) [6, 10, 12, 15-17, 24, 25]	0.014-0.89 (0.10) [6, 10-12, 15-17, 25]	0.79 (0.4)
VSSF	17.88-1417.50 (317) [6, 8, 10, 12]	0.3-5.4 (1.3) [6, 8, 10, 12]	1.17 (0.33)	102.5-2105.0 (155) [6, 8, 10, 12-14]	0.033-0.424 (0.03) [6, 8, 10, 11, 12-14]	0.023 (0.005)

* Range and standard error (in bracket)

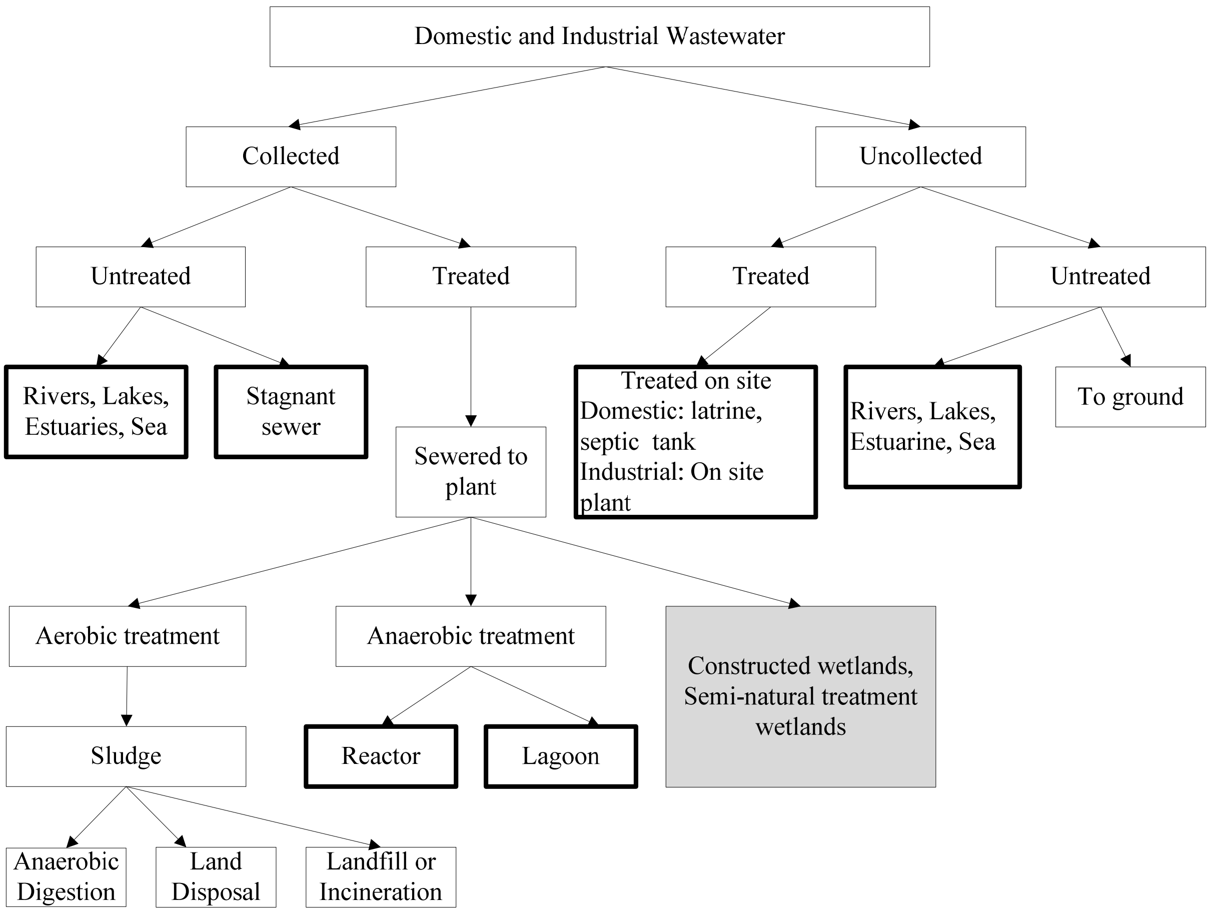
** Average and standard error (in bracket)

Source: [1] Tanner *et al*., 1997; [2] Wild *et al*., 2001; [3] Tai *et al*., 2002; [4] Johansson *et al*., 2004; [5] Stadmark and Leonardson 2005; [6] Søvik *et al.,* 2006; [7] Søvik and Kløve 2007; [8] Gui *et al*., 2007; [9] Ström *et al*., 2006; [10] Liu *et al*., 2009; [11] Van der Zaag *et al*., 2010; [12] Teiter and Mander 2005; [13] Inamori *et al*., 2007; [14] Wang *et al*., 2008; [15] Mander *et al*., 2003; [16] Mander *et al*., 2008, [17] Liikanen *et al*., 2006; [18] Garcia *et al*., 2007; [19] Picek *et al*., 2007; [20] Chiemchaisri *et al*., 2009; [21] Xue *et al*., 1999; [22] Johansson *et al*., 2003; [23] Wu *et al*., 2009; [24] Inamori *et al*., 2008; [25] Fey *et al*., 1999

6.1.2 Relation to 2006 IPCC Guidelines

This chapter is a supplement to Chapter 6 Wastewater Treatment and Discharge of the Volume 5 of the *2006 IPCC Guidelines.* The *2006 IPCC Guidelines* include a section to estimate CH_4 emissions from uncollected wastewater. The section is expanded in this supplement to cover CH_4 emissions from CWs and SNTWs. This *Wetlands Supplement* includes guidance on estimation of N_2O emissions from CWs and SNTWs. Emission factors of CH_4 and N_2O emissions from CWs and SNTWs treating industrial wastewater are the same as those treating domestic wastewater. CO_2 emissions are not included in greenhouse gases emissions from wastewater treatment as CO_2 from wastewater is considered biogenic.

Figure 6.2 Wastewater treatment systems and discharge pathways



Note: This figure was modified from the *2006 IPCC Guidelines*. Emissions from boxes with bold frames are accounted for in the *2006 IPCC Guidelines*. This supplement provides emission factors for gray-colored box: CWs and SNTWs for treatment of collected wastewater.

Coverage of wastewater types and gases

Chapter 6 of the Volume 5 of the *2006 IPCC Guidelines* provides guidance on estimation of CH_4 and N_2O emissions from domestic wastewater with emission factors based on treatment technology. Constructed wetlands in this supplement are an additional treatment technology. The emission factors provided in this chapter cover CWs and SNTWs (collected and treated; see Figure 6.2).

The methodology is provided for estimation of CH_4 and N_2O emissions from both domestic and industrial wastewater (Table 6.3). The indirect N_2O emissions from N leaching and runoff from agricultural land are covered in Chapter 11, Volume 4 of the *2006 IPCC Guidelines*. Emissions from processing factories of agricultural products and dairy farm wastewater, collected runoff from agricultural land and leachate from landfill are considered as industrial wastewater. According to Chapter 3 of the Volume 5 in the *2006 IPCC Guidelines*, all amount of degradable organic carbon (DOC) in solid waste is subjected to estimation of CH_4 in landfill site, and carbon loss with leachate is not considered because of its low percentage. That means that CH_4 emissions from leachate treatment are already covered, and are not included in Section 6.2, while N_2O emissions are considered in Section 6.3 of this supplement. If CH_4 emission from CWs is accounted, the amount of DOC in leachate must be subtracted from that in solid waste to avoid double counting. Because C in leachate is normally indicated in terms of COD, conversion rate from COD in leachate to TOC in solid waste is required in order to subtract the amount of DOC entering CWs from that in solid waste. This logic can be applied in Tier 2 or 3 estimation.

TABLE 6.3
COVERAGE OF WASTEWATER TYPES AND GREENHOUSE GAS EMISSIONS FROM CONSTRUCTED WETLANDS

Type of Wastewater	Methane	Nitrous oxide
Domestic wastewater	Included in this supplement (section 6.2) with provision of methane correction factors (MCFs)	Included in this supplement (Section 6.3) with provision of default emission factors
Industrial wastewater including wastewater from processing factories of agricultural products and dairy farm *	Included in this supplement (Section 6.2) with provision of MCFs	Included in this supplement (Section 6.3) with provision of default emission factors
Collected runoff from agricultural land	Emissions can be calculated using same methodology as industrial wastewater and are covered in this supplement (Section 6.2)	Emissions can be calculated using same methodology as industrial wastewater and are covered in this supplement (Section 6.3) Note: Indirect N_2O emissions from N leaching and runoff from agricultural land are considered in Chapter 11, Volume 4 of the 2006 IPCC Guidelines. If agricultural runoff is collected and treated by CWs or SNTWs, the amount of N flows into CWs or SNTWs must be subtracted to avoid double counting.
Leachate from landfill	The amount DOC leached from the solid waste disposal site is not considered in the estimation of DOC_f. Generally the amount of DOC lost with the leachate are less than 1 percent and can be neglected in the calculations (Chapter 3, Volume 5, *2006 IPCC Guidelines*) and not considered in this supplement	Emissions can be calculated using same methodology as industrial wastewater and are covered in this supplement (Section 6.3)

*Dairy farm wastewater does not cover manure itself but comes from other activities in the farm.

6.2 METHANE EMISSIONS FROM CONSTRUCTED WETLANDS

6.2.1 Methodological issues

Methane emissions are a function of the organic materials loaded into CWs and an emission factor.

Three tiers of methods for estimation of CH_4 from CWs are summarized 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 country-specific emission factor and country-specific activity data. For example, a specific emission factor based on field measurements can be incorporated under this method.

The Tier 3 method is used by countries with good data and advanced methodologies. A more advanced country-specific method could be based on treatment system-specific data such as plant species and composition of wastewater.

In general anaerobic conditions occur in CWs. However, CH_4 generated by CWs is not usually recovered and combusted in a flare or energy device, and so CH_4 recovery is not considered here.

The amount of vegetation harvested from CWs is generally very small and its impact on total emissions from CWs is considered insignificant. Moreover, the harvesting is usually not performed on regular basis and the quantity of harvested biomass is commonly not recorded so it is not considered in this supplement.

6.2.1.1 CHOICE OF METHOD

A decision tree for domestic or industrial wastewater is shown in Figure 6.3.

The general equation to estimate CH_4 emissions from CWs treating domestic or industrial wastewater is given in Equation 6.1.

EQUATION 6.1
CH_4 EMISSIONS FROM CONSTRUCTED WETLANDS

$$CH_4Emissions = \sum_{j}\left(TOW_j \cdot EF_j\right) + \sum_{i,j}\left(TOW_{i,j} \cdot EF_j\right)$$

Where:

CH_4 emissions = CH_4 emissions in inventory year, kg CH_4/yr

TOW_j = total organics in wastewater entering CW in inventory year, kg BOD/yr or kg COD/yr

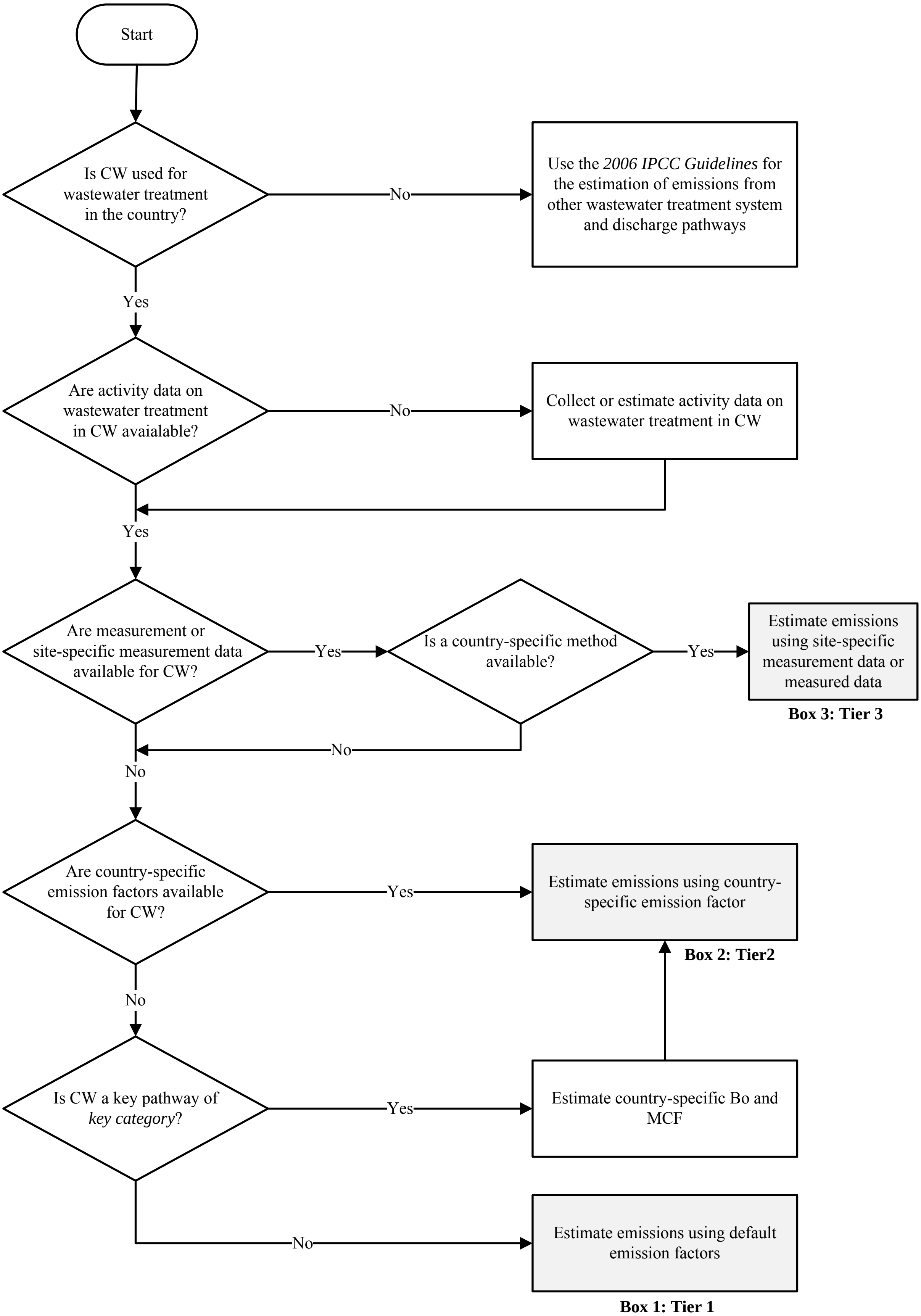
EF_j = emission factor, kg CH_4/kg BOD (for domestic wastewater only) or kg CH_4/kg COD (for both domestic and industrial wastewater)

If more than one type of CW is used in an industrial sector this factor would need to be a $TOW_{i,j}$-weighted average.

i = industrial sector

j = type of CW

258 **Figure 6.3 Decision tree for CH_4 emissions from constructed wetlands**



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6.2.1.2 CHOICE OF EMISSION FACTORS

The emission factor for wastewater treatment using CWs is a function of maximum CH_4 producing potential (B_o) and the methane correction factor (MCF).

EQUATION 6.2
CH_4 EMISSION FACTOR FOR CONSTRUCTED WETLANDS

$$EF_j = B_o \cdot MCF_j$$

Where:

EF_j = emission factor, kg CH_4/kg BOD or kg CH_4/ kg COD

j = type of CWs

B_o = maximum CH_4 producing capacity, kg CH_4/kg BOD or kg CH_4/ kg COD

MCF_j = methane correction factor (fraction), See Table 6.4

Good practice is to use country-specific data for B_o, where available, expressed in terms of kg CH_4/kg BOD removed for domestic wastewater or kg CH_4/kg COD removed for industrial wastewater to be consistent with the activity data. If country-specific data are not available, the following default values can be used.

The *2006 IPCC Guidelines* provide default B_o values for domestic and industrial wastewater: 0.6 kg CH_4/kg BOD and 0.25 kg CH_4/kg COD.

The MCF indicates the extent to which B_o is realized in each type of CWs. It is an indication of the degree to which the system is anaerobic. The proposed MCFs for SF, HSSF and VSSF are provided in Table 6.4 and derived from literature-based analysis of CH_4 conversion rates. Each MCF in Table 6.4 is calculated from the relation of initial TOC loading to CH_4 emission flux derived from references provided in Table 6.2.

TABLE 6.4
METHANE CORRECTION FACTORS BY TYPE OF CONSTRUCTED WETLAND

CW type	MCF
Surface flow (SF)	0.4
Horizontal subsurface flow (HSSF)	0.1
Vertical subsurface flow (VSSF)	0.01

These MCF values are derived based on actual measurement data and thus the operating and environmental conditions such as vegetation types and temperature effect have been taken into account. Based on the reported scientific data, there was insufficient information to distinguish the MCF values by vegetation types and operating temperatures. Nevertheless, these influencing factors can be considered for the estimation using higher tier approach. There was insufficient actual measurement data of hybrid systems to derive default MCF values. If the area fractions of SF, VSSF and HSSF for hybrid systems can be determined, the MCF values of the hybrid systems can be estimated as the area-weighted average of the MCFs for SF, VSSF and HSSF. Most commonly, SNTWs are surface flow type (Kadlec and Wallace, 2008), therefore, the default MCF of 0.4 can be used. If the type of CW cannot be recognized, the MCF of surface flow can be used in order to be conservative. Otherwise country-specific data should be used in higher tier method.

6.2.1.3 CHOICE OF ACTIVITY DATA

The activity data for this source category is the amount of organic materials (TOW) in the wastewater treated by CW. This parameter is a function of the population served by the CW system, and the biochemical oxygen demand (BOD) generation per person per day. BOD default values for selected countries are provided in the *2006 IPCC Guidelines* (Table 6.4, Chapter 6 of Volume 5 of the *2006 IPCC Guidelines*). In the case of industrial wastewater, COD loading to the CW system per day (kg COD/day) can be used. Examples of industrial wastewater data from various industries are provided in Table 6.9, Chapter 6, Volume 5 of the *2006 IPCC Guidelines*.

If industrial wastewater is released into domestic sewers, it is estimated together with domestic wastewater. The equations for TOW are:

EQUATION 6.3
TOTAL ORGANICALLY DEGRADABLE MATERIAL IN DOMESTIC WASTEWATER

$$TOW_j = P_j \cdot BOD \cdot I \cdot 0.001 \cdot 365$$

EQUATION 6.4
TOTAL ORGANICALLY DEGRADABLE MATERIAL IN INDUSTRIAL WASTEWATER

$$TOW_{i,j} = COD_i \cdot W_{i,j} \cdot 365$$

Where:

TOW_j = total organics in domestic wastewater treated in the CW in inventory year (kg BOD/year)

$TOW_{i,j}$ = total organics in wastewater from industry *i* treated in the CW in inventory year (kg COD/year)

i = industrial sector

P_j = population whose wastewater treated in CW*

BOD = per capita BOD generation in inventory year (g BOD/person/day)

I = correction factor for additional industrial BOD discharged into sewers (for collected the default is 1.25, for uncollected the default is 1.00 as given in the *2006 IPCC Guidelines*)

COD_i = COD concentration in wastewater from industry *i* entering CW in the inventory year (kg COD/m^3)

$W_{i,j}$ = daily flow rate of industrial wastewater treated by CW, m^3/day

* Population should be subtracted from total population used in an Equation 6.3 in Chapter 6, Volume 5 in the *2006 IPCC Guidelines* to avoid double-counting.

6.2.2 Time series consistency

The same method and data sets should be used for estimating CH_4 emissions from CWs treating wastewater for each year. The MCF for different treatment systems should not change from year to year, unless such a change is justifiable and documented. If the share of wastewater treated in different treatment systems changes over the time period, the reasons for these changes should be documented.

For activity data that are derived from population data, countries must determine the fraction of the population served by CW systems. If data on the share of wastewater treated are missing for one or more years, the splicing techniques such as surrogate data and extrapolation/interpolation described in Chapter 5, Time Series Consistency, Volume 1 of the *2006 IPCC Guidelines* can be used to estimate emissions. Emissions from wastewater treated in CWs typically do not fluctuate significantly from year to year.

6.2.3 Uncertainties

Chapter 3 in Volume 1 of the *2006 IPCC Guidelines* provides guidance 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. Table 6.5 provides default uncertainty ranges for emission factors and activity data for domestic and industrial wastewater. The following parameters are believed to be very uncertain:

- The quantity of wastewater that is treated in CWs or SNTWs.
- The fraction of organics that is converted anaerobically to CH_4 during wastewater collection. This will depend on hydraulic retention time and temperature in the wastewater collection pipeline, and on other

factors including the presence of anaerobic condition in the wastewater collection pipeline and possibly components that are toxic to anaerobic bacteria in some industrial wastewater.

- The amount of industrial TOW from small or medium-scale industries and rural domestic wastewater that is discharged into CWs in developing countries.
- Different plant species applied in CWs that are involved in gas exchange.

TABLE 6.5
DEFAULT UNCERTAINTY RANGES FOR DOMESTIC AND INDUSTRIAL WASTEWATER

Parameter	Uncertainty range*
Emission factor	
Maximum CH_4 producing capacity (B_o)	± 30%
Methane correction factor (MCF)	SF: ± 79% HSSF: ± 31% VSSF: ± 56%
Activity data	
Human population	± 5%
BOD per person	± 30%
Correction factor for additional industrial BOD discharged into sewers (I)	For uncollected, the uncertainty is zero %. For collected the uncertainty is ± 20%
COD loading from industrial wastewater	-55%, +103%

* Uncertainty of MCF calculated as 95% confidence interval is shown in Table 1 in Annex. Uncertainty of COD loading from industrial wastewater is calculated based on Table 6.10 in Chapter 6 in Volume 5 of the *2006 IPCC Guidelines*. Others are the same to Tables 6.7 in Chapter 6 in Volume 5 of the *2006 IPCC Guidelines*.

6.2.4 QA/QC, Completeness and Reporting

It is *good practice* to conduct quality control (QC) checks and quality assurance (QA) procedures as outlined in Chapter 6, QA/QC and Verification, Volume 1 of the *2006 IPCC Guidelines*. Some fundamental QA/QC procedures include:

Activity Data

- Make sure that the sum of wastewater flows of all types of wastewater treatment processes including CWs equal 100 percent of wastewater collected and treated in the country.
- Inventory compilers should compare country-specific data on BOD in domestic wastewater to IPCC default values. If inventory compilers use country-specific values they should provide documented justification why their country-specific values are more appropriate for their national circumstances.

Emission Factors

- For domestic wastewater, inventory compilers can compare country-specific values for B_o with the IPCC default value (0.25 kg CH_4/kg COD or 0.6 kg CH_4/kg BOD). As there are no IPCC default values for the fraction of wastewater treated anaerobically, inventory compilers are encouraged to compare values for MCFs against those from other countries with similar wastewater handling practices.
- Inventory compilers should confirm the agreement between the units used for organically degradable material in wastewater (TOW) with the units for B_o. Both parameters should be based on the same units (either BOD or COD) in order to calculate emissions. This same consideration should be taken into account when comparing the emissions.
- For countries that use country-specific parameters or higher-tier methods, inventory compilers should crosscheck the national estimates with emissions estimated using the IPCC default method and parameters.
- For industrial wastewater, inventory compilers should cross-check values for MCFs against those from other national inventories with similar CW types.

COMPLETENESS

Completeness can be verified on the basis of the degree of utilization of a treatment or discharge system or pathway (T) for all wastewater treatment system used. The sum of T should equal 100 percent. It is a *good practice* to draw a diagram for the country to consider all potential anaerobic treatment and discharge systems and pathways, including collected and uncollected, as well as treated and untreated. Constructed wetlands and SNTWs are under treated and collected pathway. In general, the amount of vegetation harvested from CWs is very small. If vegetation biomass is removed for the purpose of composting, incineration and burning, disposal in landfills or as fertilizer on agricultural lands, the amount of biomass should be consistent with data used in the relevant sectors.

Completeness for estimating emissions from industrial wastewater depends on an accurate characterization of industrial sectors that produce organic wastewater and the organic loading applied to CW systems. So 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.

REPORTING

Methane emission from CWs for wastewater treatment is reported in waste sector under the categories of domestic or industrial wastewater. Methane emission from CWs treating collected runoff from agricultural land is to be reported under the category of industrial wastewater.

6.3 NITROUS OXIDE EMISSIONS FROM CONSTRUCTED WETLANDS

6.3.1 Methodological issues

Nitrous oxide (N_2O) emissions can occur as direct emissions from wastewater treatment in CWs through nitrification and denitrification. Emissions are calculated based on the total nitrogen loaded into CWs and emission factor.

Three tier methods for N_2O from this category are summarized below.

The Tier 1 method applies default values for the emission factor and activity parameters. This method is considered *good practice* for countries with no country-specific data.

The Tier 2 method follows the same method as Tier 1 but allows for incorporation of country-specific emission factors and country-specific activity data.

The Tier 3 method is used by countries with good data and advanced methodologies. A more advanced country-specific method is based on treatment system-specific data such as plant species and composition of wastewater.

The methodology provided assumes typical vegetation harvesting practices. However, the amount of vegetation harvested from CWs (studied until now) is generally very small and the harvested plant biomass is commonly not recorded so the harvesting practice is not considered as an influencing factor in the estimation of emissions.

Emissions from SNTWs treating uncollected wastewater are estimated using the same methodology. Indirect N_2O emissions from domestic wastewater treatment effluent that is discharged into aquatic environments has already been covered in the *2006 IPCC Guidelines*.

6.3.1.1 CHOICE OF METHOD

A decision tree for domestic or industrial wastewater is shown in the Figure 6.4.

The general equation to estimate N_2O emissions from CWs treating domestic or industrial wastewater is shown in Equation 6.5.

EQUATION 6.5
N_2O EMISSIONS FROM CONSTRUCTED WETLANDS

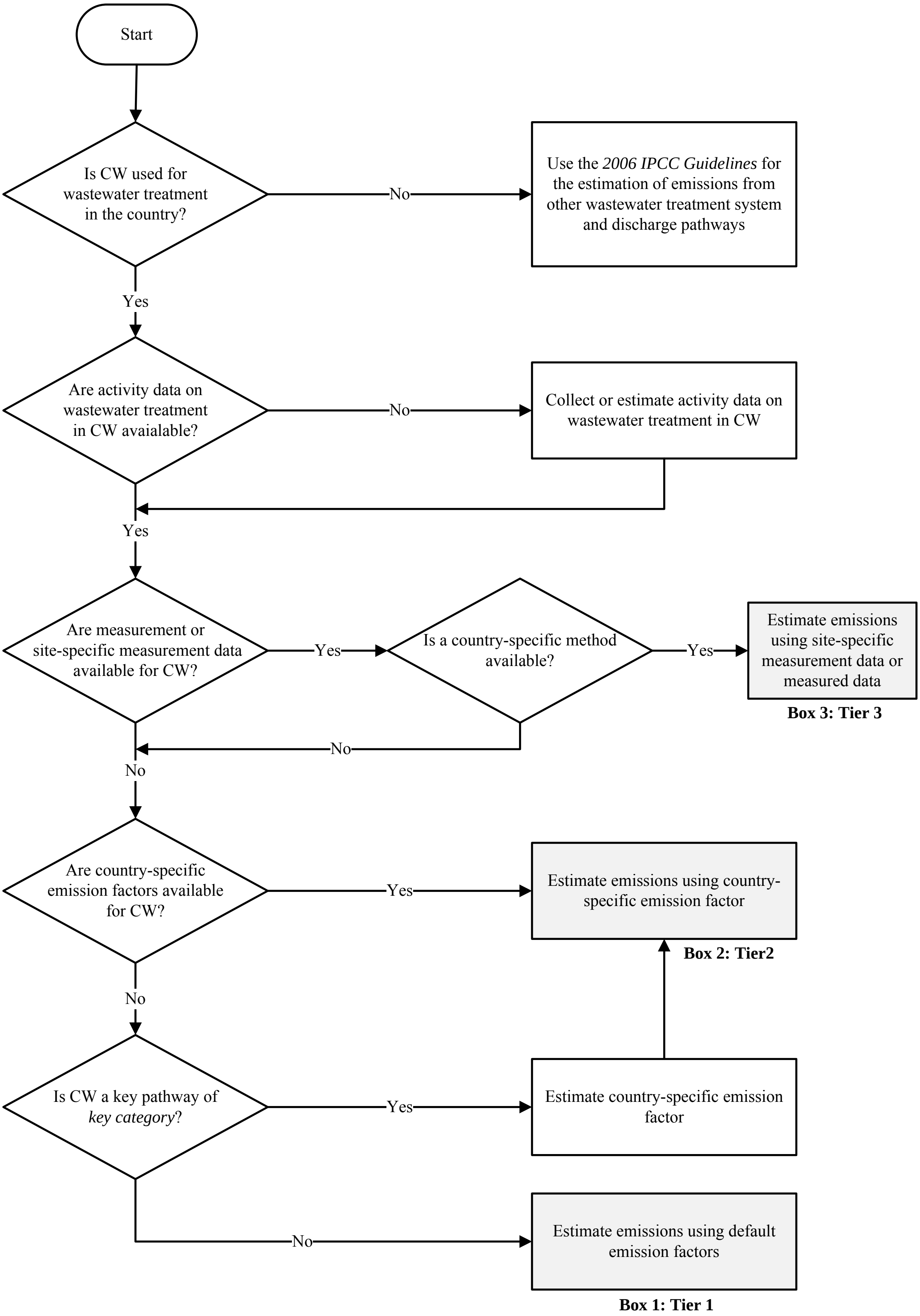
$$N_2O\ Emissions = \sum_{j} \left(N_j \cdot EF_j \cdot 44/28 \right) + \sum_{i,j} \left(N_{i,j} \cdot EF_j \cdot 44/28 \right)$$

Where:

N_2O emissions	=	N_2O emissions in inventory year, kg N_2O/yr
N_j	=	total nitrogen in domestic wastewater entering CWs in the inventory year, kg N/year
$N_{i,j}$	=	total nitrogen in industrial wastewater entering CW in the inventory year, kg N/year
EF_j	=	emission factor, kg N_2O-N/kg N
		If more than one type of CW is used in an industrial sector this factor would need to be a $N_{i,j}$-weighted average.
i	=	industrial sector
j	=	type of CWs

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

Figure 6.4 Decision tree for N_2O emission from constructed wetland



6.3.1.2 CHOICE OF EMISSION FACTORS

The default emission factors for N_2O emitted from domestic and industrial wastewater treated by CWs are 0.0013 kg N_2O-N/kg N for SF, 0.0079 kgN_2O-N/kg N for HSSF and 0.00023 kgN_2O-N/kg N for VSSF. These values are based on data provided in the literatures and influenced by the extent of nitrification and denitrification taking place in CWs, the coverage of vegetation in CWs and climatic conditions. There was insufficient actual measurement data of hybrid systems to derive emission factors. If the area fractions of SF, VSSF and HSSF for hybrid systems can be determined, the emission factors of the hybrid systems can be estimated as the area-weighted average of the emission factors for SF, VSSF and HSSF CWs. *Good practice* is to use country-specific data for emission factor, where available, expressed in term of kg N_2O-N/kg N loaded for domestic and industrial wastewater to be consistent with the activity data. The amount of N associated with N_2O emissions from CWs must be back calculated and subtracted from the $N_{EFFLUENT}$ (Equation 6.7 in Chapter 6, Volume 5 of the *2006 IPCC Guidelines*).

6.3.1.3 CHOICE OF ACTIVITY DATA

The activity data for this source category are the amount of nitrogen in the wastewater entering CWs (TN). This parameter is a function of the population served by the CW system, annual per capita protein consumption (protein) and a factor for non-consumed nitrogen added to the wastewater for domestic wastewater. In case of industrial wastewater, TN loading to the constructed wetland system in the inventory year (kg N) can be used directly. The equations for determining TN for domestic and industrial wastewater are:

EQUATION 6.6
TOTAL NITROGEN IN DOMESTIC WASTEWATER

$$N_j = P_j \cdot Protein \cdot F_{NPR} \cdot F_{NON-CON} \cdot F_{IND-COM}$$

EQUATION 6.7
TOTAL NITROGEN IN INDUSTRIAL WASTEWATER

$$N_{i,j} = TN_i \cdot W_{i,j}$$

Where:

N_j = total nitrogen in domestic wastewater entering CW in inventory year (kg N/year)

N_i = total nitrogen in wastewater from industry *i* entering CW in inventory year (kg N/year)

i = industrial sector

P_j = human population whose wastewater entering CWs

Protein = annual per capita protein consumption, kg/person/yr

F_{NPR} = fraction of nitrogen in protein (default is 0.16 kg N/ kg protein as given in the *2006 IPCC Guidelines*)

$F_{NON-CON}$ = factor for non-consumed nitrogen added to the wastewater (default is 1.1 for countries with no garbage disposals, 1.4 for countries with garbage disposals as given in the *2006 IPCC Guidelines)*

$F_{IND-COM}$ = factor for industrial and commercial co-discharged protein into sewer system (default is 1.25 as given in *2006 IPCC Guidelines*)

TN_i = total nitrogen concentration in wastewater from industry *i* entering CWs in inventory year (kg N/m^3)

$W_{i,j}$ = flow rate of industrial wastewater entering CW, m^3/yr

N_i is a function of total N concentration and flow rate which can be estimated by multiplying industrial product P (tons/yr), wastewater generation (m^3/ton) (Table 6.9, Chapter 6, Volume 5 in *2006 IPCC Guidelines*) and N content in Table 6.6 of this supplement.

TABLE 6.6
EXAMPLE OF N CONTENT IN SOME NITROGEN-RICH INDUSTRIAL WASTEWATER

Industry type	Wastewater generation W (m^3/ton)	N content (kg/m^3)
Alcohol refining	24 (16-32)[1]	2.40 (0.94-3.86)[2]
Fish processing industry	5 (2-8)[2]	0.60 (0.21-0.98)[3]
Seasoning source industry	NA	0.60 (0.22-1.00)[3]
Meat & poultry	13 (8-18)[1]	0.19 (0.17-0.20)[3]
Starch production	9 (4-18)[1]	0.90 (0.80-1.10)[4]
Nitrogen fertilizer plant	2.89 (0.46-8.3)[2]	0.50 (0.10-0.80)[2]
Landfill leachate	15-20% of annual precipitation in well compacted landfill site. 25-50% of annual precipitation for not well compacted landfill site[6].	0.74 (0.01-2.50)[5]

Note: Average value and range (in brackets) are presented

Sources: [1] *IPCC 2006*; [2]Samokhin (1986); [3] Pilot Plant Development and Training Institute (1994); [4] Hulle *et.al*. (2010); [5] Kjeldsen *et al*. (2002); [6] Ehrig (1983)

6.3.2 Time series consistency

The same method and data sets should be used for estimating N_2O emissions from CWs for each year. If a country decides to change the estimation method from the default methodology (Tier 1) to country-specific (Tier 2), this change must be made for the entire time series.

6.3.3 Uncertainties

Large uncertainties are associated with the default emission factors for N_2O emissions from CWs due to limited available data (Table 6.7).

TABLE 6.7
NITROUS OXIDE METHODOLOGY DEFAULT UNCERTAINTIES

Parameter	Default value	Range
Emission factor (kg N_2O-N/kg N)	0.0013 for SF 0.0079 for HSSF 0.00023 for VSSF	± 90% for SF ± 79% for HSSF ± 70% for VSSF
Activity data		
Human population	Country-specific	± 10%
Annual per capita protein consumption	Country-specific	± 10%
Fraction of nitrogen in protein	0.16	0.15-0.17
Factor for non-consumed nitrogen	1.1 for countries with no garbage disposals, 1.4 for countries with garbage disposals	1.0-1.5
TN loading from industrial wastewater	Country-specific	-55%, +103%

* Uncertainties of emission factors calculated as 95% confidence interval is shown in Table 6A1.1 in Annex. Uncertainty of TN loading from industrial wastewater is the same to that of COD loading from industrial wastewater (Expert judgement by Authors of this chapter). Others are derived from Tables 6.11 in Chapter 6 in Volume 5 of the *2006 IPCC Guidelines*.

6.3.4 QA/QC, Completeness and Reporting

This method makes use of several default parameters. It is recommended to solicit experts' advice in evaluating the appropriateness of the proposed default factors. The methodology for estimating emissions is based on N associated with domestic and industrial discharge either collected into the collection system and treated in CWs or uncollected and discharged into SNTWs. This estimate can be seen as conservative and covers the entire source associated with domestic and industrial wastewater discharge.

REPORTING

Nitrous oxide emission from CWs for wastewater treatment is reported in waste sector under the categories of domestic or industrial wastewater. Nitrous oxide emissions from CWs treating collected runoff from agricultural land and landfill leachate are to be reported under the category of industrial wastewater. If agricultural runoff is collected and treated by CWs or SNTWs, the amount of nitrogen flows into CWs/SNTWs must be subtracted to avoid double counting.

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Annex 6A.1 Estimation of default emission factors for CH_4 and N_2O in constructed wetlands for wastewater treatment

We reviewed about 150 papers published in international peer-reviewed journals indexed by the Thomson Reuters Web of Knowledge from 1994 to 2013. The terms "free water surface", "surface flow", constructed wetland(s)", "artificial wetland(s)", "treatment wetland(s)", "subsurface flow wetland(s)", "vertical flow" and "horizontal flow" in combination with the terms "carbon dioxide", "CO_2", "methane", "CH_4", "nitrous oxide" and "N_2O" were searched.

We found a total of 14 publications that provided information on emissions of either CH_4, N_2O or both gases in surface flow (SF) constructed wetlands (CWs). These publications presented information on 17 different SF CW systems, whereas for CH_4 and N_2O, there were 24 and 25 subsystems/measuring events respectively. Six SF CWs (Nykvarn, Lakeus, Ruka, Skjønhaug, Hässleholm, and Ibaraki) treated domestic wastewater (Johansson et al., 2003, 2004; Søvik et al., 2006, Ström et al., 2006; Gui et al., 2007; Søvik and Kløve, 2007; Liu et al., 2009), six CWs (mesocosms in Xue et al. (1999) paper, Donaumoos, Genarp, Görarp, Ormastorp, and Hovi) treated waters of agricultural non-point pollution (Xue et al., 1999; Wild et al., 2001; Stadmark and Leonardson, 2005; Søvik et al., 2006), two systems (Ngatea and Truro) were used for dairy farm wastewater treatment (Tanner et al., 1997; Van der Zaag et al., 2010), the Kompsasuo CW treated wastewater from a peat extraction area (Søvik et al., 2006), the Jiaonan CW (Tai et al., 2002) purified raw municipal wastewater, and synthetic wastewater is used in the Jinan laboratory mesocosms (Wu et al., 2009).

Regarding the vertical subsurface flow (VSSF) CWs, there were only 4 measurement periods presented for 3 CWs from which CH_4 emission data and ratios could be calculated: Kõo in Estonia (Teiter and Mander 2005; Søvik et al., 2006), Ski in Norway (Søvik et al., 2006), and Miho/Ibaraki, Japan (Gui et al., 2007; Liu et al., 2009). For N_2O emission, additionally laboratory microcosm experiments with different plant species from Ibaraki, Japan (Inamori et al., 2008; Wang et al., 2008) were included.

For CH_4 fluxes from horizontal subsurface flow (HSSF) CWs we could use data from two system in Estonia treating domestic wastewater, Kodijärve and Kõo (Mander et al., 2003, 2008; Teiter and Mander, 2005; Søvik et al., 2006), four CWs treating domestic wastewater in Ski, Norway (Søvik et al., 2006), Barcelona, Spain (Garcia et al., 2007), Miho/Ibaraki, Japan (Gui et al., 2007; Liu et al., 2007) and Slavosovice, Czech Republic (Picek et al., 2007), a HSSF treating wastewater from a peat extraction area in Kompsasuo, Finland (Liikanen et al., 2006), a HSSF treating landfill leachate in Bangkok, Thailand (Chiemchaisri et al., 2009), and a dairy farm wastewater treatment HSSF in Truro, Nova Scotia, Canada (Van der Zaag et al., 2010). For N_2O emissions from HSSFs, also a CW for dairy farm wastewater treatment in Friedelhausen, Germany (Fey et al., 1998) has been included.

Tanner et al., (1997) presented estimated values for inflow total organic carbon (TOC_{in}), Xue et al., (1999) for inflow total nitrogen (TN_{in}), and Søvik et al., (2006) for both TOC_{in} and TN_{in}. For most of the systems, TOC_{in} and TN_{in} values were calculated based on area, hydraulic load and inflow TOC and TN concentration data. For some systems only biological oxygen demand (BOD) values were usable, and for them the following approximation based on domestic wastewater data was used: TOC = 0.5 BOD (Garcia et al., 2007). For the calculations of emission factors, we used data series from one year or at least a vegetation period.

TABLE 6A1. 1
AVERAGE, STANDARD ERROR, MEDIAN, 2.5% AND 97.5% PERCENTILE VALUES OF CH_4-C AND N_2O-N EMISSION FACTORS (%) FOR DIFFERENT TYPES OF CONSTRUCTED WETLANDS

	Emission factor CH_4-C/TOC (%)					Emission factor N_2O-N/TN (%)				
	Average	Standard Error	Median	2.5%	97.5%	Average	Standard Error	Median	2.5%	97.5%
SF	42.2	20.4	18	4	446	0.13	0.024	0.11	0	0.47
HSSF	12.0	7.56	4.15	0.03	79	0.79	0.38	0.34	0.04	3.01
VSSF	1.17	0.33	1.28	0.38	1.73	0.023	0.005	0.018	0.001	0.096

Table 1 presents values of emission factors calculated based on literature sources described above.

In Figure 1, correlation between the inflow TOC loading and CH_4-C emission and between the inflow TN loading and N_2O emission in SF, HSSF and VSSF CWs is presented.

Figure 6A1.1 The relationship between inflow TOC loading and CH_4-C emission (left column) and between inflow TN loading and N_2O-N emission (right columns) in SF, HSSF, and VSSF CWs. In all cases, $p < 0.05$.