Appendix 3 CH_4 Emissions from Flooded Land: Basis for Future Methodological Development

This Appendix provides a basis for future methodological development rather than complete guidance.

Flooded Land may emit CH_4 in significant quantities, depending on a variety of characteristic such as age and depth of reservoirs, land-use prior to flooding, climate, and management practices. In contrast with CO_2 emissions, CH_4 emissions are highly variable spatially and temporally. Current measurements of CH_4 fluxes from Flooded Land are not sufficiently comprehensive to support the development of accurate default emission factors (especially for bubbles emissions and degassing emissions). In addition, data are not available for countries with substantial surface area cover by reservoirs, as India, China, and Russia.

Measurement studies do not indicate that the time elapsed since flooding has a significant influence on CH_4 fluxes from boreal and temperate reservoirs. The opposite is true in tropical regions where time elapsed since flooding may have a significant influence on both diffusive, bubbles CH_4 and degassing emissions. This trend was observed only on Petit-Saut reservoir in French Guiana (Abril *et al.*, 2005); however, some old tropical reservoirs show high bubbles emissions (Duchemin *et al.*, 2000; Stallard and Keller, 1994). The model developed on Petit-Saut reservoir predicted very well the dissolved CH_4 concentrations in an Ivory Coast reservoir (Galy-Lacaux *et al.*, 1998).

Evidence suggests that in Flooded Land, CH_4 was generally produced exclusively from flooded soils; the production of this gas could sustain measured fluxes at the water-air interface (Houel, 2003; Duchemin, 2000; Abril *et al.*, 2005).

3a.1 Flooded Land Remaining Flooded Land

This section provides information on how to estimate CH_4 emissions from *Flooded Land Remaining Flooded Land*. This information is drawn from available literature and is intended to be useful to countries that wish to develop preliminary estimates of CH_4 emissions from this source. Countries with potentially significant CH_4 emissions from Flooded Land seeking to report these emissions should consider the development of country-specific emission factors to reduce overall uncertainty. Guidance on the development of such factors is provided in Box 2a.1 in Appendix 2.

3A.1.1 CH_4 EMISSIONS FROM FLOODED LAND REMAINING FLOODED LAND

METHODOLOGICAL ISSUES

Post-flooded CH_4 emissions can occur via the following pathways:

- Diffusive emissions, due to molecular diffusion across the air-water interface;
- Bubble emissions, or gas emissions from the sediment through the water column via bubbles; this is a very important pathway for CH_4 emissions, especially in temperate and tropical regions;
- Degassing emissions, or emissions resulting from a sudden change in hydrostatic pressure, as well as the increased air/water exchange surface after reservoir waters flow through a turbine and/or a spillway (Hélie, 2004; Soumis *et al.*, 2004; Delmas *et al.*, 2005); this is a very important pathway for CH_4 emissions from young tropical reservoirs.

The Tier 1 approach only covers diffusive emissions. Tier 2 includes a term for estimating CH_4 bubble emissions, and if applicable, separate consideration of ice-free and ice-covered periods. Tier 3 methods refer to any detailed measurement-based approach that includes an estimate of all relevant CH_4 fluxes from Flooded Land, which also includes degassing emissions, and considers the depth, the geographical localization and water temperature of the reservoir for its entire life-time. Tier 3 methods are not outlined further in this chapter, but countries should refer to Box 2a.1 in Appendix 2 on the derivation of country-specific emission factors as a resource for implementing a Tier 3 approach. Table 3a.1 summarizes the coverage of the three tiers and CH_4 emission pathway.

TABLE 3A.1 SUMMARY OF METHODS AND EMISSIONS COVERAGE	
	CH_4
Tier 1	• Diffusive emissions
Tier 2	• Diffusive emissions • Bubble emissions
Tier 3	• All emissions

The following section describes the Tier 2 and Tier 1 approaches for CH_4 emissions.

CHOICE OF METHOD

Methane can be emitted from flooded lands through release of bubbles, by diffusion and by degassing. The decision tree in Figure 3a.1 guides inventory compilers through the processes of selecting an appropriate approach for CH_4 emissions from Flooded Land. Tier selection and the level of spatial and temporal disaggregation implemented by inventory compilers will depend upon the availability of activity data and emission factors, as well as the importance of reservoirs as contributors to national greenhouse gas emissions. Country-specific scientific evidence and data are always preferable to Tier 1 default data.

Tier 1

The Tier 1 method for estimating CH_4 emissions from Flooded Land includes only diffusion emissions during ice-free period. Emissions during the ice-cover period are assumed to be zero. Equation 3a.1 can be used with measured emissions provided in Table 3a.2 and country-specific total area of flooded land:

EQUATION 3A.1
CH_4 EMISSIONS FROM FLOODED LANDS (TIER 1)

$$CH_4 Emission_{WWflood} = P \bullet E(CH_4)_{diff} \bullet A_{flood\_total\_surface} \bullet 10^{-6}$$

Where:

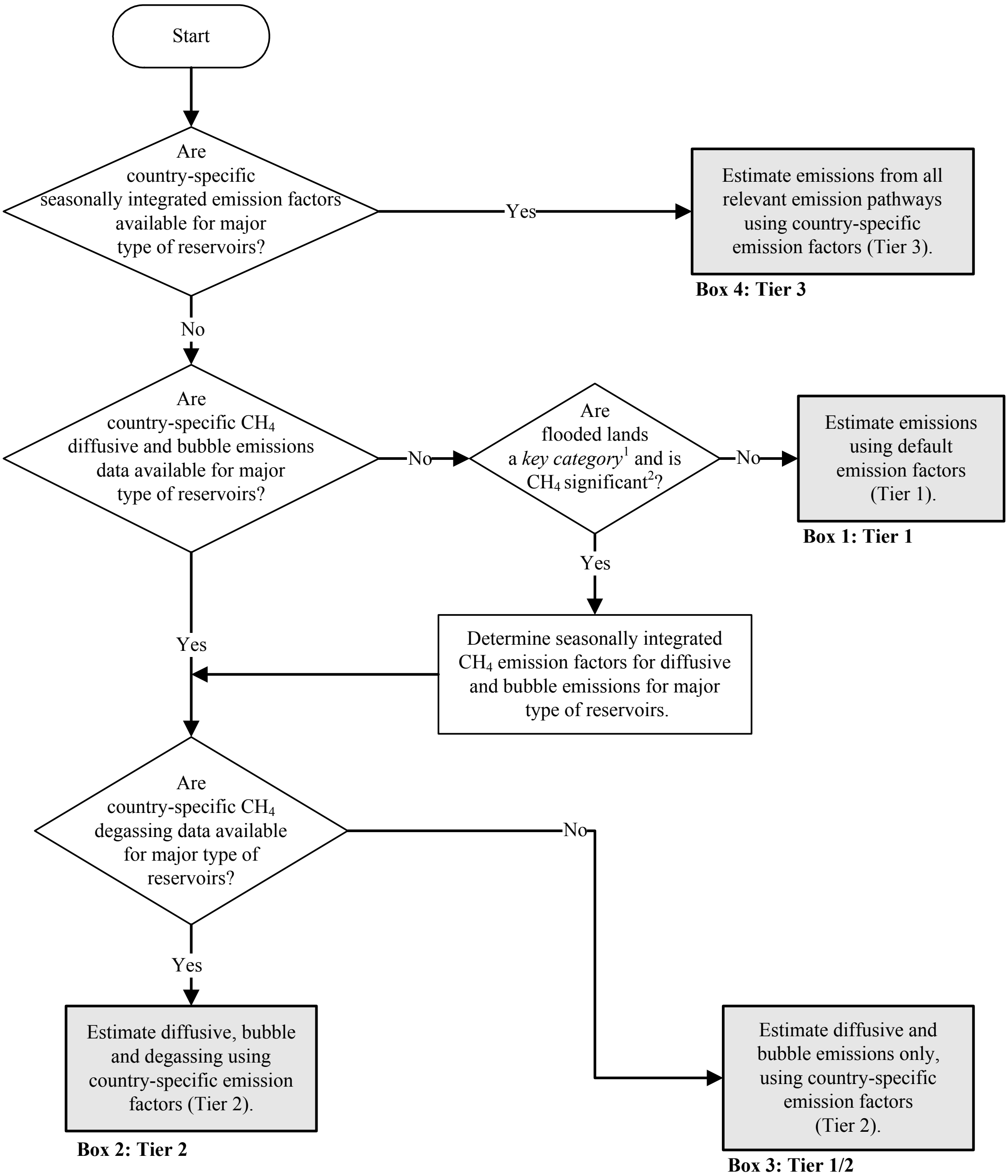
CH_4 emissions$_{WW\ flood}$ = total CH_4 emissions from Flooded Land, Gg CH_4 yr^{-1}

P = ice-free period, days yr^{-1} (usually 365 for annual inventory estimates, or less in country with ice-cover period))

$E(CH_4)_{diff}$ = averaged daily diffusive emissions, kg CH_4 ha^{-1} day^{-1}

$A_{flood,\ total\ surface}$ = total flooded surface area, including flooded land, lakes and rivers, ha

Figure 3a.1 Decision Tree for CH_4 Emissions from Flooded Land Remaining Flooded Land



Note:
1: 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.
2: A subcategory is significant if it accounts for 25-30% of emissions/removals for the overall category.

Tier 2

A Tier 2 approach for CH_4 emissions requires country-specific emission factors for diffusive and bubble emissions, and if applicable, accounts for different rates of diffusion and bubble emissions during the ice-free and ice-covered periods. Flooded land area may also be disaggregated by climatic zone, or any relevant parameter listed in Box 2a.1 in Appendix 2. This approach is described in Equation 3a.2.

EQUATION 3A.2
CH_4 EMISSIONS FROM FLOODED LANDS (TIER 2)

$$CH_4 Emissions_{WWflood} = \begin{bmatrix} \left(P_f \bullet Ef(CH_4)_{diff} \bullet A_{flood,surface}\right) + \\ \left(P_f \bullet Ef(CH_4)_{bubble} \bullet A_{flood,surface}\right) + \\ P_i \bullet \left(E_i(CH_4)_{diff} + E_i(CH_4)_{bubble}\right) \bullet A_{flood,surface} \end{bmatrix}$$

Where:

CH_4 emissions$_{WW\ flood}$ = total CH_4 emissions from Flooded Land per year, kg CH_4 yr^{-1}

P_f = ice-free period, days yr^{-1}

P_i = period with ice cover, days yr^{-1}

$Ef(CH_4)_{diff}$ = averaged daily diffusive emissions from air water-interface during the ice-free period, kg CH_4 ha^{-1} day^{-1}

$Ef(CH_4)_{bubble}$ = averaged daily bubbles emissions from air water-interface during the ice-free period, kg CH_4 ha^{-1} day^{-1}

$Ei(CH_4)_{diff}$ = diffusive emissions related to the ice-cover period, kg CH_4 ha^{-1} day^{-1}

$Ei(CH_4)_{bubble}$ = bubbles emissions related to the ice-cover period, kg CH_4 ha^{-1} day^{-1}

$A_{flood,\ surface}$ = total flooded surface area, including flooded land, lakes and rivers, ha

CHOICE OF EMISSION FACTORS

Tier 1

The key default values for Tier 1 are emission factors for CH_4 via the diffusion pathway. Table 3a.2 provides measured emissions for various climate zones. To the extent possible given available research, these measured emissions integrate spatial (intra reservoir and regional variations) and temporal variations (dry/rainy and other seasonal, inter-annual variations) in the emissions from reservoirs. Default emission factors should be used in Tier 1 for the ice-free period only. During complete ice-cover period, CH_4 emissions are assumed to be zero. When default data are not available, countries should use the closest default emission factors value (emissions of the most similar climatic region).

Tier 2

Under Tier 2, country-specific emission factors should be used instead of default factors to the extent possible. Additional estimates of winter emissions and CH_4 bubble emissions are also needed, which will require the development of country-specific emission factors. It is anticipated that a mix of default values and country-specific emission factors will be used when the latter do not cover the full range of environmental and management conditions. The development of country-specific emission factors is discussed in Box 2a.1 in Appendix 2. The derivation of country-specific factors should be clearly documented, and published in peer reviewed literature.

CHOICE OF ACTIVITY DATA

Several different types of activity data may be needed to estimate flooded land emissions, depending on the tier being implemented and the known sources of spatial and temporal variability within the national territory. These activity data types correspond to the same data required for CO_2 emissions as described in Section 7.3.2.

Flooded land area

Country-specific data on flooded land area are required for all tiers to estimate diffusive and bubble emissions. Alternatively, countries can obtain an estimate of their flooded land area from a drainage basin cover analysis, from a national dam database, from the International Commission on Large Dams (ICOLD, 1998) or from the

World Commission on Dams report (WCD, 2000). Since flooded land area could change rapidly, countries should use updated and recent data. Tier 2 and Tier 3 approaches preferably rely on a national database to track reservoirs surface area. This database should also include other parameters as reservoir depth, year of flooding, reservoir localization (see Box 2a.1 in Appendix 2).

Period of ice-free cover/Period of ice-cover

Under Tiers 2 and 3, the periods during which the reservoirs are ice-free or ice-covered are required to estimate emissions of CH_4 emissions. These data can be obtained from national meteorological services.

Outflow/Spillway volume

Under Tier 3, flooded land outflow and spillway volume are required to estimate degassing emissions of CH_4.

CH_4 concentrations upstream and downstream of dams

Under Tier 3, CH_4 concentrations upstream and downstream of dams would be needed for estimating degassing emissions. Information on how to measure these data can be obtained from the references cited in Box 2a.1 in Appendix 2.

TABLE 3A.2
CH_4 MEASURED EMISSIONS FOR FLOODED LAND

Climate	Diffusive Emissions (ice-free period) $E_f(CH_4)_{diff}$ (kg CH_4 ha^{-1} day^{-1})					References
	Median	Min	Max	N_m	N_{res}	
Polar/Boreal, wet	0.086	0.011	0.3	253	13	Blais 2005; Tremblay *et al.* 2005; Therrien, 2004; Therrien, 2005; Huttunen *et al.*, 2002; Lambert, 2002; Duchemin, 2000
Cold temperate, moist	0.061	0.001	0.2	233	10	Tremblay *et al.*, 2005; Therrien, 2004; Blais, 2005; Lambert, 2002; Duchemin *et al.*, 1999
Warm temperate, moist	0.150	- 0.05	1.1	416	16	Tremblay *et al.*, 2005; Soumis *et al.*, 2004; Duchemin, 2000; Smith and Lewis, 1992
Warm temperate, dry	0.044	0.032	0.09	135	5	Therrien *et al.*, 2005; Therrien, 2004; Soumis *et al.*, 2004
Tropical, wet	0.630	0.067	1.3	303	6	Tavares de lima, 2005; Abril *et al.*, 2005; Therrien, 2004; Rosa *et al.*, 2002; Tavares de lima *et al.*, 2002; Duchemin *et al.*, 2000; Galy-Lacaux *et al.*, 1997; Galy-Lacaux, 1996; Keller and Stallard, 1994
Tropical, dry	0.295	0.070	1.1	230	5	Rosa *et al.*, 2002; Dos Santos, 2000

The values in the second column represent the medians of CH_4 emissions reported in the literature, which themselves are arithmetic means of flux measured above individual reservoirs. The medians are used because the frequency distributions of underlying flux measurements are not normal, and their arithmetic means are already skewed by extreme values. Min and Max values are, respectively, the lowest and highest of all individual measurements within a given climate region; these are provided as an indication of variability only. N_m = number of measurements; N_{res} = number of reservoirs sampled.

These measurements may include non-anthropogenic emissions (e.g., emissions from carbon in the upstream basin) and possible double counting of anthropogenic emissions (e.g., waste water from urban areas in the region of the reservoir) and so may overestimate the emissions.

UNCERTAINTY ASSESSMENT

The two largest sources of uncertainty in the estimation of CH_4 emissions from Flooded Land are the quality of emission factors for the various pathways (diffusive, bubble and degassing) and estimates of the flooded land areas.

Emission factors

As shown in Table 3a.2, average diffusive emissions can vary by an order of magnitude in boreal and temperate regions, and by one to three orders of magnitude in tropical regions. The same variability in bubble emissions is observed in all regions (about one order of magnitude). Therefore, the use of any default emission factor will result in high uncertainty.

CH_4 degasssing emissions are also an important source of uncertainty. Degassing emissions are important component of GHG emissions from flooded tropical lands (Galy-lacaux *et al*., 1997), accounting for more than 40% of the total GHG emissions from a nine year old reservoir (Delmas *et al.*, 2005). However, for many reservoirs degassing emissions are small or negligible (Duchemin, 2000; Soumis *et al.*, 2004). Hence, until additional knowledge becomes available on the dynamics of CH_4 degassing emissions, estimation should be conducted on a case-by-case basis.

To reduce the uncertainties on emissions factors, countries should develop appropriate, statistically-valid sampling strategies that take into account natural variability of the ecosystem under study (Box 2a.1 in Appendix 2). When applicable, the distinction between ice-free and ice-covered periods may be a significant improvement in accuracy (Duchemin *et al.*, 2005). Those sampling strategy should include enough sampling stations per reservoir, enough reservoirs and sampling periods. The number of sampling stations should be determined using recognized statistical approach. Moreover, countries should consider factors included in Box 2a.1 in Appendix 2.

Flooded land surface area

Information on the flooded area retained behind larger dams (>100 km^2) should be available and will probably be uncertain by approximately 10%, especially in countries with large dams and hydroelectric reservoirs. For countries with many flooded lands and where national databases are not available, flooded area retained behind dams will probably be uncertain by more than 50%. Detailed information on the location, type and function of smaller dams may be also difficult to obtain, though statistical inference may be possible based on the size distribution of reservoirs for which data are available. In addition, reservoirs are created for variety of reasons that influence the availability of data, and, consequently, the uncertainty on surface area is dependent on country-specific conditions.

3a.2 Land Converted to Flooded Land

With the actual knowledge, for *Land Converted to Flooded Land*, it is suggested to use measured emissions in Table 3a.2. Inventory compilers should use Tier 1, Tier 2, and Tier 3 methods described in Section 3a.1 to estimate CH_4 emissions from *Land Converted to Flooded Land*.

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