Appendix 2 Possible Approach for Estimating CO_2 Emissions from Lands Converted to Permanently Flooded Land: Basis for Future Methodological Development

The time elapsed since flooding has a significant influence on greenhouse gas fluxes from flooded lands and also on the partition of the gases. Recent statistical analyses on reservoirs worldwide indicate that there is a rapid surge of emissions immediately after flooding, after which emissions return to a relative stable level (Tremblay *et al.*, 2005; Therrien *et al.*, 2005; Soumis *et al.*, 2005; and Huttunen *et al.*, 2002, 2003). The rate of the post-flooding decrease in emissions may depend on the region in which the reservoir is located, but seems to vary in about a 10-year period (Delmas *et al.*, 2005; Abril *et al.*, 2005; Tremblay *et al.*, 2005).

Evidence suggests that CO_2 emissions for approximately the first ten years after flooding are the results of decay of some of the organic matter on the land prior to flooding. The easily degradable carbon and nutrients are made available to producer organisms upon flooding and metabolized. Beyond this time period, CO_2 emissions are sustained by the input of organic material transferred into the flooded area from the watershed (Houel, 2003; Hélie, 2004; Cole and Caraco, 2001). To avoid double-counting of CO_2 emissions, which may already been captured in the greenhouse gas budget of managed lands in the watershed and in the absence of conclusive evidence on the longer term impact of flooding on these emissions, the default methodology only considers the first 10 years post flooding.

Any emissions caused by land-use change activity itself (e.g., CO_2 or non-CO_2 emissions due land clearance before flooding of the land) should be estimated using the methodologies provided elsewhere in this Volume.

Prior to flooding land may be cleared. Organic material may be burnt or may be harvested (e.g., for timber). The resultant emissions should be estimated using the appropriate methodologies in this Volume for estimating the change in the carbon stock before flooding. These emissions should be estimated in the year they occur.

Subsequent to flooding and any land clearing, carbon dioxide emissions from *Land Converted to Flooded Land* can occur via the following pathways:

- Diffusive Emissions, due to molecular diffusion across the air-water interface; this is the major pathway for CO_2 emissions;
- Bubble Emissions, or gas emissions from the sediment through the water column via bubbles; this is a very minor pathway for CO_2 emissions;
- 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 (Duchemin, 2000; Hélie, 2004; Soumis *et al.*, 2004; and Delmas *et al.*, 2005)

This Appendix presents a hierarchy of 3 methods of increasing sophistication called Levels 1, 2 and 3.

Levels 1 and 2 estimate diffusive emissions only. A level 3 method, based on detailed measurements, includes all relevant fluxes of carbon dioxide emissions from flooded lands. Level 3 includes degassing emissions and considers the age, and the geographical location and the water temperature of the reservoir. The Level 3 method is not outlined further in this Appendix, but countries should refer to the Box 2a.1 on derivation of country-specific emission factors as a resource for implementing Level 3. When using Level 3, all relevant emissions from flooded lands should be estimated for the life-time of the reservoir. Table 2a.1 summarizes the coverage of the three levels with respect to CO_2 emission pathways.

BOX 2A.1
DERIVATION OF COUNTRY-SPECIFIC EMISSION FACTORS

Programs to derive country-specific emission factors should carefully consider the potential overlap with other sectors and the proper attribution of emissions. For example, N_2O emissions ultimately due to fertilizer application or sewage treatment in the watershed should not be reported in the Flooded Land category.

In general, the derivation of country-specific emission factors requires actual measurements of greenhouse gas fluxes from reservoir surfaces. Separate emission factors should be developed for the predominant types of reservoirs in the national territory. To minimize the required effort, reservoirs should first be grouped into categories that take into account the main factors responsible for variability among reservoirs, especially climate zone and geological basement (which strongly affects pH). Maps and national ecological stratification can be useful to carry out this task.

Within each reservoir category, a measurement strategy should be designed to obtain representative flux values by reservoir age, morphology, management regime, nutrient status and other relevant factors if necessary. Finally, within any single reservoir, a rigorously designed flux sampling scheme should be applied to take into account the spatial variability caused by variations in depth and water current, proximity to the shore, and presence of aquatic vegetation; and the temporal variability caused by diurnal and seasonal cycles. Flux measurements should be taken over an entire year, preferably over several years.

Useful information can be obtained from the following references: Therrien *et al.*, 2005; Duchemin *et al*., 2006; Delmas *et al.*, 2005; Abril *et al*., 2005; Rosa *et al.*, 2004; Soumis *et al.*, 2004; Tavares de lima, 2002; Huttunen *et al*., 2002; Duchemin, 2000; Duchemin *et al.*, 1999; Rosa *et al*., 1996; and Duchemin *et al.*, 1995.

The development of emission factors should take into account predominant emission types: diffusive, bubbles, and degassing. Measurements of CH_4 and CO_2 aqueous concentrations at various points upstream and downstream of the reservoir are needed to estimate degassing emissions.

TABLE 2A.1
LEVELS AND CO_2 EMISSION PATHWAYS FOR LAND CONVERTED TO FLOODED LAND

	CO_2
Level 1	• Diffusive emissions
Level 2	• Diffusive emissions
Level 3	• All emissions

CHOICE OF METHOD

The flow chart in Figure 2a.1 guides inventory compilers through the processes of selecting the appropriate level. Level selection and the level of spatial and temporal disaggregation implemented by inventory agencies will depend upon the availability of activity and emissions factor data, as well as the importance of reservoirs as contributors to national greenhouse gas emissions.

Level 1

Level 1 provides a simplified approach to estimating CO_2 emissions from reservoirs using default emission factors and highly aggregated area data. The only CO_2 emission pathway included under Level 1 is diffusion during the ice-free period. CO_2 diffusive emissions related to ice-cover period are assumed to be zero. The default assumption is that CO_2 emissions are limited to the first 10 years after the flooding took place, and any subsequent emissions of CO_2 come from carbon entering the reservoir from other land areas (e.g., upstream agriculture). Equation 2.16 of Chapter 2 can be used to estimate the carbon stock change in above-ground living biomass due to land conversion to Flooded Land if above-ground biomass is cleared before flooding. If the above-ground biomass is burned, one should use Equation 2.14 or 2.27 of Chapter 2 (Emissions from biomass burning). In addition, the flux equation, as described below, should be used in all cases to estimate CO_2 emissions from carbon not cleared.

Decay of above-ground biomass left on site and soil organic matter will both contribute to the emissions. Equation 2a.1 shows the Level 1 method for these CO_2 emissions.

EQUATION 2A.1
CO_2 EMISSIONS FROM LAND CONVERTED TO FLOODED LAND (LEVEL 1)

$$CO_2 Emissions_{LWflood} = P \bullet E(CO_2)_{diff} \bullet A_{flood,total\_surface} \bullet f_A \bullet 10^{-6}$$

Where:

CO_2 Emissions$_{LW\ flood}$ = total CO_2 emissions from *Land Converted to Flooded Land*, Gg CO_2 yr^{-1}

P = number of days without ice cover during a year, days yr^{-1}

$E(CO_2)_{diff}$ = averaged daily diffusive emissions, kg CO_2 ha^{-1} day^{-1}

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

f_A = fraction of the total reservoir area that was flooded within the last 10 yrs

The CO_2 emissions estimated by Equation 2a.1 are highly uncertain because the default emission factor does not account for differences in site-specific conditions and time since flooding. The use of Equation 2a.1 may also lead to overestimating emissions when used in conjunction with Equations 2.14, 2.16, or 2.27 in Chapter 2. Countries using a Level 2 method can more accurately represent the proper time profile of the CO_2 emissions following flooding. Guidance on Level 2 methods is given below.

Level 2

Under Level 2, country-specific emission factors are used to estimate CO_2 diffusive emissions. In Level 2, CO_2 emissions can be estimated from reservoirs following the approach shown in Equation 2a.2. As with Level 1, the CO_2 emissions from *Land Converted to Flooded Land* should be estimated only for ten years after flooding when using Level 2 method unless country-specific research indicates otherwise.

The estimation of diffusive emissions can also be extended to distinguish between periods in which the reservoirs are ice-free and those in which they are ice-covered (Duchemin *et al.*, 2006). This may be a significant improvement in accuracy for countries in colder climates. The flooded land area may be further disaggregated by climatic zone, geological basement, or any relevant parameter listed in Box 2a.1.

EQUATION 2A.2
CO_2 EMISSIONS FROM LAND CONVERTED TO FLOODED LAND (LEVEL 2)

$$CO_2 Emissions_{LWflood} = \begin{bmatrix} \left((P_f \bullet E_f(CO_2)_{diff}) + (P_i \bullet E_i(CO_2)_{diff}) \right) \bullet \\ \left(A_{flood,surface} \bullet f_A \bullet 10^{-6} \right) \end{bmatrix}$$

Where:

CO_2 emissions$_{LW\ flood}$ = total CO_2 emissions from *Land Converted to Flooded Land*, Gg CO_2 yr^{-1}

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

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

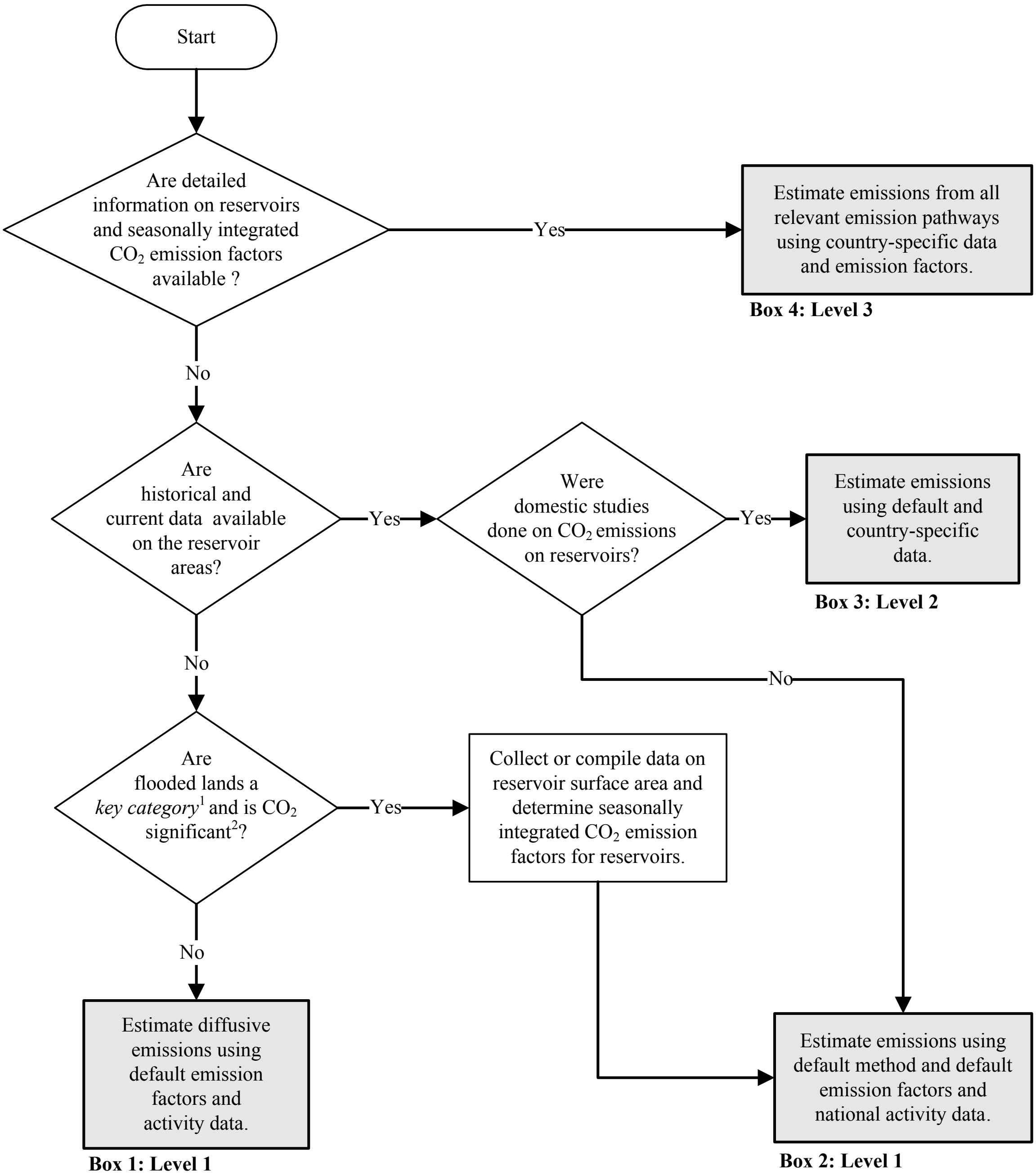
$E_f(CO_2)_{diff}$ = averaged daily diffusive emissions from air water-interface during the ice-free period, kg CO_2 ha^{-1} day^{-1}

$E_i(CO_2)_{diff}$ = diffusive emissions related to the ice-covered period, kg CO_2 ha^{-1} day^{-1}

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

f_A = fraction of the total area flooded within the last 10 yrs, dimensionless

Figure 2a.1 Flow Chart for selection of appropriate level



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.

Level 3

The Level 3 methods for estimating CO_2 emissions are comprehensive and must include additional country-specific data on all relevant CO_2 emission pathways, such as degassing emissions. Emission factors are disaggregated to reflect all relevant sources of temporal and spatial variability (see Box 2a.1). To avoid double counting, Level 3 also requires partitioning emissions from the degradation of flooded organic matter and from the decay of organic matter originating from the watershed.

CHOICE OF EMISSION FACTORS

The key default values needed to implement Level 1 method are emission factors for CO_2 via the diffusion pathways. Table 2a.2 presents measured emissions for various climate zones. These measured emissions integrate known spatial (intra-reservoir and regional variations) and temporal variations (dry/rainy and other seasonal variations, inter-annual variations) in the emissions from reservoirs, as well as fluxes at the water-air interface of reservoirs. Level 1 applies only to the ice-free period. During complete ice-cover period, CO_2 emissions are assumed to be zero, although in reality emissions do occur. All data have been obtained from measurements in hydroelectric or flood control reservoirs.

For Level 2, country-specific emission factors should, to the extent possible, be used and should include emissions during the winter (ice-cover) period. The development of country-specific emission factors is discussed in Box 2a.1. The derivation of country-specific factors should be clearly documented, and ideally published in peer reviewed literature. Guidance in Box 2a.1 is applicable also for derivation of emission factors for Level 3.

CHOICE OF ACTIVITY DATA

Several different types of activity data may be needed to estimate flooded land emissions, depending on the level being implemented and the potential sources of spatial and temporal variability within the national territory.

Flooded land area

For Level 1, the total reservoir area is required, and the proportion flooded in the last ten years (f_A). The use, in a higher level, of more detailed emission profiles over time will require corresponding information on the age distribution of flooded lands. Countries can obtain 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, and because of the 10-year time limit, countries should use updated and recent data of reservoir surface area. Under Level 2, this activity data should be disaggregated by relevant categories (see Box 2a.1). For Level 2 and Level 3, countries should create a national reservoir database with relevant data or information on reservoir names, types, geographical coordinates, year of impoundment, surface area, depth, outflow rate, and other relevant parameters as described in Box 2a.1.

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

Under all levels, the periods during which the reservoirs are ice-free or completely ice-covered are required to estimate CO_2 emissions. This information can be obtained from national meteorological services.

Outflow/Spillway volume

Under Level 3, flooded land outflow and spillway volume are required to estimate degassing emissions of CO_2.

CO_2 concentrations upstream and downstream of dams

Under Level 3, CO_2 concentrations upstream and downstream of dams would be needed for estimation of the degassing emissions. Information on measurement techniques can be obtained from the references cited in Box 2a.1.

TABLE 2A.2 CO_2 MEASURED EMISSIONS FOR FLOODED LAND						
Climate	**Diffusive emissions (ice-free period)** **$E_f(CO_2)_{diff}$ (kg CO_2 ha^{-1} day^{-1})**					**References**
	Median	**Min**	**Max**	**N_m**	**N_{res}**	
Polar/Boreal wet	11.8	0.8	34.5	1011	20	Bergström *et al.*, 2004; Åberg *et al.,* 2004; Huttunen *et al.*, 2002
Cold temperate, moist	15.2	4.5	86.3	633	20	Duchemin, 2000; Schlellhase *et al.,* 1994 ; Duchemin *et al.*, 1999 ; Duchemin *et al.*, 1995; Tremblay *et al.,* 2005
Warm temperate, moist	8.1	-10.3	57.5	507	33	Duchemin, 2000; Duchemin, 2002a ; St-Louis *et al.*, 2000; Smith and Lewis, 1992 ; Tremblay *et al.,* 2005
Warm temperate, dry	5.2	-12.0	31.0	390	43	Soumis *et al.,* 2004 ; Therrien *et al.,* 2005
Tropical, wet	44.9	11.5	90.9	642	7	Keller and Stallard, 1994; Galy-Lacaux *et al.*, 1997; Galy-Lacaux, 1996; Duchemin *et al.*, 2000; Pinguelli Rosa *et al.*, 2002; Tavares de lima *et al.*, 2002; Tavares de lima, 2005
Tropical, dry	39.1	11.7	58.7	197	5	Pinguelli Rosa *et al.*, 2002; Dos Santos, 2000
The values in the second column represent the medians of CO_2 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 greenhouse gas emissions from reservoirs are the emission factors from the various pathways (diffusive, bubble and degassing) and the estimates of reservoir surface areas.

Emission factors

The CO_2 diffusive emissions shown in Table 2a.2 vary by one to two orders of magnitude in boreal and temperate regions, and by one to three in tropical regions. Therefore, the use of any emission factor derived from Table 2a.2 will result in high uncertainty. Since the age of reservoirs has a significant influence on CO_2 fluxes during the first 10 years, the method may result in an underestimation of CO_2 emissions.

CO_2 degasssing emissions, which are typically significant in temperate and tropical regions, are an important source of uncertainty for Level 3. Research demonstrated that these CO_2 emissions accounted for all the greenhouse gas emissions from a reservoir in a temperate dry region, and for up to 30% in temperate moist region (Soumis *et al.*, 2004). In cold temperate regions, degassing CO_2 emissions accounted for less than 5% of the total greenhouse gas emissions from reservoirs (Duchemin, 2000; Hélie, 2003).

To reduce the uncertainties on emissions factors, countries should develop appropriate, statistically valid sampling strategies that take into account factors underlying the temporal and spatial variability of the ecosystem studied (see Box 2a.1).

Flooded land surface area

National statistical information on the flooded area retained behind large dams (> 100km^2) should be available and will probably be accurate to within 10%. Where national database on dams are not available, and other information is used, the flooded land areas retained behind dams will probably have an uncertainty of more than 50%, especially for countries with large flooded land areas. 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. Reservoirs are created for a variety of reasons that influence the availability of data, and, consequently, the uncertainty on surface area is dependent on country-specific conditions.

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