CHAPTER 7

WETLANDS

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7.1 INTRODUCTION

No refinement.

7.1.1 Greenhouse gas emissions and removals from wetlands

No refinement. See guidance in 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands

7.2 MANAGED PEATLANDS

No refinement. See guidance in 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.

7.3 FLOODED LAND

This section provides new guidance.

Flooded Land is comprised of waterbodies where human activities create or change the amount of land area flooded with water, or change the hydrology of existing waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural flux of greenhouse gases. Therefore, Flooded Land includes a broad variety of waterbodies used to meet a number of important human needs (Table 7.7).

TABLE 7.7
TYPES OF FLOODED LAND, THEIR HUMAN USES AND GREENHOUSE GAS EMISSIONS CONSIDERED IN THIS CHAPTER

Flooded Land types	Human Uses	Greenhouse gas emissions for which guidance is provided in this Chapter
Reservoirs (including open water, drawdown zones, and degassing/downstream areas)	Hydroelectric Energy Production, Flood Control, Water Supply, Agriculture, Recreation, Navigation, Aquaculture	CO_2, CH_4
Canals	Water Supply, Navigation	CH_4
Ditches	Agriculture (e.g. irrigation, drainage, and livestock watering)	CH_4
Freshwater Ponds	Agriculture, aquaculture, recreation	CH_4
Saline Ponds	Aquaculture (e.g. fish, crustaceans, algae)	CH_4

Flooded Land emits CO_2, CH_4 and N_2O in significant quantities, depending on a variety of characteristics such as age, land-use prior to flooding, climate, upstream catchment characteristics and management practices. Emissions vary spatially and over time.

CO_2 EMISSIONS

Emissions of CO_2 from Flooded Land remaining Flooded Land are primarily the result of decomposition of soil organic matter and other organic matter within the water body or entering the water body from the catchment, as well as respiration of biota (e.g. bacteria, macroinvertebrates, plants, fish, and other aquatic species). No guidance is provided in this section on these emissions because they are either accounted for elsewhere (Volume 4, Chapter 4, Forest Land, CO_2 emissions from soils Section 4.2.3, Chapter 5, Croplands, CO_2 emission from soils, Section 5.2.3) or reflect short-term carbon cycling by the aquatic biota. When land is flooded for reservoirs, CO_2 emissions occur as the organic matter decomposes, therefore guidance for CO_2 emissions is provided for Land converted to Flooded Land (Section 7.3.2.1).

CH_4 EMISSIONS

Emissions of CH_4 from Flooded Land are primarily the result of methanogenic production of CH_4 induced by anoxic conditions in the sediment (see Annex 7.1). CH_4 emissions are generally higher in waterbodies with high organic matter loading and/or high internal biomass production, and low oxygen status. Due to their high emission rates and large numbers, small ponds of area < 0.1 ha have been estimated to generate 40% of diffusive CH_4 emissions from open waters globally (Holgerson and Raymond, 2016). Whilst emissions from natural ponds can (at least in part) be considered natural, those from small constructed ponds cannot. High organic loadings and low oxygen levels can also occur in drainage ditches (Evans et al., 2016), constructed ponds for agriculture (e.g. Selvam et al. 2014) and aquaculture (Vnimelch and Ritvo 2003), and flooded pastures (Kroeger et al. 2017). Emission rates of CH_4 from small constructed waterbodies may exceed those from small natural waterbodies where nutrient loadings from agriculture or other sources are high (Yang et al. 2017), and may equal or exceed those observed in small lakes and reservoirs (Bastviken et al. 2011). Emissions of CH_4 from aquaculture ponds may be reduced where mixing or aeration occurs or when water is saline as part of aquaculture management (Vasanth et al. 2016, Yang et al. 2017, Robb et al. 2017). Because CH_4 emissions from constructed waterbodies can be considered a direct consequence of the construction of that water body, guidance on reporting these emissions is provided in this chapter.

NITROUS OXIDE EMISSIONS

Nitrous oxide emissions from Flooded Lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. The current section does not consider these emissions in order to avoid double-counting of N_2O emissions already captured in other source categories, such as N_2O from managed soils (see Volume 4, Chapter 11) and wastewater management (see Volume 5, Chapter 6). Nitrous oxide emissions from aquaculture ponds constructed on coastal wetlands are given in Chapter 4 of the 2*013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (2013 Wetlands Supplement)* (Chapter 4, Section 4.3.2).

Reservoirs

Reservoirs are designed to store water over time scales ranging from hours to several years. Their use can serve single (e.g. water supply) or multiple purposes, and the operation may vary depending on different user needs (Table 7.7). Hydropower reservoirs can be divided in three categories: storage, run-of-the-river and pumped storage reservoirs. These categories generally describe the relationship between storage volume, inflow and residence times, but in reality, reservoirs exist on a spectrum. Natural lakes may also be used as reservoirs, often by damming to expand their volume and surface area. Flooded lands are exposed to natural or anthropogenic regulation of water levels, creating a drawdown zone. Greenhouse gas emissions from the drawdown zones are considered significant and similar per unit area to the emissions from the water surface and are therefore included when estimating greenhouse gas emissions from Flooded Lands. Lakes converted into reservoirs without substantial changes in area or residence times are not considered to be managed Flooded Lands, in accordance with the *2006 IPCC Guidelines*.

Reservoirs are classified according to the length of time they have been flooded:

(a) *Land Converted to Flooded Land* – includes reservoirs that were flooded less than 20 years ago.

(b) *Flooded Land Remaining Flooded Land* – includes reservoirs that were converted to Flooded Land more than 20 years ago.

Other Flooded Lands: Constructed ponds, canals, drainage channels, ditches and flooded pastures

Ponds are constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture. They often receive high organic matter and nutrient loadings, have low oxygen levels, and exhibit substantial CH_4 emissions from anaerobic sediments. Artificial linear waterbodies such as canals, drainage channels and ditches are also extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances. The guidance for *Other Flooded Lands* is the same for all age classes of other flooded lands as there are insufficient data to disaggregate based on age classes of the water bodies.

Flooded Lands Excluded Here, But Considered Elsewhere

Emissions from various kinds of Flooded Lands that are not considered in this chapter are provided in the *2013 Wetlands Supplement* and in other parts of the *2006 IPCC Guidelines*. Table 7.8 provides the Ramsar classification, the IPCC terminology used here, and where guidance for greenhouse gas emissions is provided. Some rice paddies are cultivated through flooding of land, but because of the unique characteristics of rice cultivation, rice paddies are addressed in Volume 4, Chapter 5 (Cropland). Emissions from wetlands created or used for wastewater treatment are considered in Chapter 6 of the *2013 Wetlands Supplement* (Constructed Wetlands for Waste Water Treatment) and not considered in this chapter. Seasonally flooded agricultural land (including intensively managed or grazed wet meadow or pasture) that is formed via human modification of natural hydrological processes may also be considered Flooded Land, and can be a significant source of methane emissions (Kroeger et al. 2017). Seasonally flooded agricultural land may be coastal or inland, on mineral or organic soils, and relevant guidance for these categories is provided in the *2013 Wetlands Supplement* (Chapters 3-5, see Table 7.8 for details). Emissions associated with construction of aquaculture ponds in coastal wetlands are also considered in the *2013 Wetlands Supplement* (Section 4.2.4 and Section 4.3.2). Flooding of land to create wetlands in coastal settings due to management activities such as breaching of sea defences are accounted for under "rewetting" within the *2013 Wetlands Supplement* (Section 4.2.3 for CO_2 and 4.3.1 for CH_4). Constructed seawater canals are not considered.

TABLE 7.8
RAMSAR CLASSES OF HUMAN-MADE WETLANDS, IPCC TERMINOLOGY USED AND METHODOLOGICAL GUIDANCE PROVIDED

RAMSAR class[1]	Corresponding wetlands sub-categories in the IPCC terminology	Methodological guidance available?
Water storage areas	Flooded Land	Yes (this chapter)
Ponds	Flooded Land	Yes (this chapter)
Canals and drainage channels, ditches.	Flooded Land	Yes (this chapter)
Aquaculture	Flooded Land	Yes (this chapter) Yes (2013 Wetlands Supplement, Chapter 4)2
Irrigated land (if cultivated)	Cropland	Yes (Vol. 4, Chapter 5)
Seasonally flooded agricultural land	Rice Cultivation	Yes (Vol. 4, Chapter 5)
Seasonally flooded agricultural land including intensively managed or grazed wet meadow or pasture	Wetlands	Yes (*2013 Wetlands Supplement,* Chapters 3, 4 and 5)[3]
Salt exploitation sites	Wetlands	Yes (*2013 Wetlands Supplement,* Chapter 4)
Excavations (partly)	Peatlands managed for peat extraction	Yes (*2013 Wetlands Supplement*, Chapter 2)
Wastewater treatment areas	"Constructed wetlands" or Waste Sector	Yes (*2013 Wetlands Supplement*, Chapter 6; Volume 5, Chapter 6)

NOTES:

[1] Source: Ramsar, 2009

[2] *2013 Wetlands Supplement,* Chapter 4, Section 4.3.2 for N_2O

[3] *2013 Wetlands Supplement* Chapter 3 for guidance on rewetted organic soils (Section 3.2.1 for CO_2, Section 3.2.2. for CH_4 and Section 3.2.3 for N_2O); Chapter 4 for guidance for seasonally flooded agricultural land on land that was previously coastal wetlands (Section 4.2.3 for CO_2; Section 4.3.1 for CH_4) and Chapter 5 for seasonally flooded agricultural land on inland mineral soils (Section 5.2.1 for CO_2 and 5.2.2 CH_4)

Choice of method, activity data and emission factors

We provide guidance for choice of methods, activity data and emission factors for CH_4 emissions for *Flooded Land Remaining Flooded Land* and CO_2 and CH_4 emissions for *Land Converted to Flooded Land*. Tier selection and the level of spatial and temporal disaggregation will depend upon the availability of activity data and emission factors, as well as the importance of Flooded Lands as an emission source based on the key category analysis for a country's national greenhouse gas inventory. Country-specific scientific evidence and data are always preferable to Tier 1 default data.

Box 7.1 provides additional information on factoring out of emissions and removals that would otherwise occur in the absence of the flooded area and how they relate to the Managed Land Proxy. The guidance within the *Flooded Land Remaining Flooded Land* and *Land Converted to Flooded Land* sections adheres to the Managed Land Proxy (See Chapter 3 of this volume).

BOX 7.1 ADDITIONAL INFORMATION ON FACTORING OUT OF EMISSIONS AND REMOVALS FROM UNMANAGED LAND THAT WOULD OTHERWISE OCCUR IN THE ABSENCE OF THE FLOODED AREA

Land converted to Flooded Land may be a source of greenhouse gas emissions or removals prior to flooding. If this land area is already Managed Land, these emissions and removals will be included in existing emissions inventories, and any resulting changes in emissions will be captured by implementing the guidance presented in this Chapter. However, in some circumstances, pre-existing emissions or removals will not be captured in existing inventories. Where these are associated with unmanaged land, the Managed Land Proxy approach dictates that these emissions should not be reported, and guidance for calculating these emissions and removals is therefore not provided in the chapter. However, this Box provides an overview of an approach that could be used, if countries do wish to factor these emissions and removals out of their inventories (see Box 7.2 regarding the treatment of waste water-derived CH_4 emissions from Flooded Land). Potential sources of emissions and removals from Unmanaged Land converted to Flooded Land are:

1) Natural lakes expanded by dam construction: Natural lakes can act as sources of CO_2 derived from carbon transported from the catchment, sinks for CO_2 converted into organic matter and stored in sediments (Appendix 7.2), and sources of CH_4 emissions. The guidance on calculating CO_2 and CH_4 emissions provided in this chapter is based on Flooded Land area calculated as the difference between total reservoir area minus the pre-existing lake area. This effectively factors out pre-existing emissions and removals by the natural lake, (since this area is not part of the Flooded Land, and therefore remains Unmanaged Land) and is consistent with the Managed Land Proxy approach.

2) Unmanaged Wetlands: Natural wetlands in freshwater environments can function as natural sources of CH_4 emissions. Flooding of natural wetlands for reservoir construction therefore reduces natural CH_4 emissions, but simultaneously increases anthropogenic emissions from the Flooded Land area. Wetlands that act as significant sources of CH_4 emissions include inland organic soils (peatlands), inland wetland mineral soils, and low-salinity coastal wetlands (see *2013 Wetlands Supplement* for definitions). Inland wetland mineral soils incorporate seasonally inundated floodplain forests, which can act as significant CH_4 emission sources (Gauci et al., 2018). Natural wetlands on organic soil can also act as continuous sinks for CO_2 via peat formation. All natural wetlands are considered to have negligible N_2O emissions (see *2013 Wetland Supplement*). Because any CH_4 emissions and CO_2 removals by natural wetlands before conversion to Flooded Land occur on Unmanaged Land, factoring out of these emissions would not conform to the Managed Land Proxy approach (*2006 IPCC Guidelines*) and methods for calculating these emissions are therefore not included in the guidance presented in this chapter. However, any countries wishing to factor out emissions and removals associated with Unmanaged Wetlands converted to Flooded Land may consider the approach set out in this Box and in Figure 2.

3) Other Unmanaged Lands: Carbon pools in other Unmanaged Lands, including Forest Land, are likely to be close to long-term steady state. Exceptions may occur at a local or regional level due to natural disturbances such as fires or insect/pathogen attacks, and subsequent ecosystem recovery. Over larger scales and longer time periods, however, net CO_2 emissions or removals should be near-zero. Similarly, CH_4 and N_2O emissions from unmanaged lands (other than CH_4 emissions from wetlands, as noted above) may be considered negligible. Consequently, in most cases it should not be necessary to factor out emissions and removals from Other Unmanaged Lands.

The Decision tree in Figure 2 describes the steps that would be required to factor out emissions from unmanaged land converted to Flooded Land. Emissions and removals from natural lakes that existed prior to reservoir construction are already captured by the existing guidance, as noted above. The key additional requirement is therefore to calculate CO_2 emissions or removals, and CH_4 emissions, from unmanaged wetland areas. As noted above, N_2O emissions can be considered zero because N_2O emissions are largely driven by nitrogen management in non-wetland land uses (particularly cropland and settlements), and considered indirect emissions; see also *2013 Wetlands Supplement*, Chapters 3, 4 and 5).

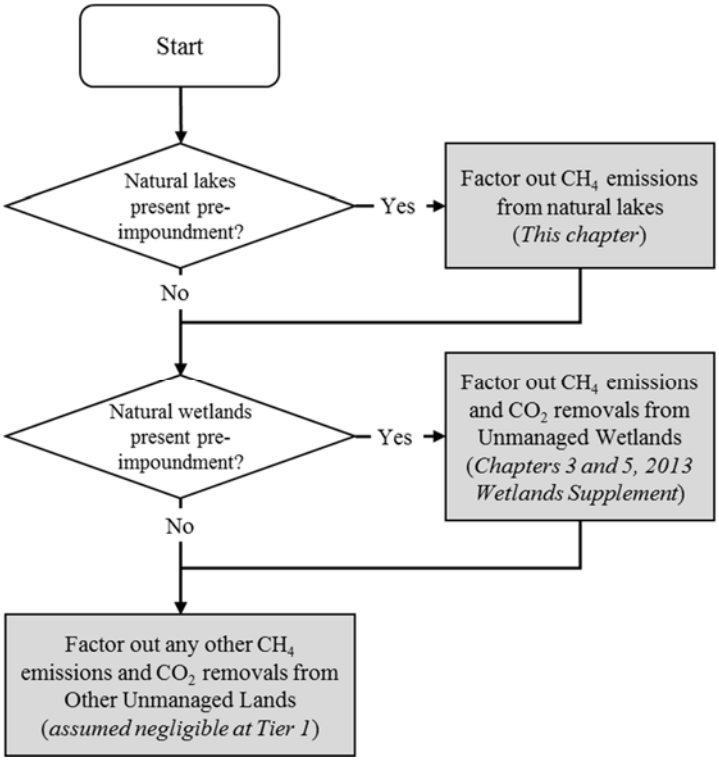
For wetlands on organic soil, relevant information is available in Chapter 3 of the *2013 Wetlands Supplement* (Rewetted Organic Soils). Default emission factors for CO_2 (emission and removals) and CH_4 (emissions) are provided by climate zone and nutrient status (nutrient-poor bog peat and nutrient-rich fen peat) in the *2013 Wetlands Supplement* (Tables 3.1 and 3.3). These emission factors were partly based on empirical data from natural sites (see *2013 Wetland Supplement,* Annexes 3A.1, 3A.3) as a proxy for re-wetted sites, and are therefore appropriate for estimating emissions and removals from unmanaged wetlands on organic soil.

For coastal wetlands, relevant information is available in Chapter 4 of the *2013 Wetlands Supplement*. A single Tier 1 emission factor for CH_4 emissions from re-wetted tidal freshwater and brackish wetlands is given in the *2013 Wetlands Supplement* Table 4.14, providing the best available analogue for CH_4 emissions from natural wetlands in this category. Saline coastal wetlands (salinity > 18 ppt) are considered to have zero CH_4 emissions.

For unmanaged inland wetland mineral soils, it should only be necessary to estimate CH_4 emissions. Relevant information for this category is provided in Chapter 5 of the *2013 Wetlands Supplement*. Default Tier 1 emission factors for CH_4 from inland wet mineral soils with raised water levels are provided, by climate zone, in *2013 Wetlands Supplement* Table 5.4. These emission factors were mainly derived from studies of natural wetlands (see *2013 Wetland Supplement* Annex 5A.2) and are therefore appropriate for this purpose.

If other emissions or removals from unmanaged land are considered to be important, it will be necessary to develop a higher-tier approach to account for these, because no default emission factors are available in existing guidance. However, in most circumstances there should be no significant long-term net emissions or removals of any greenhouse gas by any non-wetland land categories that are not managed.

Figure 7.2 Decision tree for factoring out emissions from Unmanaged Land converted to Flooded Land. See Box 7.1



7.3.1 Flooded Land Remaining Flooded Land

This section provides new guidance.

7.3.1.1 CO_2 EMISSIONS FROM FLOODED LAND REMAINING FLOODED LAND

This section provides new guidance.

The initial flooding of land can cause elevated CO_2 emissions as inundated soil and biomass decay. After this initial phase, the CO_2 emitted from Flooded Land is largely derived from carbon input from the catchment, which is accounted for elsewhere as emissions from other land categories. Therefore, no methodologies to report CO_2 emissions for *Flooded Land Remaining Flooded Land* are provided. It is assumed that any CO_2 emissions that are occurring result from C losses in the watershed are already covered by methodologies in other land use sectors (i.e., Volume 4, Chapter 4 Forest Land, Chapter 5 Cropland, Chapter 6 Grassland, Chapter 8 Settlements and the *2013 Wetland Supplement*).

7.3.1.2 NON-CO_2 EMISSIONS FROM FLOODED LAND REMAINING FLOODED LAND

This section provides new guidance.

RESERVOIRS

Choice of Method

The following methodology is provided for estimating CH_4 emissions from reservoirs more than 20 years old. The Tier 1 methodology includes diffusive and ebullitive CH_4 emissions (see Glossary) from reservoirs over differing climate zones (F_{CH4tot}). The methodology can be adjusted for the area of Flooded Land prior to reservoir construction for countries that want to factor out these prior emissions (see Box 7.1) and for downstream emissions (see Glossary) of CH_4 associated with the reservoir.

If sufficient data exist, it is *good practice* for the compiler to develop country-specific emission factors using a Tier 2 or Tier 3 method to reduce overall uncertainty. Guidance on the development of country-specific factors and methods is provided below in the Tier 2 and 3 sections. For reservoirs less than 20 years old, see section 7.3.2.3, within *Land Converted to Flooded Lands*.

Tier 1

A Tier 1 approach to calculate CH_4 emissions from Flooded Lands Remaining Flooded Lands (flooded > 20 years prior to inventory):

EQUATION 7.10
ANNUAL CH_4 EMISSIONS FOR RESERVOIRS >20 YEARS OLD (*FLOODED LAND REMAINING FLOODED LAND*)

$$F_{CH_4tot} = \sum_{j=1}^{6} \sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH_4age>20,j} \bullet A_{flooded,j,i} + R_d \bullet EF_{CH_4age>20,j} \bullet A_{total,j,i} \right)$$

Where:

$A_{flooded,j,i}$ Area of land that is newly flooded as a result of reservoir construction for reservoir 'i' located in climate zone 'j'. [ha]

$A_{total,j,i}$ Total area of reservoir water surface for reservoir 'i' located in climate zone 'j' [ha]

$EF_{CH4\ age>20,j}$ Emission factor for methane emitted from the reservoir surface for reservoir > 20 years old located in climate zone 'j' [kg CH_4 ha^{-1} y^{-1}] (Table 7.9 - *Emissions factors table*)

F_{CH4tot} Total annual flux of methane from all reservoirs > 20 years old in all climate zones [kg CH_4 yr^{-1}]

$nres_j$ Number of reservoirs of this age class in climate zone 'j'

R_d A constant equal to the ratio of total downstream emission of methane to the total flux of methane from the reservoir surface [dimensionless]. Equals 0.09 by default for Tier 1 (Table 7.10). See text below for Tiers 2 & 3 R_d values.

α_i Emission factor adjustment for trophic state in reservoir i within a given climate zone. [dimensionless] Equals 1.0 by default for Tier 1. See Equation 7.11 for Tiers 2 & 3.

Equation 7.10 takes into account that land cover by natural lakes and rivers prior to flooding is not included as Flooded Land.

Tier 2

At the Tier 2 level, downstream emissions can be estimated based on water withdrawal depths at individual reservoirs. If water is withdrawn from the oxic (upper) part of the water column, downstream emissions can be assumed to be zero. If water is withdrawn from the anoxic (lower) part of the water column, downstream emissions should be estimated following equation 7.10 using the R_d factor found in Table 7.10 or by a Tier 3 methodology.

If a country has characterized the trophic status of its reservoirs, a compiler can improve estimates of CH_4 emissions from these systems by multiplying default CH_4 emission factors (from Table 7.8) by a factor, α_i, either computed from measured chlorophyll-*a* (Chl-*a*) data using Equation 7.11, or taken from Table 7.11 where trophic state may be known but Chl-*a* data are lacking. Equation 7.11 generally provides a more accurate approach where reservoir Chl-*a* concentrations [Chl-*a*] have been measured. If sufficient data are available locally to determine a country-specific relationship between trophic status and CH_4 fluxes, then local values should be used in equation 7.8 rather than these global averages.

Countries can factor out emissions and removals that would otherwise occur in the absence of the reservoir (see Box 7.1). For example, it is also possible to include the effect of carbon burial in the sediments in case there is a net removal of carbon in the reservoir (see Box 7.2).

BOX 7.2 ADDITIONAL INFORMATION ON SEDIMENTATION AND CARBON BURIAL IN RESERVOIRS

Reservoirs are often sites of significant accumulation of sediments, and therefore carbon (Clow et al. 2013). However, to consider such carbon accumulation as an offset to greenhouse gas emissions is complex because it depends strongly on the origin of the sediments and what the fate of the associated carbon would have been in the absence of a reservoir (Prairie et al. 2017). For example, particulate organic carbon from the upstream catchment sediments would, prior to impoundment, have been transported and possibly stored further downstream. Only the net additional C storage induced by the sediment trapping within the reservoir would constitute removal. Similarly, if carbon burial is the result of autochthonous (inside the reservoir) primary production by algae or aquatic plants, such carbon removal would necessarily be reflected in the CO_2 exchange occurring at the air-water interface. Subtracting C sedimentation from the air-water exchange would thus lead to a double counting of the same carbon flux. Lastly, in many reservoirs, maintenance operations involve the sluicing of excess sediments to the downstream river by opening gates located at the base of the dam, thereby releasing large but unknown amounts of accumulated sediment carbon over a short period.

As a result of the processes described above and the difficulties in quantifying them, a Tier 1 methodology cannot be developed for the reporting of sediment carbon accumulation. For the development of higher Tier methodologies for carbon accumulation in reservoirs, an important guiding principle is that only the portion of the carbon permanently buried in reservoir sediments that would not have been stored elsewhere in the hydrological network (including the coastal ocean) could potentially be considered as an offset to reservoir greenhouse gas emissions.

Tier 3

Direct measurements of CH_4 diffusion and ebullition fluxes across the reservoir surface provide the most accurate alternative to the Tier 1 and Tier 2 approaches. It is *good practice* to undertake measurements at sufficient different locations and sufficient different times of year to capture both the spatial and temporal variability of CH_4 emissions from a reservoir (see UNESCO/IHA 2010 for additional guidance). CH_4 emissions are often highly spatially variable, with 50-90 % of total reservoir emissions emanating from 10-30% of a reservoir's surface (typically in areas subject to high organic matter deposition such as the distal arms receiving significant catchment inflows (Sherman et al 2012)).

Downstream emissions are composed of degassing emissions (see Glossary) and diffusive CH_4 emissions from the river downstream of the dam. Degassing can be measured directly in the water conduit from the reservoir or where the water from the reservoir is exposed to atmospheric pressure. Degassing can also be estimated as the difference between the dissolved gas concentration at the water intake depth upstream of the dam, and the dissolved gas concentration downstream of the dam, multiplied by the outlet discharge. Diffusive emission from the downstream river can be directly measured or estimated using a mass balance approach. See UNESCO/IHA 2010 section 2.4.1.2.3.

Accuracy is improved when measurements are undertaken across a full seasonal cycle because methane dynamics are very temperature sensitive. The measurement data should be area-weighted and seasonally averaged to provide the most accurate estimate of emissions from the reservoir as a whole (See Annex 7.1 for details).

CH_4 emissions from individual reservoirs can also be estimated by application of the Greenhouse Gas Reservoir Tool (G-res) model (Prairie et al. 2017b) with reservoir-specific data covering: reservoir morphometry, littoral areas, and local climate data including temperature and solar radiation. G-res is described in more detail in Annex 7.1. Other detailed models could be developed that include the range of environmental and management conditions that influence emissions (see Annex 7.1).

Choice of Emission Factors

Tier 1

Emission factors for CH_4 via diffusion and ebullition from the reservoir surface, $EF_{CH4,j}$, in the six aggregated climate zones are provided in Table 7.9. The emission factors integrate both spatial and temporal variations and have been derived from the application of empirical models to a large (>6000) number of reservoirs with a worldwide distribution (see Annex 7.1 for details) and are averaged per climate zone.

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TABLE 7.9

CH_4 EMISSION FACTORS FOR RESERVOIRS OLDER THAN 20 YEARS (> 20 YEARS) – FLOODED LAND REMAINING FLOODED LAND

Climate Zone		CH_4 Emission Factors $EF_{CH4\ age>20,j}$ (kg CH_4 ha^{-1} $year^{-1}$)		
	j	**Lower 95% CI**	**Average**	**Upper 95% CI**
Boreal	1	1.0	13.6	153.8
Cool Temperate	2	2.9	54.0	262.8
Warm temperate/dry	3	7.8	150.9	848.7
Warm temperate/moist	4	9.2	80.3	434.6
Tropical dry/montane	5	12.2	283.7	1188.4
Tropical moist/wet	6	9.2	141.1	608.3

References. Boreal: Tremblay et al. 2005; Teodoru et al. 2012; Demarty et al. 2011; Demarty et al. 2009; Brothers et al. 2012; Kelly et al. 1994; Roehm et al. 2006; Tadonléké et al. 2012; Duchemin et al. 1995; Huttunenet al. 2002; Fedorov et al. 2015. Cool temperate: Harrison et al. 2018; Matthews et al. 2005; Hendzel et al. 2005; Venkiteswaran et al. 2013; Kelly et al. 1997; Deemer et al. 2011; Maeck et al. 2013; Huttunenet al. 2002; Gruca-Rokosz et al. 2011; Gruca-Rokosz et al. 2010; Beaulieu et al. 2014a; Beaulieu et al. 2014b. Warm temperate/dry: Warm temperate/moist: Rosa et al. 2004; Dos Santos et al. 2006; Harrison et al. 2018; Li et al. 2015; Maeck et al. 2013; Gruca-Rokosz et al. 2010; Zhao et al. 2013; Wu 2012; Yang et al. 2013; Chen et al. 2011; Lu et al. 2011; Zhen 2012; Xiao et al. 2013; Zhu et al. 2013; Zhao et al. 2015; Li et al. 2014; Bevelhimer et al. 2016; Mosher et al. 2015. Tropical dry/montane: Diem et al. 2012; Ometto et al. 2013; Pacheco et al. 2015; Roland et al. 2010; Sturm et al. 2014; DelSontro et al. 2011; Selvam et al. 2014; Bansal et al. 2015; DelSontro et al. 2010; Eugster et al. 2011; Kumar & Sharma 2016; Teodoru et al. 2015; Almeida et al. 2016. Tropical moist/wet: Therrien et al. 2005;Tremblay et al. 2005; Bergström et al. 2004; Guérin et al. 2006; Kemenes et al. 2007; Kemenes et al. 2011; Musenze et al. 2014; Rosa et al. 2004; Dos Santos et al. 2006; St. Louis et al. 2000; Ometto et al. 2013; Bergier et al. 2011; Duchemin et al. 2000; Roland et al. 2010; Keller et al. 1994; Joyce et al. 2003; Selvam et al. 2014; Deshmukh 2013; Deshmukh et al. 2014; Abril et al. 2005; Rosa et al. 2003; Lima 2005; Lima et al. 2002; Lima et al. 1998; Marcelino et al. 2015

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TABLE 7.10

RATIO OF TOTAL DOWNSTREAM FLUX OF METHANE (KG CH_4 HA^{-1} YR^{-1}) TO THE FLUX OF METHANE FROM A RESERVOIR'S SURFACE TO THE ATMOSPHERE (KG CH_4 HA^{-1} YR^{-1}) – R_D

Median	Upper 95% CI of the median	Lower 95% CI of the median	Number of reservoirs
0.09	0.22	0.05	36

Note: The default Tier 1 value is the median of all R_d values reported in the literature. The 95% confidence interval of the median was calculated using the bias-corrected and accelerated (BCa) bootstrap interval.

References: Teodoru et al. 2012, Diem et al. 2012; DelSontro et al. 2016; Maeck et al. 2013; Soumis et al. 2004, Beaulieu et al. 2014; Bevelhimer et al. 2016; Descloux et al. 2017; Delsontro et al. 2011; dos Santos et al. 2017; Kumar and Sharma. 2017; Chanudet et al. 2011; Abril et al. 2005; Bastien et al. 2013; Deshmukh et al. 2016; Serca et al. 2016; Guérin et al. 2006; Kemenes et al. 2007

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447 ***Tier 2***

448 Under Tier 2, reservoir-specific emission factors may be developed that take into account additional country-
449 specific circumstances as well as specific properties of individual reservoirs including: reservoir operation, size,
450 and depth; relative locations of oxic/anoxic water and water intakes; trophic status; sedimentation and
451 sequestration of carbon; and other environmental (e.g. seasonal ice cover) and management factors. CH_4 emissions
452 due to wastewater inflow can be estimated and factored out of reservoir emissions (see Box 7.3).

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BOX 7.3 ADDITIONAL INFORMATION ON EMISSIONS ARISING FROM WASTEWATER WITHIN RESERVOIRS

Emissions of CH_4 from both *Land Converted to Flooded Land* and *Flooded Land Remaining Flooded Land* result from the degradation of autochthonous and allochthonous organic carbon in anoxic conditions (Bastviken et al. 2004). Eutrophic reservoirs may receive allochthonous organic carbon from treated and/or untreated wastewater that is converted to CH_4 within the reservoirs (Deemer et al. 2016). At Tier 3 level it is a *good practice* to factor out CH_4 emission from wastewater treatment and discharge, (included in Volume 5, Chapter 6), to avoid double counting.

Tier 3

Under Tier 3, emission factors derived from models (mechanistic or statistical) or measurement campaigns may be used instead of the default equations and/or default factors (see Annex 7.1). It is anticipated that a mix of country-specific emission factors and modelled values will be used when the latter do not cover the full range of environmental and management conditions within a country. The development of reservoir- or region-specific emission factors that are influenced by eutrophication is discussed below. The derivation of reservoir or region-specific factors should be clearly documented.

EQUATION 7.11

EQUATION USED TO SCALE CH_4 EMISSION FACTORS FOR THE INFLUENCE OF EUTROPHICATION USING MEASURED VALUES OF CHLOROPHYLL A

$$\alpha_i = 0.26 \bullet Chla_i$$

Where:

α_i Emission factor adjustment for trophic state in reservoir 'i'. [dimensionless] Equals 1.0 for Tier 1.

$Chla_i$ Mean annual chlorophyll-a concentration in reservoir 'i' [µg L^{-1}]

When chlorophyll values are not available, the trophic state adjustment factor (α_i, Eq. 7.11) can be estimated from other general assessments of reservoir trophic status according to Table 7.11.

TABLE 7.11 RELATIONSHIPS BETWEEN TROPHIC INDEX (TI), SURFACE CONCENTRATIONS OF CHLOROPHYLL-A (Chl-*a*), AND TOTAL PHOSPHORUS (TP), AND, SECCHI DEPTH (SD, METRES), AND TROPHIC CLASS[1] AND TROPHIC STATE ADJUSTMENT FACTOR (α_i)

TI	Chl-*a* (µg/L)	TP (µg/L)	SD (m)	Trophic Class	Trophic State Adjustment Factor α_i Range and (recommended value)
<30 - 40	0 - 2.6	0 - 12	> 8 - 4	Oligotrophic	0.7 (0.7)
40 - 50	2.6 - 20	12 - 24	4 - 2	Mesotrophic	0.7 - 5.3 (3)
50 - 70	20 - 56	24 - 96	2 - 0.5	Eutrophic	5.3 - 14.5 (10)
70 - 100+	56 - >155	96 - >384	0.5 - < 0.25	Hypereutrophic	14.5 - 39.4 (25)

[1] Carlson 1977

Choice of Activity Data

Several different types of activity data may be needed to estimate Flooded Land emissions, depending on the Tier and the known sources of spatial and temporal variability within the national territory.

Tier 1

Flooded land area

Country-specific data on the area of reservoirs within each climate zone are required to estimate CH_4 emissions from Flooded Lands. Estimates of Flooded Land area for reservoirs behind large dams can be obtained from the International Commission on Large Dams (ICOLD, 1998), from the World Commission on Dams report (WCD, 2000), or from the Global Reservoir and Dam (GRanD) database (Lehner et al., 2008). However, country-specific datasets are likely to be more complete.

Tier 2

Estimates of flooded land area for reservoirs can be obtained from a drainage basin cover analysis or from a national dam database. Because flooded land area could change over time, countries should use updated and recent data from national databases in order to obtain more accurate emission estimates. Water withdrawal depths and anoxic zone depths are required for estimating downstream emissions at the Tier 2 level. These data can be obtained from national dam operation databases.

Data to directly calculate the trophic status adjustment, α_i, (Eq 7.11, Table 7.11) can usually be sourced from water quality databases held by the relevant water authorities. Remote sensing of Chl *a* concentrations may also be possible for larger reservoirs.

Information on wastewater input to the reservoir, or other anthropogenic sources to be factored out, must be derived from national or local information for each reservoir (see Box 7.3).

Tier 3

Tier 3 approaches include modelled assessments validated by local methane emission measurements (see UNESCO/IHA 2010 for additional guidance). Such assessments may include modifying the models presented here to more accurately reflect local measurements, or the development of other validated and transparent local or national models. Compilers may also consider within-year and between-year variation in emissions as a function of climatic or land-management variability, or maintenance activities such as dredging. Tier 3 approaches are likely to require the development of process-based models or spatial and temporal models based on measurements to address these additional variables and activities influencing emissions.

OTHER CONSTRUCTED WATERBODIES (FRESHWATER PONDS, SALINE PONDS, CANALS, DRAINAGE CHANNELS AND DITCHES)

The procedure presented here expands the methodology developed for quantifying CH_4 emissions from drainage ditches in organic soils described in the *2013 Wetlands Supplement*, to include all other constructed waterbodies apart from reservoirs, which are considered separately in the previous section. The approach described here allows for the reporting of emissions from other Flooded Lands including constructed freshwater and saline ponds used for agriculture, aquaculture or other activities, and canals, drainage channels and ditches. Inventory compilers may also choose to 'embed' emissions from small channels such as drainage ditches within their reporting of other Managed Land categories (applying the methodology described here, together with Equation 2.6 of the *2013 Wetlands Supplement*[1]). The same emissions should however not be included in both categories.

Choice of Method

Methodology is provided for estimating CH_4 emissions from all other constructed waterbodies, including ditches and ponds. If CH_4 emissions from other constructed waterbodies are a key category, then it is *good practice* for the compiler to develop country-specific emission factors with application of a Tier 2 method or develop a country specific method with a Tier 3 approach to reduce overall uncertainty. Guidance on the development of country-specific factors or methods is provided below in Tier 2 and Tier 3 approaches.

Tier 1

The Tier 1 method extends the methodology developed for quantifying CH_4 emissions from drainage ditches in organic soils for the *2013 Wetlands Supplement* (Section 2.2.2.1) to include a wider range of constructed waterbodies.

[1] Note that the approach described to account for ditch CH_4 emissions in the *2013 Wetlands Supplement* combined these emissions with those from adjacent terrestrial areas, to provide a single emission estimate. Implicitly, this approach considered ditches to form part of the terrestrial land-use category, rather than as a separate Flooded Land category. Either approach may be used, but not both.

Total emissions are calculated for a given waterbody type using Equation 7.12.

Equation 7.12
Annual CH_4 emission from Other Constructed Water Bodies

$$F_{CH_4other} = \sum_{j=1}^{6}\sum_{w=1}^{3}\sum_{i=1}^{nother_{w,j}} \left(A_{j,w,i} \bullet EF_{CH4,j,w} \bullet \alpha_{j,w,i} \right)$$

Where:

$F_{CH4other}$ Total annual flux of methane from ponds and channels [kg CH_4 yr^{-1}]

$A_{j,w,i}$ Area of other water body 'i' of type 'w' in climate zone 'j' [ha]

$\alpha_{j,w,i}$ Emission factor adjustment for trophic state other water body 'i' of type 'w' located in climate zone 'j'. Currently = 1 for all tiers. [dimensionless] Refer to Eq. 7.11, Table 7.11.

$EF_{CH4,j,w}$ Emission factor for other water body of type 'w' in climate zone 'j' [kg CH_4 ha^{-1} y^{-1}]. Refer to Table 7.12.

$nother_{w,j}$ Number of other waterbodies of type 'w' in climate zone 'j'

Tier 2

The Tier 2 approach for CH_4 emissions from constructed agriculture and aquaculture ponds, and from canals, drainage channels and ditches, incorporates country-specific information in Equation 7.12 to estimate the emissions. Tier 2 emission factors may be further stratified by sub-classifying waterbodies according to type (w) and trophic status ($\alpha_{j,w,i}$). In addition, it may be possible to incorporate additional modifiers such as soil type (e.g. mineral versus organic); water flow rate; salinity; presence of emergent vegetation (which may increase emissions) and species (for aquaculture); or take account of site management activities that may increase or decrease overall CH_4 emissions (e.g., controlling organic matter loadings or aeration, including pond drainage).

Tier 3

A Tier 3 approach for constructed ponds and channels used for agricultural purposes may take account of soils and land-use within the catchment area of each waterbody as controls on organic matter and nutrient inputs. It could also disaggregate the different components of CH_4 emissions (diffusive flux across the water surface, ebullition and plant-mediated emissions) and the associated controlling factors in order to provide more site-specific emission estimates. Compilers may also consider within-year and between-year variation in emissions as a function of climatic or land-management variability, or maintenance activities such as dredging. Tier 3 approaches are likely to require the development of a process-based model to address these additional variables and activities influencing emissions as the small size and large number of water bodies in some countries may make measurement based approaches infeasible. For aquaculture ponds, Tier 3 approaches could also include models incorporating management practices (e.g. species, yield, aeration, drainage regimes).

Choice of Emission Factors

Tier 1

Tier 1 emission factors for agriculture and aquaculture ponds, and from canals, drainage channels and ditches, are provided in Table 7.12. At present, available data are not sufficient to derive emission factors for any category by climate zone, or to disaggregate emissions from canals, drainage channels and ditches, which are therefore considered as a single Tier 1 category. Disaggregation by surrounding land-use, nutrient loading and/or yield is also not currently possible at Tier 1. For ditches in organic soils, the Tier 1 emissions factors presented in Table 2.4 of the *2013 Wetlands Supplement* may be used.

588

589

TABLE 7.12
CH_4 EMISSION FACTORS FOR OTHER CONSTRUCTED WATER BODIES (FRESHWATER PONDS, SALINE PONDS, CANALS, DRAINAGE CHANNELS AND DITCHES)

Waterbody type	Climate zone	EF_{CH4} [a] (kg CH_4 ha^{-1} yr^{-1})	95% confidence intervals[b] (kg CH_4 ha^{-1} yr^{-1})	No. of sites
Saline ponds	All	30	16-55	15
Freshwater and brackish ponds	All	183	118-228	68
Canals, drainage channels and ditches	All	416	259-669	24[c]

[a] Emissions factors for each category were calculated from the mean of log_{10}-transformed values, because untransformed observations showed a positively skewed distribution in all cases

b 95% confidence intervals shown are derived from standard errors, and thus represent the uncertainty in the mean emission factor rather than the variability of the original measurements.

[c] Ditch data are mostly aggregated to study level, where studies reported multiple measurements from the same ditch network or from sites in close proximity; therefore the total number of individual ditches used to derive the emission factor exceeds the number shown.

References. Saline ponds: Cameron et al., 2018; Castilo et al., 2018; Chen et al., 2016; Hai, 2014; Strangmann et al., 2008; Vasanth et al., 2016; Yang et al., 2005; Freshwater and brackish ponds: Baker-Blocker et al., 1997; Casper et al., 2000; Grinham et al., 2018; Hu et al., 2016; Huang 2016; Liu et al., 2017; Merbach, 1996; Natchimuthu et al., 2014; Selvam et al., 2014; Stadmark & Leonardsson, 2005; van Bergen, 2015; Singh et al., 2000; Xiong et al., 2017; Yang et al., 2017; Zhu et al., 2016; Canals, drainage channels and ditches: Best & Jacobs, 1997; Chamberlain et al., 2015; Chistotin et al., 2006; Evans et al., 2017; Harrison, 2003; Hendricks et al., 2007; Kosten et al., 2018; McPhillips et al., 2016; McNamara, 2013; Peacock et al., 2017; Schrier-Uijl et al., 2010; Schrier-Uijl et al., 2018; Selvam et al., 2014; Sirin et al., 2012; Teh et al., 2011; van den Pol-van Dasselaar et al., 1999; Vermaat et al., 2011; Wang et al., 2009; Yu et al., 2017.

590

591 ***Tier 2***

592 At Tier 2, country-specific emission factors may be further stratified according to waterbody type, nutrient status
593 or other potential explanatory factors (e.g. management practices or yield for aquaculture), as described in the
594 preceding section.

595 ***Tier 3***

596 To develop a model-based Tier 3 approach, additional empirical data are needed to define relationships between
597 each component of the CH_4 emission and the relevant explanatory variables. These components could include the
598 effects of temperature, organic matter and nutrient supply on CH_4 production; effects of salinity, water depth and
599 flow on methane production in the sediment and oxidation within the water column; relationships between
600 sediment composition and bubble production; and influence of vegetation type and cover on plant-mediated
601 emissions.

602

603 ## Choice of Activity Data

604 All constructed ponds and ditches are assumed to emit CH_4 at a constant average rate for as long as the land
605 remains flooded. However, they may move between emission categories as a function of changes in site factors if
606 higher tier approaches are applied. Activity data consist of the total area of (non-reservoir) constructed
607 waterbodies, stratified according to the waterbody type and any additional factors used to disaggregate emissions.
608 Since flooded land area could change over time, countries should use updated and recent data. Tier 2 and Tier 3
609 approaches are preferably based on a national database to track flooded land surface area in order to obtain more
610 accurate emission estimates. For aquaculture ponds, additional data on product yields from ponds or management
611 could be collected and related to CH_4 emissions to derive more accurate emission estimates.

612 ***Tier 1***

613 Activity data required to support Tier 1 reporting are either complete mapping data for all constructed waterbodies,
614 or alternatively a reliable estimate of the proportion of land area occupied by each waterbody type, such as
615 estimated derived from a land use survey. For agricultural ponds, it may be possible to evaluate small
616 representative areas within a larger land category in order to estimate the total proportion (and therefore total area)

of ponds present. In many cases, drainage occurs at regular spacing within agricultural landscapes, such that the proportion of ditches in an area ($Frac_{ditch}$) can be estimated from data on mean ditch width and spacing, as described in Section 2.2.2.1 of the *2013 Wetland Supplement*. For irregularly distributed ditches or other constructed channels such as canals, it may be possible to estimate overall extent and area by digitizing or estimating total channel length within representative areas. For area of aquaculture ponds, estimates of area are available from FAO (http://www.fao.org/fishery/statistics/global-aquaculture-production/en).

Tier 2

Additional activity data required to apply a Tier 2 approach are likely to include information on waterbody distribution (e.g. from remotely sensed imagery), waterbody type, nutrient status, flow rates, vegetation and other factors as described in the *Choice of Method* section. For aquaculture ponds national databases of pond area or pond yields on an area basis, disaggregated by region or species cultivated could be used.

Tier 3

Tier 3 approaches could include dynamic modelling of emissions evaluated from monitoring of greenhouse gas concentrations and fluxes in representative systems or measurements of emissions on fine spatial and temporal scales. Additional activity data required to apply a Tier 3 approach are likely to include information on waterbody distribution from remotely sensed imagery, waterbody type, nutrient status, flow rates, vegetation and other factors as described above. National level information capturing the effect of pond management (e.g. drainage, Yang et al. 2015) or activity (Gusmawati et al. 2017) may also be appropriate to use with a Tier 3 method.

7.3.2 Land Converted to Flooded Land

This section provides new guidance.

7.3.2.1 CO_2 Emissions from Land Converted to Flooded Land

RESERVOIRS

Conversion of land to Flooded Land is a disturbance that affects all five terrestrial C pools in the area impounded (above-ground biomass, below-ground biomass, litter, dead wood and soil organic matter; see *2006 IPCC Guidelines* (Volume 4 Chapter 2, Fig. 2.1). The *2006 IPCC Guidelines* and *2013 Wetlands Supplement*, in addition to Chapter 2 of this volume, give guidance on how to estimate the five carbon pools in the land to be flooded and guidance is provided in Chapter 12 for estimating harvested wood products (HWP). This Chapter gives new guidance on emissions related to the land use conversion and the subsequent emissions from the newly flooded land.

Carbon stock changes in the five pools that occur prior to Land Converted to Flooded Land need to be taken into account using the *2006 IPCC Guidelines* (Volume 4, Chapter 2; Equation 2.3). The amount and fate of flooded biomass depends largely on management decisions prior to flooding. The area to be impounded may be totally or partially cleared of biomass including vegetation and the organic matter in soils prior to flooding. Another management procedure may be the burning of the biomass. If the pre-impoundment area was forested, and the forest was harvested before flooding, part of the biomass removed can go to harvested wood products (HWP), but organic matter from grasslands or croplands most likely remains.

The time elapsed since flooding has a significant influence on greenhouse gas fluxes from Flooded Lands and also on the partitioning of the gases. Statistical analyses on reservoirs worldwide indicate that there is a rapid surge of emissions immediately following flooding, after which emissions return to a relatively 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 a reservoir is located, but seems to vary mainly during the decade following initial flooding (Delmas *et al.*, 2005; Abril *et al.*, 2005; Tremblay *et al.*, 2005; Teodoru et al, 2012). Since reporting of Flooded Land may be a new category for countries, refer to *2006 IPCC Guidelines* (Volume 1, Chapter 5) to recalculate the inventory time series.

Evidence suggests that CO_2 emitted during approximately the first decade after flooding results from decay of some of the organic matter on the land prior to flooding. Upon flooding, the easily degradable carbon and nutrients are made available to the microbial community and metabolized. Beyond this time period, CO_2 emissions are sustained by the decomposition of organic matter in soils and the input of organic material transferred into the flooded area from the watershed (Houel, 2003; Hélie, 2004; Cole and Caraco, 2001).

In addition to managed lands, unmanaged lands such as natural forests and peatlands, existing (smaller) waterbodies and other land cover types not considered to be managed land may be converted to Flooded Land (see Box 7.1). This guidance describes methods for reporting emissions from each land use / land cover type converted to Flooded Land.

Choice of Method

Organic matter is subject to slow decay after flooding. Therefore it is not appropriate to report C losses of all biomass, dead wood, litter and soil organic matter in the first year after land is converted to Flooded Land. Because *Land Converted to Flooded Land* is defined as the first 20 years after flooding, the expected emissions of the CO_2 from the flooded stock of organic matter is distributed over these 20 years (see below). C stocks are estimated using existing methodologies when possible (e.g. *2006 IPCC Guidelines*, e.g. Volume 4, Chapter 2).

The most important factors considered for estimating on-site CO_2 emissions upon conversion to Flooded Lands are the flooded organic matter stock, the time elapsed since flooding, climate, land cover, and previous land use. Therefore, the Tier 1 methodologies developed in this chapter are based on soil organic carbon stock as an indicator of the overall carbon stock of the system that integrates the impact of land cover and land use in the pre-flooded conditions. The scientific background for the approach is described in Annex 7.1.

Organic C pools that remain in the impoundment area after flooding are subject to slow decomposition constrained by reduced presence of oxygen. The fate of organic matter removed from the area prior to flooding can vary. For example, biomass removed from the impoundment area prior to impoundment, e.g., by harvesting of timber, slash or stumps, is reported according to the *Guidance* for HWP (Volume 4, Chapter 12). The CO_2 and non-CO_2 emissions of deliberately burned biomass are reported according to *2006 IPCC Guidance* (Volume 4, Chapter 2). The biomass remaining in the impoundment area after flooding becomes submerged (except for that in the drawdown zone) and a fraction of this organic matter is subsequently decomposed to CO_2 (for more details, see Annex 7.1). The carbon in biomass, dead wood, litter and soil organic matter in the drawdown zone of a reservoir is considered completely lost during the first year following the conversion.

Annex 7.1 explains how the G-res model generates CO_2 emissions for newly flooded land using average organic carbon stock in the top 30 cm soil layer as an empirically-based proxy for the total flooded organic matter decay (Annex 7.1, Section 1.5). Tier 1 emission factors are derived by determining the average, spatially interpolated soil organic C stock for the flooded landscape area from a global soil carbon map (FAO, or default reference soil organic C stocks from Volume 4, Chapter 2. Table 2.3)

Tier 1

The basic methodology for estimating annual carbon loss as CO_2 on recently flooded land (<20 years old) is specified in Equation 7.13.

EQUATION 7.13
ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM NEWLY FLOODED LAND

$$F_{CO2} = \sum_{j=1}^{6} \sum_{i=1}^{nres_j} \sum_{k=1}^{nsoil} A_{flooded,j,i} \bullet \phi_{i,k} \bullet SOC_{j,k} \bullet M_j$$

Where:

$A_{flooded,j,i}$ Area of land that is newly flooded as a result of construction of reservoir 'i' located in climate zone 'j' [ha]

$\underline{F_{CO2}}$ Net annual CO_2 emissions from land converted to Flooded Land less than 20 years ago [tonnes C yr^{-1}].

$nres_j$ Number of reservoirs ≤ 20 years old in climate zone 'j'

$SOC_{j,k}$ Soil C stock (tonnes C ha^{-1} in 0-30 cm depth) values per climate zone (j) and soil type (k) from Table 2.3 (2006-Guidelines) or from FAO Global Soil organic C map (http://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/1070492/)

i Summation index for the number of waterbodies of same type in same climate zone

j Summation index for climate zones (j = 1-12, see table 7.11)

k Summation index for soil type

$\phi_{i,k}$ The fraction of reservoir '*i*' area with soil type k [dimensionless]

M_j Scaling factor per climate zone to convert SOC stocks based on empirical relationships between emissions estimated from G-res (integrated 100 year emissions post-flooding reported as a constant yearly flux for the first 20-year post-flooding) and soil C stocks and climate. (see Annex 7 for more explanations). [y^{-1}] Values in Table 7.13.

nsoil Number of soil types (= 6, see Volume 2, Table 2.3)

Guidance on CO_2 emissions from removal of mangrove and tidal marsh vegetation for aquaculture is given in the *2013 Wetland Supplement* (Chapter 4, Coastal Wetlands).

TABLE 7.13 SCALING FACTOR VALUE FOR EQUATION 7.13, ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM NEWLY FLOODED LAND. M_J = SCALING FACTOR [Y^{-1}]

IPCC climate zones	Aggregated climate zone	*M*			
		Nb reservoir	Lower 95% CI	Average	Upper 95% CI
Boreal dry	Boreal	118	0.0075	0.0091	0.0107
Boreal moist					
Polar dry					
Polar moist					
Cool temperate dry	Cool temperate	2103	0.0141	0.0146	0.0151
Cool temperate moist					
Warm temperate dry	Warm temperate dry	679	0.0541	0.0568	0.0595
Warm temperate moist	Warm temperate moist	2095	0.0291	0.0302	0.0312
Tropical dry	Tropical dry/montane	902	0.0846	0.0900	0.0954
Tropical montane					
Tropical moist	Tropical moist/wet	920	0.0628	0.0668	0.0708

Note: Scaling factors were derived from the integrated CO_2 emissions attributable to the reservoir estimated from the Gres model (see Annex 7.1 for details, Praire et al. 2017b) expressed as a fraction of soil organic carbon content (SOC) and applied to the first 20 years post-impoundment.

Tier 2

Tier 2 methods for determining annual CO_2 emissions/removals from newly flooded land would include knowledge of country and climate zone emission factors in equation 7.13. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Improvements to the Tier 1 approach may include: 1) a derivation of country-specific emission factors; 2) specification of climate sub-domains considered suitable for refinement of emission factors; 3) a finer, more detailed classification of management systems with a differentiation of pre-flooding land-uses; 4) differentiation of emission factors by time since flooding, 6) a finer, more detailed classification of nutrient status or other water quality attributes, e.g. nitrogen, phosphorus, chlorophyll.

For compatibility of approach, country-specific Tier 2 factors for CO_2 emissions and removals, compiled using domestic flux data measured at the water-atmosphere boundary should follow a similar general concept to the G-res model, used in this guidance for generating Tier 1 emission factors (see details in Annex 7.1).

An alternative method can use observed data on the decay curve of CO_2 release to the atmosphere from the surface of the water body. These observations include a declining annual CO_2 emission due to the newly flooded organic matter, and a natural annual background release of CO_2 that should not be included in the annual emissions. Instead, the natural emissions should be subtracted from the declining emissions in order to obtain the apparent CO_2 release from the newly flooded land. The shape of the declining curve of annual CO_2 release does not need to follow a specific equation, as long as it asymptotically declines until as reservoirs age and can be integrated.

It is *good practice* to derive country-specific emission factors if measurements representing the national circumstances are available. Countries need to document that methodologies and measurement techniques are consistent with the scientific background for Tier 1 emission factors in Annex 7.1. Moreover, it is *good practice* for countries to use a finer classification for climate and management systems. Note that any country-specific emission factor must be accompanied by sufficient national or regional land-use/management activity and environmental data to represent the appropriate climate sub-domains and management systems for the spatial domain for which the country-specific emission factor is applied.

Tier 3

CO_2 emissions/removals at Tier 3, compared to those at Tier 2, would use detailed data and models of soil carbon and other remaining carbon pools prior to flooding and time series of CO_2 emissions after flooding for a range of reservoirs that encompass an appropriate range of environmental conditions. Details for the development of measurement and model based methods are discussed in Annex 7.1.

Choice of Emission Factor

Tier 1

CO_2 emissions are calculated using the scaling factors in Table 7.13.

Tier 2

The Tier 2 approach for CO_2 emissions/removals from Flooded Land incorporates country-specific information with derivation of country-specific scaling factors. The compiler may address other drivers of emissions including: 1) specification of climate sub-domains considered suitable for refinement of emission factors; 2) a finer, more detailed classification of management systems; 3) time-series data that incorporate seasonal/annual variation in CO_2 emissions/removals. Country-specific soil maps, measured in situ data, or updated versions of global soil databases with GIS tools can be used in estimating the soil organic carbon stocks for 0-30 cm top soil layer within the flooded area.

Tier 3

The Tier 3 method explicitly addresses the pre-flooding management of Flooded Land and its impact on CO_2 emissions following flooding with process-based modelling and/or measurement-based approaches. These factors are discussed in Annex 7.1.

Choice of Activity Data

Tier 1

Areas of newly flooded lands are available from dam operators such as hydropower companies. In many cases recent impoundments have been extensively described in Environmental Impact Assessment (EIA) documents of specific projects. Those documents are often publicly available. In absence of such information sources, satellite images and aerial images taken during the past 20 years are commonly available and allow determination of flooded land areas by comparison of pre-impoundment and post-impoundment images. Estimation of drawdown zone areas can be done using remote sensing images taken during the time period of low water level in reservoirs.

Tiers 2 and 3

Tier 1 methods can be used for determining the areas of flooded lands. When more accurate management systems are identified with pre-impoundment land use characteristics of the flooded land, such information could be derived from project-specific Environmental Impact Assessment documents, forest surveys from the pre-impoundment period, or remotely-sensed land cover assessments.

Many countries also monitor water quality parameters from watercourses impacted by management activities. These include industrial effluent disposal, mining, land drainage, wastewater treatment, etc. In the best cases, time series of water quality parameters are available in national registers for over 20 years and may be useful for applying Tier 3 emission factors differentiated by those parameters.

OTHER CONSTRUCTED WATERBODIES (DITCHES, CANALS, FARM PONDS AND AQUACULTURE PONDS)

No specific methodologies are provided to account for CO_2 emissions resulting from land conversion to other constructed waterbodies as there are insufficient CO_2 emission data. However, compilers may estimate CO_2

emissions for coastal wetlands converted to aquaculture ponds by excavation based on guidance in the *2013 Wetlands Supplement* (Chapter 4, Coastal Wetlands). For all types of pond created by damming, the methodology described above to account for CO_2 emissions from land converted to reservoirs may be used.

7.3.2.2 NON-CO_2 EMISSIONS FROM LAND CONVERTED TO FLOODED LAND

This section provides new guidance.

RESERVOIRS

In reservoirs, high levels of CH_4 emissions can occur in the first 20 years following flooding (see Annex 7.1).

Choice of Method

Tier 1

For Tier 1 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*. The Tier 1 approach to calculate CH_4 emissions from *Land Converted to Flooded Land* (flooded < 20 years prior to inventory) is represented by Equation 7.14, which differs from Equation 7.10 only in the values of the emission factors, $EF_{CH4\ age<20,j}$.

EQUATION 7.14
ANNUAL CH_4 EMISSIONS FOR RESERVOIRS < 20 YEARS OLD (*LAND CONVERTED TO FLOODED LAND*)

$$F_{CH_4 tot} = \sum_{j=1}^{6} \sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH_4 age<20,j} \bullet A_{flooded,j,i} + R_d \bullet EF_{CH_4 age<20,j} \bullet A_{total,j,i} \right)$$

Where:

$A_{flooded,j,i}$ Area of land that is newly flooded as a result of reservoir construction for reservoir 'i' located in climate zone 'j'. [ha]

$A_{total,j,i}$ Total area of reservoir water surface for reservoir 'i' located in climate zone 'j' [ha]

$EF_{CH4\ age<20,j}$ Emission factor for methane emitted from the reservoir surface for reservoir > 20 years old located in climate zone 'j' [kg CH_4 ha^{-1} y^{-1}] (Refer Table 7.14)

F_{CH4tot} Total annual flux of methane from all reservoirs < 20 years old in all climate zones [kg CH_4 yr^{-1}]

$nres_j$ Number of reservoirs of this age class in climate zone 'j'

R_d A constant equal to the ratio of total downstream emission of methane to the total flux of methane from the reservoir surface [dimensionless]

α_i Emission factor adjustment for trophic state in reservoir i within a given climate zone. [dimensionless] Equals 1.0 for Tier 1.

Tier 2

For Tier 2 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Tier 3

For Tier 3 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Choice Emission Factors

Emission factors for CH_4 via diffusion and ebullition for Land converted to Flooded Land in the six aggregated climate zones are provided in Table 7.14. As for Flooded Land remaining Flooded Land (Table 7.9), the Emission Factors integrate both spatial and temporal variations and have been derived from the application of empirical models to a large (>6000) number of reservoirs with a worldwide distribution (see Annex 7.1 for details) and are averaged per climate zone.

TABLE 7.14
CH_4 EMISSION FACTORS FOR RESERVOIRS < 20 YEARS OLD – LAND CONVERTED TO FLOODED LAND

Climate Zone		CH_4 Emission Factors $EF_{CH4\ age<20,j}$ (kg CH_4 ha^{-1} $year^{-1}$)		
	j	**Lower 95% CI**	**Average**	**Upper 95% CI**
Boreal	1	2.4	27.7	172.8
Cool Temperate	2	7.8	84.7	299.3
Warm temperate dry	3	20.0	195.6	966.0
Warm Temperate moist	4	19.0	127.5	489.6
Tropical dry/montane	5	28.2	392.3	1374.8
Tropical moist/wet	6	25.8	251.6	858.0

References: Boreal: Tremblay et al. 2005; Teodoru et al. 2012; Demarty et al. 2011; Demarty et al. 2009; Brothers et al. 2012; Kelly et al. 1994; Roehm et al. 2006; Tadonléké et al. 2012; Duchemin et al. 1995; Huttunenet al. 2002; Fedorov et al. 2015. Cool temperate: Harrison et al. 2018; Matthews et al. 2005; Hendzel et al. 2005; Venkiteswaran et al. 2013; Kelly et al. 1997; Deemer et al. 2011; Maeck et al. 2013; Huttunenet al. 2002; Gruca-Rokosz et al. 2011; Gruca-Rokosz et al. 2010; Beaulieu et al. 2014a; Beaulieu et al. 2014b. Warm temperate/dry: Warm temperate/moist: Rosa et al. 2004; Dos Santos et al. 2006; Harrison et al. 2018; Li et al. 2015; Maeck et al. 2013; Gruca-Rokosz et al. 2010; Zhao et al. 2013; Wu 2012; Yang et al. 2013; Chen et al. 2011; Lu et al. 2011; Zhen 2012; Xiao et al. 2013; Zhu et al. 2013; Zhao et al. 2015; Li et al. 2014; Bevelhimer et al. 2016; Mosher et al. 2015. Tropical dry/montane: Diem et al. 2012; Ometto et al. 2013; Pacheco et al. 2015; Roland et al. 2010; Sturm et al. 2014; DelSontro et al. 2011; Selvam et al. 2014; Bansal et al. 2015; DelSontro et al. 2010; Eugster et al. 2011; Kumar & Sharma 2016; Teodoru et al. 2015; Almeida et al. 2016. Tropical moist/wet: Therrien et al. 2005;Tremblay et al. 2005; Bergström et al. 2004; Guérin et al. 2006; Kemenes et al. 2007; Kemenes et al. 2011; Musenze et al. 2014; Rosa et al. 2004; Dos Santos et al. 2006; St. Louis et al. 2000; Ometto et al. 2013; Bergier et al. 2011; Duchemin et al. 2000; Roland et al. 2010; Keller et al. 1994; Joyce et al. 2003; Selvam et al. 2014; Deshmukh 2013; Deshmukh et al. 2014; Abril et al. 2005; Rosa et al. 2003; Lima 2005; Lima et al. 2002; Lima et al. 1998; Marcelino et al. 2015

Choice of Activity Data

Tier 1

For Tier 1 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Tier 2

For Tier 2 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Tier 3

For Tier 3 Guidance refer to section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

OTHER CONSTRUCTED WATERBODIES (DITCHES, CANALS, FARM PONDS AND AQUACULTURE PONDS)

For Guidance, see section 7.3.1 Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*. There is insufficient information to derive separate emission factors for CH_4 emissions for recently constructed ponds and canals, drainage channels and ditches.

7.3.3 Uncertainty Assessment

This section has further elaboration of methods.

The two largest sources of uncertainty in the estimation of CH_4 emissions from Flooded Land are the quality of emission factors and estimates of the flooded land areas.

Flooded Land surface area

For reservoirs, national statistical information on the flooded area retained behind large dams (> 100 km^2) should be available and will probably be accurate to within 10 percent. Where national databases 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 percent, 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, and this will influence the availability of data. Consequently, the uncertainty on surface area is dependent on country specific conditions.

Uncertainties in estimating emissions and removals from other constructed water bodies (ditches, canals, farm ponds and aquaculture ponds) are to a large extent derived from assumptions and uncertainties in the area to which the EFs are applied. Variation in salinity of aquaculture ponds may also contribute to uncertainty in CH_4 emissions (see *2013 Wetland Supplement*, Chapter 4).

Emission factors

As shown in Tables 7.9 and 7.14, average emissions can vary both within and among climate regions. Therefore, the use of any default emission factor will result in high uncertainty as reflected in the 95% confidence intervals and discussed in Annex 7.1.

Downstream CH_4 emissions occur primarily when anoxic and methane-rich hypolimnetic water (i.e. the lower water layer in a stratified water column) is withdrawn from a reservoir and passed through the dam structure, including turbines in hydropower reservoirs, and discharged to a downstream river (see Annex 7.1 for a more detailed description). Accordingly, downstream emissions are typically negligible in well-oxygenated reservoirs (Diem et al. 2012) or those with epilimnetic withdrawal (Beaulieu et al. 2014), but can exceed emissions from the reservoir surface in thermally stratified systems with hypolimnetic withdrawal (Kemenes et al. 2007, Abril 2005). At the Tier 1 level, downstream emissions are estimated from R_d, defined as the average ratio of downstream to surface emissions. Sources of uncertainty in R_d include differences among studies in how fluxes from the reservoir surface and downstream or the reservoir were measured. Uncertainty can be reduced at the Tier 2 and 3 levels by accounting for the reservoir mixing patterns and withdrawal depths 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. When applicable, the distinction between ice-free and ice-covered periods may be a significant improvement in accuracy (Duchemin *et al.*, 2005). Those sampling strategies should include enough sampling stations per reservoir, enough reservoirs and sampling periods. The number of sampling stations should be determined using a recognized statistical approach (see IHA (2010) for measurement guidelines).

The EF values for EF in Table 7.12 represent global averages and have large uncertainties due to variability in climate and management practices, including depth of the water body, salinity of water, presence of emergent vegetation, recharge rate and (for aquaculture) the intensity of management, including fish feeding characteristics and pond aeration.

7.4 INLAND WETLAND MINERAL SOILS

No refinement. See guidance in 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.

No refinement.

7.5 COMPLETENESS, TIMES SERIES CONSISTENCY, AND QA/QC

No refinement.

~~7.6 FUTURE METHODOLOGICAL GUIDANCE~~

This section from the 2006 Guidelines is no longer relevant with the guidance provided in the 2013 Wetlands Supplement and the Flooded Lands guidance provided in Section 7.3 of this chapter.

Annex 7.1 Estimation of Default Emission Factor(s) for greenhouse gas emissions from Flooded Lands

A7.1.1 Background on CH_4 cycling in Flooded Land

CH_4 emissions from aquatic environments are the combined result of CH_4 production, oxidation and transport processes, which are described in e.g. Bastviken (2009), Bridgham et al. (2013), Duc et al. (2010), and Bogard et al. (2014) (the two former being reviews and the two latter describing updates). A summary is provided below:

Production and oxidation of CH_4

Methane production is a microbially-mediated process that primarily occurs in anoxic sediment. Sediment methanogenesis represents the terminal step in the anaerobic degradation of organic matter, and is strongly stimulated by anoxic conditions, a high load of labile organic matter, and a high temperature. Inhibition is induced by the presence of molecular oxygen (O_2) and other alternative electron acceptors in organic matter degradation, such as nitrate, iron (III), manganese (IV) and sulphate. Because sulphate is common in waters with high salinity, methanogenesis in the upper sediments is often low under saline conditions (Reeburgh 2007).

Methane oxidation in aquatic environments is primarily a microbial process in which dissolved CH_4 is used as a carbon and energy source. Therefore, CH_4 oxidation takes place at redox gradients where both CH_4 and suitable electron accepting compounds are present. Anaerobic CH_4 oxidation using e.g. nitrate and sulphate has been observed and sulphate-dependent methane oxidation can be important in saline sediments. In freshwater environments, O_2 dependent CH_4 oxidation is considered to dominate (Bogard et al., 2014). By being confined to redox gradients, CH_4 oxidation is therefore often most intense in spatially restricted zones near the interface between anoxic and oxic conditions in water columns, or in the top millimetres of sediments overlain with oxic water (below a few mm depth most sediments are anoxic). The oxidation of CH_4 can be extensive and reported removal of dissolved CH_4 during passage through a zone with oxidation often range from 50 to >95% (Bastviken et al., 2009). Aerobic CH_4 oxidation *in situ* is considered to be primarily substrate dependent, i.e. to depend largely on concentrations and supply rates of CH_4 and O_2.

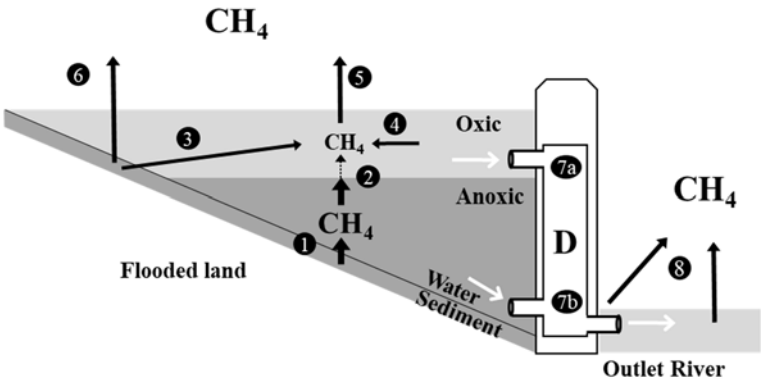
The transport of CH_4 through waterbodies

With reference to processes numbered in Figure A1, the transport of CH_4 through a reservoir can be described as follows (Bastviken 2009):

CH_4 produced in anoxic sediments, and subsequently dissolved in the water, is transported along the concentration gradient by Fickian transport (molecular diffusion or eddy diffusion) into the hypolimnion water **(1)**. The transport of CH_4 from the hypolimnion into the epilimnion is often very small due to limited mixing between water layers and because extensive microbial CH_4 oxidation occurs at the interface where both CH_4 and O_2 are present (Bastviken et al. 2008) **(2)**. The release of CH_4 from epilimnetic sediments is also constrained by CH_4 oxidation, similarly occurring at the oxycline in the top several mm of the sediment **(3)**. However, water movements such as waves can speed up CH_4 transport across the epilimnetic sediment-water interface (Bussman 2005), reducing the fraction being oxidized. Additional epilimnetic CH_4 can be sustained by production in the oxic water (Bogard et al. 2014) **(4)**. The dissolved CH_4 in surface water is emitted across the diffusive boundary layer at the water-atmosphere interface (diffusive emission). The diffusive emission rates are stimulated by high CH_4 concentrations and high turbulence in the water **(5)**. The solubility of CH_4 in water is rather low, and therefore CH_4 bubbles are formed in the sediment. Emissions to the atmosphere by ebullition occur when such CH_4-rich bubbles are released and rapidly rise through the water column into the atmosphere **(6)**. Ebullition can be the dominant flux pathway, and is influenced by CH_4 production rates in the sediment, physical triggers releasing bubbles such as drops in barometric pressure, changes in the water level or waves. CH_4 emissions can also occur via rooted emergent aquatic plants with gas transporting aerenchyma tissue. These structures can function as gas conduits between sediments and the atmosphere. Such plant-mediated emission can be substantial and depends on CH_4 production, plant abundance, activity and species composition. In reservoirs, water, with its dissolved CH_4, is withdrawn into the dam structure (D) inlet and released to the outlet river **(7a and 7b)**. The dissolved CH_4 can then be degassed to the atmosphere upon passage through dam structures or emitted after release to the outlet river **(8)**. Both degassing and reservoir-related emissions from the outlet river are a result of the reservoir, but occur downstream of the reservoir surface and are collectively referred to in this chapter as downstream emissions. Downstream emissions are low if oxic epilimnetic water with low CH_4 concentrations is withdrawn **(7a)**, but can be high if anoxic, CH_4 rich hypolimnetic water is withdrawn **(7b)**.

The degassing of the water in the turbines is relevant in hydroelectric reservoirs only, but the other parts of the description in Figure A1 are valid for non-hydroelectric reservoirs and for non-reservoir waterbodies.

Figure A1 Methane related transport within and from waterbodies, exemplified with a reservoir with an anoxic hypolimnion. For explanations of numbered processes, see text.



Emissions of CH_4

Aquatic CH_4 emissions are favoured by high methane production and by conditions facilitating transport pathways where most CH_4 escapes oxidation. Conditions leading to a high whole system methane production rates include low salinity (Camaco et al 2017), high temperatures (Yvon-Durocher et al. 2014; Deemer et al. 2016); Delsontro et al. 2016), and a high load of labile organic matter (Delsontro et al. 2016; Delsontro et al. 2018; Deemer et al. 2016). Because the whole-system potential for primary production of labile organic matter increases with area, the overall CH_4 production potential in freshwaters in a given climate zone is also positively related to the flooded area. In this guidance: salinity is considered to improve the estimation of emissions from coastal aquaculture ponds (Tier 1); temperature is considered by disaggregating emission factors by climate zones and including temperature seasonality when generating emission factors (Tier 1); methanogenic habitat extent is considered by including the area of the flooded land in calculations (Tier 1); and the supply of labile organic matter is considered via the trophic state adjustment option (Tier 2; see also below).

Conditions favouring rapid transport from sediments to the atmosphere by ebullition or via plants, bypassing CH_4 oxidation zones, include shallow water depth and a high abundance of emergent aquatic plants. These conditions are indirectly considered at the whole climate zone level at the Tier 1 via validation to available data, but are highly variable among waterbodies and consideration for individual waterbodies can therefore only be performed at the Tier 3 level. Downstream emissions also represent situations where high water turbulence causes rapid emission of CH_4 with little time for oxidation. Downstream emissions are considered at Tier 1, and are estimated using empirical relationships between CH_4 fluxes from water body surfaces and observed downstream emissions.

Trophic status and greenhouse gas emissions from Flooded Lands

Flooded lands with high inputs of nutrients and high rates of biological production (eutrophic systems) generally emit methane to the atmosphere more rapidly on a per-area basis than less productive (meso- or oligotrophic) systems. This relationship is seen in meta-analyses examining fluxes from many reservoirs (Narvenkar et al., 2013, Deemer et al., 2016), and a positive relationship between local primary production and methane emission has also been demonstrated in laboratory assays using sediments from individual lakes (West et al., 2015). One recent review of available data found that, on average globally, per-area CH_4 fluxes are 8.0 times higher for eutrophic reservoirs than for mesotrophic reservoirs, which in turn have CH_4 fluxes that are, on average, 1.7 times as high as those from oligotrophic systems (Deemer et al., 2016). Therefore, when possible, we recommend that countries include an estimate of trophic status in their estimates of reservoir CH_4 emissions allowing adjustment of emission factors at Tier 2. Trophic status designation is generally achieved using either total phosphorus or chlorophyll *a* data and latitude-specific classification cut-offs (Carlson 1977).

It has been suggested that eutrophication can enhance CO_2 uptake and burial (Pacheco et al., 2015), but there is no evidence that this occurs consistently, and, when it does occur, the magnitude of this effect on CO_2 is generally much smaller (in overall greenhouse gas flux terms) than the effect of eutrophication on CH_4 emissions (Deemer et al., 2016).

A7.1.2 Reservoirs

Introduction

Correctly estimating the anthropogenic component of greenhouse gas emissions from reservoirs requires a careful assessment of the source and fate of reservoir carbon fluxes as such estimates are prone to double counting and inappropriate attribution of fluxes to human activity (Prairie et al. 2017a). The greenhouse gas emission factors from Flooded Lands presented in this methodology report are composited output from an empirical model (Prairie et al., 2017b), developed and calibrated with field measurements from diverse types of reservoirs located in various regions of the world (see section A7.1.2.3 Data Sources). The model allows us to annualize emissions that are often measured over short periods (e.g. during the ice-free period for boreal systems) and account for changes in reservoir greenhouse gas activity that have been observed to occur as reservoirs age. We anticipate that the models will continue to improve over time as more measurements are made and additional models become available, but at the time of this report, the modeling approach used here represents best available scientific knowledge.

A7.1.2.1 Developing Tier 1 emission factors for CO_2 and non-CO_2 emissions from field measurements

Recent, largely overlapping, literature compilations of field greenhouse gas measurements from over 220 distinct reservoirs (Deemer et al. 2016, Prairie et al. 2017b) form the basis of the emissions factors listed in Tables 7.9 and 7.14. The field measurements are a mixture of diffusive CO_2, CH_4 diffusive and/or bubble emissions and, for a new but smaller subset, downstream emissions for either or both gases. The method used to estimate greenhouse gas fluxes from reservoirs is critical because different techniques can give quite different flux estimates (Schubert et al. 2012; Deemer et al., 2016), and because some techniques integrate spatial and temporal variability to different degrees (Wik et al., 2016). Flux estimates used to derive reservoir EFs in Chapter 7 were attained in a variety of ways. For CO_2, diffusive fluxes were estimated using near-surface concentrations in combination with a thin boundary layer model for the majority of systems (Deemer et al., 2016), floating chambers, or, in a minority of cases, eddy flux measurements. For CH_4, diffusive fluxes were estimated using near-surface concentrations in combination with a thin boundary layer model or chamber flux measurements. Ebullition fluxes of CH_4 were estimated using inverted funnel traps and echo sounders. Combined ebullitive and diffusive CH_4 fluxes were estimated using floating chambers or eddy flux techniques, or a combination of available methods. Downstream emissions for either or both gases were available for a subset of the studied reservoirs.

Deriving Emission Factors directly from the compiled data is subject to a number of assumptions that can lead to potential biases. First, it requires an assumption that sampled systems are statistically representative of overall reservoir distribution, a potentially problematic assumption given that measurement campaigns may occur in systems and periods in time where or when greenhouse gas emissions are high (e.g. where CH_4 bubbling is visible) or low. Second, it assumes that sampling of reservoirs is representative in time, potentially leading to biases as there is considerable evidence that greenhouse gas emissions decrease markedly to alternative equilibrium states as reservoirs age (Abril et al. 2005, Barros et al. 2011, Teodoru et al. 2012, Serça et al. 2014).

The approach used here to derive the Emissions Factors from reservoirs was developed to account for these potential biases. The Greenhouse Gas Reservoir (G-res) model (Prairie et al., 2017b) uses empirical relationships between environmental drivers and emissions to estimate reservoir greenhouse gas fluxes from a large, diverse set of reservoirs (>6000 reservoirs with global distribution). Depending on available input data, the G-res model can also be used to make Tier 2 or Tier 3 estimates.

The methodology used to develop the G-res model and its usage to estimate reservoir greenhouse gas emissions is described in more detail in Prairie et al. (2017b) but, briefly, consists of the following steps:

1) Data annualization: field sampling campaigns reported in the literature are rarely carried through the entire annual cycle. For this reason, greenhouse gas data obtained over sub-annual time periods were annualized by taking into account the annual temperature cycle at the reservoir site and the known temperature dependence of processes leading to the production of CO_2 and CH_4.
2) Identifying relationships between annualized flux estimates and environmental variables: environmental characteristics for each reservoir where greenhouse gas fluxes have been measured were extracted using available global database (GIS layers) and used as input variables for predictive models with an elastic net variable selection procedure. This statistical analysis of the relevant data yielded the following model equations:

EQUATION A1
CH_4 DIFFUSIVE EMISSION (MG C M^{-2} D^{-1})

$$\log_{10}\left(CH_{4\_diff}\right) = 0.88(\pm 0.16) - 0.012(\pm 0.002)\ Age + 0.048(\pm 0.006)\ T_{factor} + 0.61(\pm 0.706)\ \log_{10}\left(pcA_{littoral}\right)$$

EQUATION A2
CH_4 BUBBLING EMISSION (MG C M^{-2} D^{-1})

$$\log_{10}\left(CH_{4\_ebul}\right) = -0.99(\pm 0.63) + 0.049(\pm 0.011)\ Q_{rad} + 1.01(\pm 0.028)\log_{10}\left(pcA_{littoral}\right)$$

EQUATION A3
CO_2 DIFFUSIVE EMISSION (MG C M^{-2} D^{-1})

$$\log_{10}\left(CO_{2\_diff}\right) = 2.035 + 0.033T_{factor} - 0.293\log_{10}\left(Age\right) + 1.78\cdot 10^{-3} SOC + 0.706\log_{10}\left(A_{res}\right)$$

$$\log_{10}\left(CO_{2\_iff}\right) = c_1 + c_2 T_{factor} - c_3\log_{10}\left(Age\right) + c_4 SOC + c_5\log_{10}\left(A_{res}\right)$$

$$c_1 = 2.035 \pm 0.19$$

$$c_2 = 0.033 \pm 0.005$$

$$c_3 = 0.29 \pm 0.06$$

$$c_4 = 0.00178 \pm 0.006$$

$$c_5 = 0.71 \pm 0.03$$

where

Age	G-res Reservoir age since construction [yr]
A_{res}	G-res Surface area of reservoir [km^2]
$pcA_{littoral}$	G-res percentage of reservoir area, A_{res} < 3 m deep [%]
CH_{4_diff}	Diffusive emission of CH_4 used in G-res [mg-C m^{-2} d^{-1}]
CH_{4_ebul}	Ebullitive (bubble) emission of CH_4 used in G-res [mg-C m^{-2} d^{-1}]
CO_{2_diff}	Diffusive emission of CO_2 used in G-res [mg-C m^{-2} d^{-1}]
Q_{rad}	G-res mean daily solar irradiance [kWh m^{-2} d^{-1}]
SOC	G-res Soil organic carbon from (0-30 cm) [kg m^{-2}]
T_{factor}	G-res temperature factor derived from air temperature [dimensionless?]

Here, *Age* is reservoir age (in years since construction), $pcA_{littoral}$ area was operationally defined as the percent reservoir surface area shallower than 3m as derived from modelled reservoir bathymetry, *SOC* is surface Soil Organic Carbon (0-30cm), T_{factor} is a temperature factor, and Q_{rad} is the mean daily solar irradiance averaged over a latitude-dependent period (see G-res documentation for details), and Ares is cumulative radiance and reservoir area, the surface area of the reservoir (km^2). Further details on the statistical analysis, the input environmental variables, their definition and sources can be found in Prairie et al. (2017b). All resulting empirical models (Equation A1 to A3) were statistically highly significant and explained between 37 and 47% of the variation in the greenhouse gas flux component (log scale).

3) Application of the models to larger database: To enhance the robustness and wider applicability of the EFs, the empirical models described above were applied to the larger Global Reservoir and Dam (GRanD) database, Lehner et al. 2011) consisting of 6684 reservoirs with capacity >0.1 Mm^3 located worldwide (Figure A1). These reservoirs are estimated to comprise collectively over 75% of the global surface area of reservoirs and are distributed in all climate zones (Table 1, Figure A2). The environmental variables required by the models

were extracted for each reservoir as previously described and were used as inputs in Equations A1 to A3 to estimate the various components of greenhouse gas emissions. In total, greenhouse gas emissions could be estimated for more than 6000 reservoirs worldwide.

Figure A2. Location of the reservoirs in the GranD database and shadowgram of their latitudinal distribution.

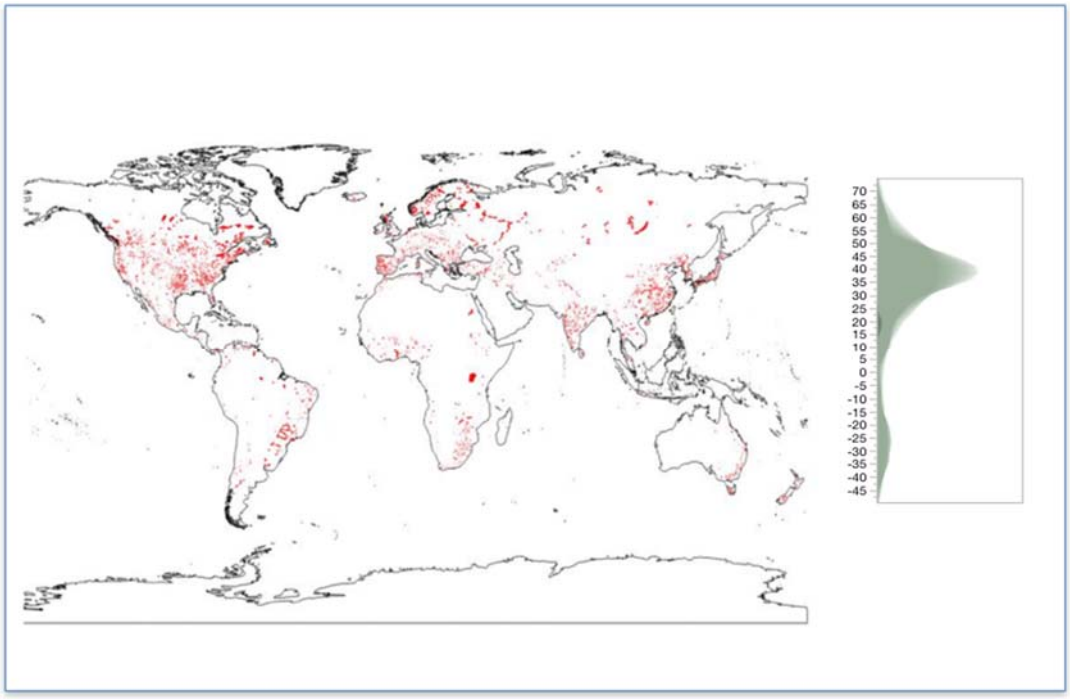


TABLE A1
NUMBER OF RESERVOIRS WITH GREENHOUSE GAS EMISSION ESTIMATES DERIVED FROM G-RES IN EACH IPCC CLIMATE ZONE.

IPCC Climate zone	N rows
Boreal dry	3
Boreal moist	87
Cool temperate dry	333
Cool temperate moist	1746
Polar moist	27
Tropical dry	625
Tropical moist	793
Tropical montane	227
Tropical wet	126
Warm temperate dry	623
Warm temperate moist	2072

4) Derivation of Emissions Factors:

Methane

CH_4 emission is the sum of ebullitive and diffusive emissions (Equations A1 and A2). However, because the diffusive component is not constant in time but declines with age, Equation A.1 was integrated to estimate the

average annual emission over different periods. Based on the available literature, much of the initial greenhouse gas pulse occurs within the first 20 years following impoundment and this time interval was assumed to represent Land converted to Flooded Land. For Flooded Land remaining Flooded Land, the integration period was from 20 to 100 years post-impoundment. In addition to the diffusive and ebullitive emissions, downstream CH_4 emissions are estimated as a multiplier (R_d, see Table 7.9) to the other emissions, thus yielding the following formulas:

EQUATION A4

LAND CONVERTED TO FLOODED LAND

$$EF = \left[\frac{\int_0^{20} CH_{4-diff}\ dAge}{20} + CH_{4-bubbling} \right]$$

EQUATION A5

FLOODED LAND REMAINING FLOODED LAND

$$EF = \left[\frac{\int_{20}^{100} CH_{4-diff}\ dAge}{80} + CH_{4-bubbling} \right]$$

In addition to the diffusive and ebullitive emissions, downstream CH_4 emissions are estimated as a multiplier (R_d) to the other emissions. R_d is thus defined as the ratio of total CH_4 emissions (kg CH_4-C y^{-1}) below the reservoir (i.e. degassing at the dam and emissions from the downstream river) to CH_4 emissions from the surface of the reservoir (diffusion + ebullition; kg CH_4-C y^{-1}). Downstream emissions are influenced by local climate, reservoir morphology, and design features of the dam and spillway (Deemer et al 2016). In general, these emissions will be large in thermally stratified reservoirs with anoxic, CH_4-rich bottom waters and hypolimnetic withdrawal (dos Santos et al 2017). These emissions can be further enhanced by high air-water gas exchange rates at the dam or spillway that promote the rapid evasion of CH_4 to the atmosphere before it can be oxidized to CO_2 in the downstream river (Abril et al. 2005). Accurately predicting downstream emissions requires detailed knowledge of the dam design (i.e. withdrawal depth) and operating conditions (i.e. withdrawal rates) and is beyond the scope of the Tier 1 methodology. However, if appropriate at a higher tier, downstream emissions may be estimated using climate zone specific R_d values in Table 7.10 derived from a literature compilation listed in section A7.1.2.3 Data Sources.

Downstream emissions have received much less attention than emissions from reservoir surfaces, but have been reported for 36 reservoirs distributed across the 6 aggregated IPCC climate zones (see section A7.1.2.3 Data Sources, Table A5). It should be noted, however, that reported downstream emissions can be biased high or low, depending on study-specific methodological details. For example, several studies assumed that all excess dissolved CH_4 (i.e. the difference between actual dissolved CH_4 concentration and atmospheric equilibrium) entering the dam would evade to the atmosphere via a combination of degassing at the dam and diffusion from the river surface (Beaulieu et al. 2014, Teodoru et al. 2012). This approach will overestimate downstream emissions because up to 85% the CH_4 that enters the downstream waterbodies can be oxidized to CO_2 (Kemenes et al. 2007). Other studies only reported degassing in turbines (i.e. did not estimate downstream water body emissions), thereby biasing downstream emissions low (Maeck et al. 2013). Although methodological differences can bias downstream emission values, the effect of methodology was not apparent in the pooled data, likely because other factors, such as the depth of water withdrawal relative to the oxycline, were more important drivers. Similarly,

differences among climate zones were not apparent in the data, therefore the Tier 1 R_d value were not disaggregated by climate zone. Due to the strong influence of a few high values, the Tier 1 R_d value is based on the median value. At the Tier 2 level the downstream emission term in Equation 7.10 can be set to zero in reservoirs where epilimnetic water is withdrawn and discharged to the river downstream. Countries can directly measure downstream emissions at the Tier 3 level using the methods discussed in the references cited in section A7.1.2.3 Data Sources (Table A5).

5) Grouping of reservoirs according to IPCC climate zones

The 6014 estimates of CH_4 emissions (diffusive + ebullitive) from worldwide reservoirs generated by the G-res tool were grouped according to the IPCC climate regions. A regression tree approach was used to lump certain climate categories together based on their abilities to separate groups with different CH_4 emissions. The final grouping comprised 6 aggregated climate zones (Table A2) that are applied throughout this Methodology Report.

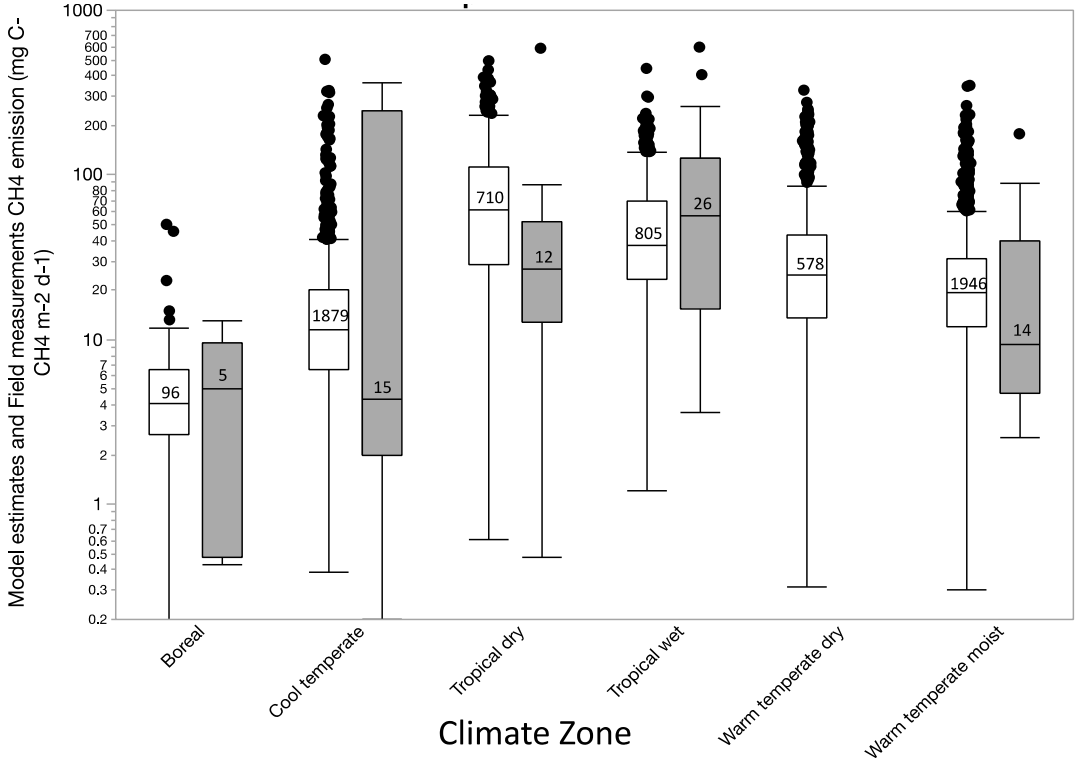
TABLE A2
AGGREGATED CLIMATE ZONES BASED ON DIFFERENCES IN CH_4 EMISSIONS BETWEEN CATEGORIES

IPCC Climate zone	Aggregated climate zone
Boreal dry	Boreal
Boreal moist	
Polar dry	
Polar moist	
Cool temperate dry	Cool temperate
Cool temperate moist	
Warm temperate dry	Warm temperate dry
Warm temperate moist	Warm temperate moist
Tropical dry	Tropical dry/montane
Tropical montane	
Tropical moist	Tropical moist/wet
Tropical wet	

Validation of the data-model approach

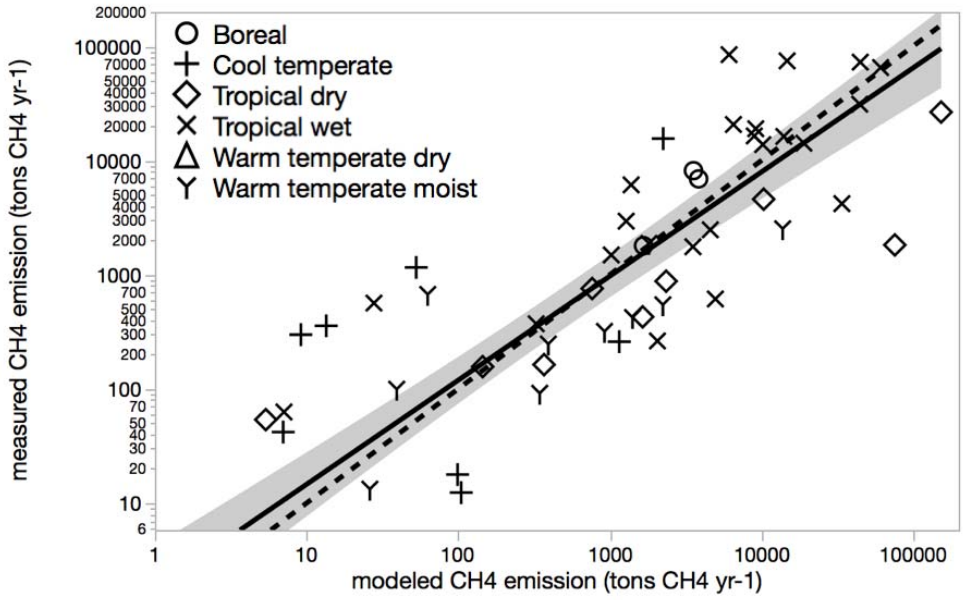
Model estimations and direct measurements are not strictly comparable in that the former have been annualized and represent the integrated average annual emissions of the first 20 years post-impoundment (plus ebullitive emissions) while the latter are point measurements encompassing varying degrees of spatial and temporal integration depending on the study. Nevertheless, it is informative to compare the central tendency and variability in CH_4 emissions among reservoirs in each of the climate zones. Both model estimations and field measurements were highly variable and positively skewed in each of the climate zone (Figure A3).

Figure A3. Box plots of model estimates (empty) and Field measurements (filled) of CH_4 emissions (note logarithmic scale) in aggregated IPCC climate zones. Field measurements are from Deemer et al. (2016) while modelled estimates are derived from G-res model applied to about 6000 reservoirs worldwide. Outliers in both data sets appear as filled circles. Numbers in box plots correspond to the number of observations in each.



While the distribution of modelled and measured greenhouse gas emission estimates generally overlapped in each climate zone, a more direct measure of correspondence is shown by the relationship between field measurements versus model estimates of CH_4 emissions (Figure A4). CH_4 emissions from individual reservoirs predicted using the Tier 1 approach agreed reasonably well with measured CH_4 emissions (Nash-Sutcliffe Efficiency: 0.8, with no detectable bias in either slope or intercept of least-squares regression; Figure A4). These comparisons collectively provide evidence that the model estimates capture both the variability and central tendency in CH_4 emission rates. Furthermore, because of the large number of reservoirs in each climate zone, the model estimates can provide more stable Emissions Factors for each climate zone.

Figure A4. **Figure A4. Comparison of measure CH_4 emissions with estimates based on the Emission Factors (EFs, Tables 7.9 and 7.14) of Tier 1 methodology. Solid line and shaded area correspond to least-squares regression line and 95% confidence interval respectively, while dashed line is 1:1 line. Estimates based on recommended EFs show no evidence of systematic bias. Different symbols represent the various aggregated climate zone (see Table A3).**



A7.1.2.2 CO_2 EMISSION FACTORS FOR LAND CONVERTED TO FLOODED LAND.

The creation of reservoirs as well as other Flooded Lands often involves the flooding of terrestrial ecosystems and their organic matter pools. A portion of these pools is rapidly degraded by microbial activity generating a CO_2 pulse that diminishes steadily during the 10-20 years following flooding until the Flooded Land attains a new steady state emission rate (Abril et al, 2005; Barros et al, 2011; Teodoru et al. 2012). The new steady state emission rate generally falls in the range typical of other freshwater ecosystems that have remained flooded for > 20 years (Prairie et al. 2017a). A meta-analysis of published emission studies (Prairie et al., 2016) suggests that the rate of decline decreases with time (faster in the early years, slower later on) and that the temporal evolution of CO_2 emissions is expressed as a general negative power function. The literature suggests that a decade is a realistic period for the return to a quasi-equilibrium (e.g. Tremblay et al. 2005), reflecting the new balance between primary production and respiration of the reservoir ecosystem. A more conservative approach assumes, instead, that this new equilibrium is reached only after 100 years - a value that is often used to represent the expected lifetime of reservoirs in life-cycle analysis (e.g. Gagnon and others 2002). Over such a period, it is considered that about 75% of the cumulative CO_2 flux is natural, i.e. that only 25% can be considered the result of the impoundment process (Prairie et al. 2017b).

The carbon stocks of the land prior to impoundment are specific for each land use / land cover, and the default Tier 1 estimates for these pools can be derived from the *2006 IPCC Guidelines*, FAO 2017 database as refined in this volume, and the *2013 Wetland Supplement*, while masses for dry matter in undrained and drained peatlands are given in the *2013 Wetland Supplement* Table 2.6. The guidelines recognize five terrestrial C pools: above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter. In preparation of the impoundment area, the carbon losses from harvested biomass and the emissions from deliberately burned biomass are reported according to the 2006 IPCC GL as refined in this volume. The CO_2 emissions from the decay of dead organic matter in the newly flooded land is described below.

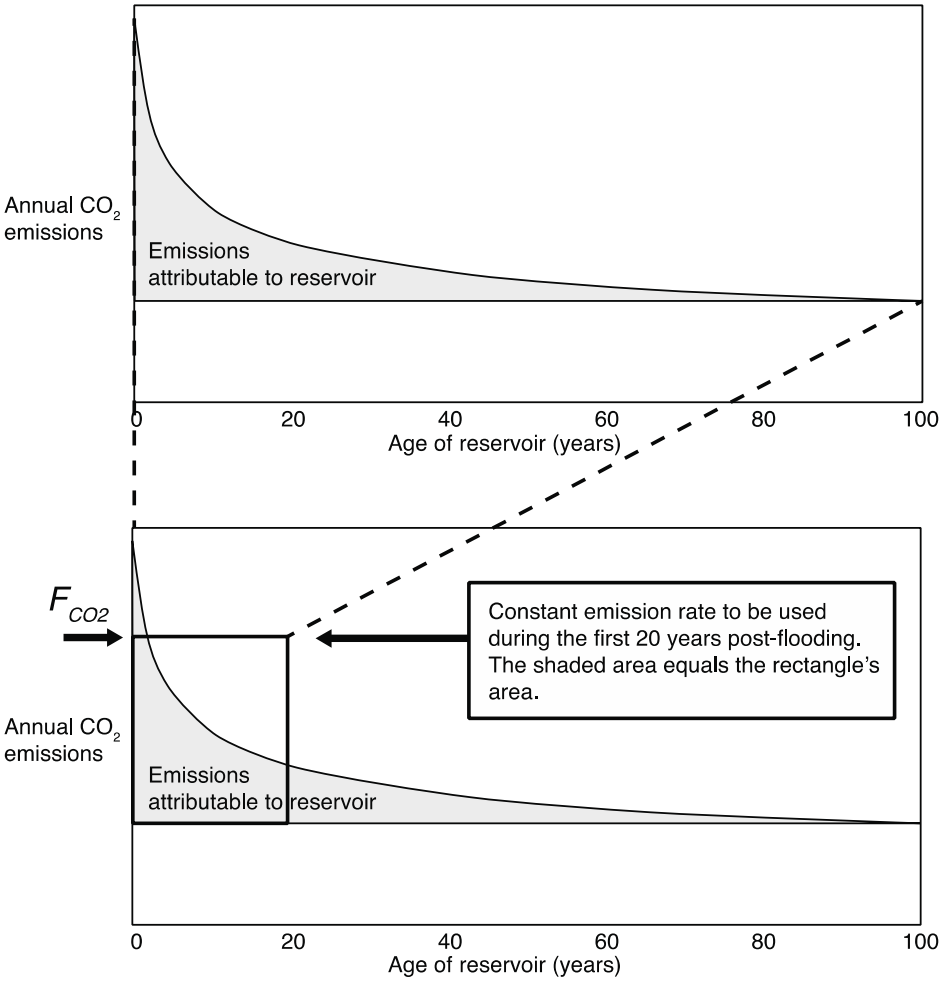
The easily decomposable organic matter fractions (litter, foliage, twigs, fine roots, organic soils) contribute to the post-flooding CO_2 pulse, while the more recalcitrant fractions (tree boles, mineral soils) are for the most part preserved. However, it is noteworthy that following flooding, the mineral soil layer rapidly becomes (and remains indefinitely) anoxic below a depth of a few mm (Lorke et al. 2003). Anaerobic remineralisation occurs very slowly and below this depth, organic carbon can be considered permanently buried for practical inventory accounting purposes. In organic soils and in humus layers, flooding may produce an analogous anaerobic zone. In thermally stratified reservoirs, remineralisation of organic matter will be retarded in anoxic hypolimnia.

The surge in CO_2 emission post-flooding is caused by the remineralisation of pre-flooding organic matter pools and it can be considered as a net loss of the carbon stock from the previous land use. At the moment, there is little information to quantify how individual terrestrial organic carbon pools contribute to the post-flooding CO_2 surge. Nevertheless, the abundant amount of reservoir emission measurements for young (< 20 y) reservoirs (Deemer et al. 2016) has made possible the development of models such as G-res that can be used to estimate net post-flooding CO_2-C emissions (Table 7.13).

The approach used to derive net CO_2 emissions from reservoirs is the same as that used to derive emissions of CH_4 (section A7.1.2.1) and is based on the greenhouse gas reservoir (G-res) model (Prairie et al., 2017b) which uses empirical relationships between environmental drivers and greenhouse gas emissions to estimate reservoir greenhouse gas fluxes from a large, diverse set of reservoirs (>6000 reservoirs with global distribution). Instantaneous greenhouse gas flux measurement data are annualized to take into consideration seasonal changes in temperature that may be different from the moment when empirical measurements were conducted in the field.

An example of generating annual fluxes from momentary measurements is described in the technical documentation of the IHA G-Res tool (Prairie et al., 2017b). There are two approaches to derive emissions. First, a power function for annual flux, $CO_2 = C \cdot Age^{-b}$ (Prairie et al. 2017a), where C is a reservoir specific constant depending on nutrients, temperature, reservoir area etc. and b is estimated by fitting to the data, is assumed to reach the natural equilibrium level of CO_2 flux at the reservoir age of 100 years. That level determines how much of the annual CO_2 flux should be subtracted each year from the integrated area under the flux CO_2 curve, see Prairie et al. (2017a). The second approach, which is applied to derive Tier 1 emission factors, uses an empirical relationship between the derived integrated decay curve and soil organic carbon stock as well as climate under the newly flooded area (Fig. A4 and Equation A3). The emissions attributable to the creation of the reservoir over a 100-year period are reported as a constant rate over the first 20 years post-flooding. Accordingly, the rates of emissions are dependent on climate and soil C content (to 30 cm depth) of the flooded area (see text in A7.1.2 and Equation A3 and section 7.3.2, Equation 7.13).

Figure A4. Relationship between CO_2 surge estimates from the newly flooded lands using the decay curve approach and the flooded soil organic carbon stock approach.



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1331 A7.1.2.3 DATA SOURCES

1332 Data sources used for the directly measured methane emissions are within Table A3. Data sources used to develop
1333 models (Equations A1, A2 and A3) can be found in Annex VI of Prairie et al. (2017b) and were used in section
1334 1.3 of Annex A1 to validate the Emission Factors provided in Tables 7.9 and 7.14.

1335 Data sources (including systems assessed and citations) for estimating the multiplier (R_D, Table 7.10) which is the
1336 ratio of total CH_4 emissions (kg CH_4-C y^{-1}) below the reservoir (i.e. degassing at the dam and emissions from the
1337 downstream river) to CH_4 emissions from the surface of the reservoir (diffusion + ebullition; kg CH_4-C y^{-1}) are
1338 within Table A4.

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TABLE A3.
DATA SOURCES USED FOR MODELLING CH_4 EMISSIONS FROM RESERVOIRS WITHIN DIFFERENT CLIMATE ZONES.

IPCC Climate Type Group	Latitude Band	Number of systems with CH_4 measurements in category	Citations
Polar moist, boreal dry and moist	Boreal Polar	6	Tremblay et al. 2005; Teodoru et al. 2012; Demarty et al. 2011; Demarty et al. 2009; Brothers et al. 2012; Kelly et al. 1994; Roehm et al. 2006; Tadonléké et al. 2012; Duchemin et al. 1995; Huttunenet al. 2002; Fedorov et al. 2015
Cool temperate moist and dry*	Temperate	16	Harrison et al. 2018; Matthews et al. 2005; Hendzel et al. 2005; Venkiteswaran et al. 2013; Kelly et al. 1997; Deemer et al. 2011; Maeck et al. 2013; Huttunenet al. 2002; Gruca-Rokosz et al. 2011; Gruca-Rokosz et al. 2010; Beaulieu et al. 2014a; Beaulieu et al. 2014b
Warm temperate moist	Temperate	14	Rosa et al. 2004; Dos Santos et al. 2006; Harrison et al. 2018; Li et al. 2015; Maeck et al. 2013; Gruca-Rokosz et al. 2010; Zhao et al. 2013; Wu 2012; Yang et al. 2013; Chen et al. 2011; Lu et al. 2011; Zhen 2012; Xiao et al. 2013; Zhu et al. 2013; Zhao et al. 2015; Li et al. 2014; Bevelhimer et al. 2016; Mosher et al. 2015
Tropical dry and montane	Tropical	13	Diem et al. 2012; Ometto et al. 2013; Pacheco et al. 2015; Roland et al. 2010; Sturm et al. 2014; DelSontro et al. 2011; Selvam et al. 2014; Bansal et al. 2015; DelSontro et al. 2010; Eugster et al. 2011; Kumar & Sharma 2016; Teodoru et al. 2015; Almeida et al. 2016
Tropical wet and moist	Tropical	26	Therrien et al. 2005;Tremblay et al. 2005; Bergström et al. 2004; Guérin et al. 2006; Kemenes et al. 2007; Kemenes et al. 2011; Musenze et al. 2014; Rosa et al. 2004; Dos Santos et al. 2006; St. Louis et al. 2000; Ometto et al. 2013; Bergier et al. 2011; Duchemin et al. 2000; Roland et al. 2010; Keller et al. 1994; Joyce et al. 2003; Selvam et al. 2014; Deshmukh 2013; Deshmukh et al. 2014; Abril et al. 2005; Rosa et al. 2003; Lima 2005; Lima et al. 2002; Lima et al. 1998; Marcelino et al. 2015

Note: No measurements from reservoirs from the warm temperate dry region have been found in the literature

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TABLE A4.
RESERVOIRS AND CITATIONS FOR MEASURED R_D VALUES

System Name	IPCC climate zone	*Citation
Eastmain-1	Boreal	Teodoru et al. 2012
Gruyere, Lake Grimsel, Lake Luzzone, Lake Sihl, Wohlen, Serrig, Dworshak	Cool temperate	Diem et al. 2012; DelSontro et al. 2016; Maeck et al. 2013; Soumis et al. 2004
F.D. Roosevelt, New Melones, Wallula	Warm temperate dry	Soumis et al. 2004
William H Harsha Lake, Allatoona, Douglas, Fontana, Guntersville, Hartwell, Watts Bar, Eguzon, Oroville, Shasta	Warm temperate moist	Beaulieu et al. 2014; Bevelhimer et al. 2016; Descloux et al. 2017; Soumis et al. 2004
Lake Kariba, Xingó, Tehri	Tropical dry/montane	Delsontro et al. 2011; dos Santos et al. 2017; Kumar and Sharma. 2017
Nam Leuk, Nam Ngum, Funil, Itaipu, Segredo, Serra da Mesa, Três Marias, Petit Saut, Koombooloomba, Nam Theun 2, Tucuruí, Samuel, Balbina	Tropical moist/wet	Chanudet et al. 2011; dos Santos et al. 2017; Abril et al. 2005; Bastien et al. 2013; Deshmukh et al. 2016; Serca et al. 2016; Guérin et al. 2006; Kemenes et al. 2007

*See references section for full citations.

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1368 A7.1.3 Other constructed waterbodies (agricultural ponds, 1369 aquaculture ponds, canals, drainage channels and 1370 ditches)

1371 Many forms of agricultural and silvicultural land management involve the creation of artificial waterbodies. For
1372 example, ditches are often used for land drainage or irrigation; small constructed ponds are used for small scale
1373 irrigation or as a water source for livestock; and canal systems are used for water level management, water transfers
1374 and navigation. Aquaculture ponds and flooded pastures can occupy extensive areas on the landscape (Yang et al.
1375 2017, Kroeger et al. 2017).

1376 Similar to reservoirs, CO_2 emissions from smaller volume constructed waterbodies including ditches, canals, farm
1377 ponds and aquaculture ponds, are the result of decomposition of soil organic matter and other organic matter within
1378 the water body or entering the water from the catchment, as well as from biological components (e.g. fish). No
1379 guidance is provided here since these emissions are either accounted for elsewhere (e.g. as soil carbon loss) or
1380 represent short-term natural carbon cycling (e.g. biological turnover).

1381 CH_4 emissions from small constructed waterbodies are primarily the result of new methanogenic production of
1382 CH_4 induced by anoxic conditions, which occurs when waterbodies have high organic matter loading and low
1383 oxygen status. These conditions often occur in small constructed waterbodies, such as slow-flowing ditches (Evans
1384 et al., 2016), agricultural ponds (Selvam et al. 2014) and aquaculture ponds (Robb et al. 2017), but may be lower
1385 where mixing or aeration occurs as part of aquaculture management (e.g. Vasanth et al. 2016) and are sensitive to
1386 temperatures (Davidson et al. 2012). Area-specific emissions from these constructed waterbodies may equal or
1387 exceed those observed in small lakes and reservoirs (Bastviken et al. 2010; see above). Furthermore, the CH_4
1388 emissions from small constructed waterbodies are a direct consequence of the construction of the water body.

1389 CH_4 emission factors from small constructed waterbodies (Section 7.3.1.2, Table 7.12) are based on review of the
1390 peer reviewed literature using appropriate search terms. Literature was obtained using Web of Science and Google
1391 Scholar. In some cases (e.g. PhD Theses), data were obtained directly from authors. For each study or sites within
1392 studies, a mean CH_4 flux was extracted from tables, figures or text. Fluxes were converted to annual fluxes by
1393 simple scaling (e.g. multiplying per day rates by 365 days), or if more information was provided (e.g. days per
1394 aquaculture production cycle and production cycles per year), data were annualized using this additional
1395 information. Methane emissions from land and water surfaces are rarely normally distributed within datasets due
1396 to the heterogeneity of emission pathways and controlling factors, and data were therefore log-transformed during
1397 the calculation of mean emission factors. The high variability and relatively small number of observations also
1398 precluded disaggregation of Tier 1 EFs by climate zone or other factors (apart from water body type and (for ponds)
1399 salinity), and 95% confidence intervals are correspondingly large

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