CHAPTER 7

WETLANDS

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7 WETLANDS

7.1 INTRODUCTION

No refinement.

Greenhouse gas emissions and removals from wetlands

No refinement.

7.2 MANAGED PEATLANDS

No refinement.

7.3 FLOODED LAND

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 (See A7.1.1). Therefore, Flooded Land includes a broad variety of waterbodies (Table 7.7).

TABLE 7.7
(NEW) 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 waterbody or entering the waterbody 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 for emissions associated with decomposition of organic matter delivered from the catchment or respiration of biota 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. The one exception is for *Land Converted to Flooded Lands*. CO_2 emissions occur as the flooded organic matter decomposes, which is a consequence of anthropogenic management, and methods are provided for estimating the resulting CO_2 emissions (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). Methane can be emitted from small lakes or reservoirs via diffusive, ebullitive, and downstream emissions. Downstream CH_4 emissions are subdivided into degassing emissions (see Glossary) and diffusive emissions, which occur downstream from the flooded land. Methane 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 & Raymond 2016). Whilst emissions from natural ponds can (at least in part) be considered natural, those from small constructed waterbodies are the result of anthropogenic activity. 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) aquaculture (Avnimelech & 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 (Tangen *et al.* 2015), (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 as part of aquaculture management, including mixing or aeration, periodic drainage or when water is saline (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 the waterbody, 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, which are already captured in other source categories, such as indirect N_2O emissions 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, (IPCC 2014)* Chapter 4, Section 4.3.2).

TYPES OF FLOODED LANDS

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 reservoir 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 water 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 land is 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 Land*. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed *Flooded Land*, in accordance with the *2006 IPCC Guidelines*.

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

(a) *Flooded Land Remaining Flooded Land* – includes reservoirs that were converted to *Flooded Land* more than 20 years ago.
(b) *Land Converted to Flooded Land* – includes reservoirs that were flooded less than or equal to 20 years ago.

Other Flooded Land: 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 are sites of substantial CH_4 emissions from anaerobic sediments. However, because seawater suppresses production of CH_4, emissions from saline aquaculture ponds are lower compared to freshwater ponds. Constructed 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. For CH_4 emissions from Other Flooded Land, there are insufficient data to disaggregate based on age classes of the waterbodies.

Flooded Land Excluded Here, But Considered Elsewhere

Emissions from various kinds of *Flooded Land* that are not considered in this chapter are provided in the *2013 Wetlands Supplement* and in other parts of this guidance. Table 7.8 provides the Ramsar classification, which provides the framework for the terminology used in this guidance. 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 provided in

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

RAMSAR class[1]	Corresponding wetlands sub-categories in IPCC Chapters	Methodological guidance available?
Water storage areas	Reservoir	Yes for CH_4 and CO_2 and for *factoring out* CH_4 and CO_2 (this chapter)
Ponds	Other constructed waterbodies	Yes for CH_4 and for *factoring out* CH_4 and CO_2 (this chapter)
Canals and drainage channels, ditches.	Other constructed waterbodies	Yes for CH_4 and for *factoring out* CH_4 and CO_2 (this chapter) Yes for CH_4 in peatlands (*2013 Wetlands Supplement*, Chapter 2)
Aquaculture	Other constructed waterbodies	Yes for CH_4 and for *factoring out* CH_4 and CO_2 (this chapter) Yes for CO_2 during construction and for N_2O (*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 for CH_4 (*2013 Wetlands Supplement,* Chapters 3, 4 and 5)[3,4]
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 2014)

[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)

[4] Including permanently flooded lands associated with rewetting of converted wetlands

Chapter 6 of the *2013 Wetlands Supplement* (Constructed Wetlands for Waste Water Treatment). 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). CO_2 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 found 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 because there are insufficient data to derive an emission factor. Furthermore, water in seawater canals is assumed to have salinity greater than 18 ppt, and therefore will have no CH_4 emissions, consistent with guidance in the *2013 Wetland Supplement*.

CHOICE OF METHOD, ACTIVITY DATA AND EMISSION FACTORS

Guidance is provided for choice of methods, activity data and emission factors for *Flooded Land Remaining Flooded Land* (Reservoirs > 20 years old) and other constructed waterbodies, and for *Land Converted to Flooded Land* (Reservoirs ≤ 20 years old). Guidance for selecting the type of waterbody based on human modification, hydrology, size and function and associated emission factors and activity data is presented in the decision tree in Figure 7.2. 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 Land* as an emission source based on the key category analysis for a country's national greenhouse gas inventory. Figure 7.3 provides a decision tree to select appropriate tier level for estimating emissions from *Flooded Land*. Country-specific emission factors and data are generally preferable to Tier 1 default data.

Factoring out emissions (removals) that would otherwise occur from Unmanaged Land without conversion to Managed Flooded Lands

Greenhouse gas emissions (removals) occur on unmanaged land prior to conversion into managed land for both *Flooded Land remaining Flooded Land and Land converted to Flooded Land*. Furthermore, greenhouse gas emissions (removals) would continue to occur in the absence of anthropogenic activity. From a climate forcing perspective, the anthropogenic impact on greenhouse gas emissions from managed flooded land reflect the net changes in greenhouse gas fluxes to the atmosphere resulting from the landscape transformation into a reservoir or other flooded lands, recognizing that emissions (removals) would continue to occur on the unmanaged land without anthropogenic activity (Prairie *et al.* 2017a). Therefore, the anthropogenic impact on greenhouse gas emissions is due to the additional emissions (removals) occurring on the flooded land after subtracting the emissions (removals) from unmanaged land (see Annex Box A1).

However, it is typical for the greenhouse gas emissions in the AFOLU sector to be estimated using the managed land proxy, in which all emissions from managed land are considered anthropogenic (See Chapter 3, Volume IV). Special consideration is given to Flooded Land due to the high levels of emissions that occur if the land was flooded when it was unmanaged land. Anthropogenic activity may have a limited impact on the total emissions, relative to emissions occurring from unmanaged land for these cases. Other land uses typically, although not exclusively, have insignificant amounts of net greenhouse gas emissions as unmanaged lands, such as unmanaged forest land, grassland, or other land that have reached a near steady-state condition. Therefore, it is reasonably accurate to assume that all greenhouse gas emissions from managed forest land, grassland and other land are associated with anthropogenic activity although there are some exceptions to this generality (See "Methodological approach to estimate the contribution of natural disturbance to the emissions and removal reported for managed lands" in Chapter 2, Volume IV).

Potential sources of emissions (removals) from Unmanaged Land converted to *Flooded Land* include: 1) natural lakes and rivers (collectively termed 'natural waterbodies') expanded by dam construction; 2) Unmanaged Wetlands (excluding lakes and rivers) converted to *Flooded Land*; and 3) Other Unmanaged Lands (including Unmanaged Forest Land, Grassland and Other Land) converted to *Flooded Land*. If the *Land Converted to Flooded Land* is already Managed Land, the emissions and removals are not factored out as they are already included in the inventory reporting from the baseline year, and furthermore are anthropogenic so would not be factored-out. Therefore, no guidance on factoring out is provided for Managed Land converted to *Flooded Land*. The Decision tree below (Figure 7.4) describes the steps required to factor out emissions from Unmanaged Land converted to *Flooded Land*.

The factoring out methods provided in this section are scientifically-based but with practical consideration for application of the methods by compilers. For transparency, the methods are applied so that the total emissions (removals) from flooded lands are estimated based on the managed land proxy, and then the net emissions are determined based on emissions (removals) that would occur if the flooded land remained unmanaged. As with other sources, Tier 1 methods have large uncertainties that may be reduced with development of Tier 2 or 3 methods.

Figure 7.2 (New) Decision tree for types of *Flooded Land*.

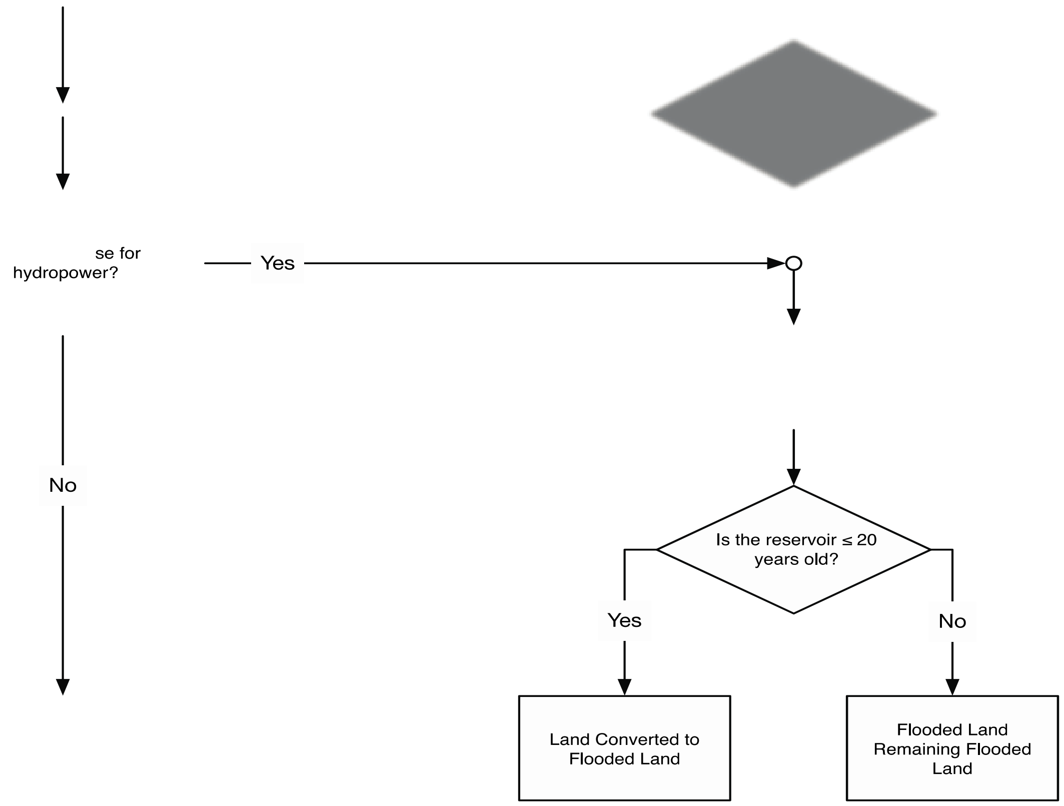


Figure 7.3 (New) Decision tree for choice of Tier level to estimate emissions of CO_2 and CH_4 from waterbodies

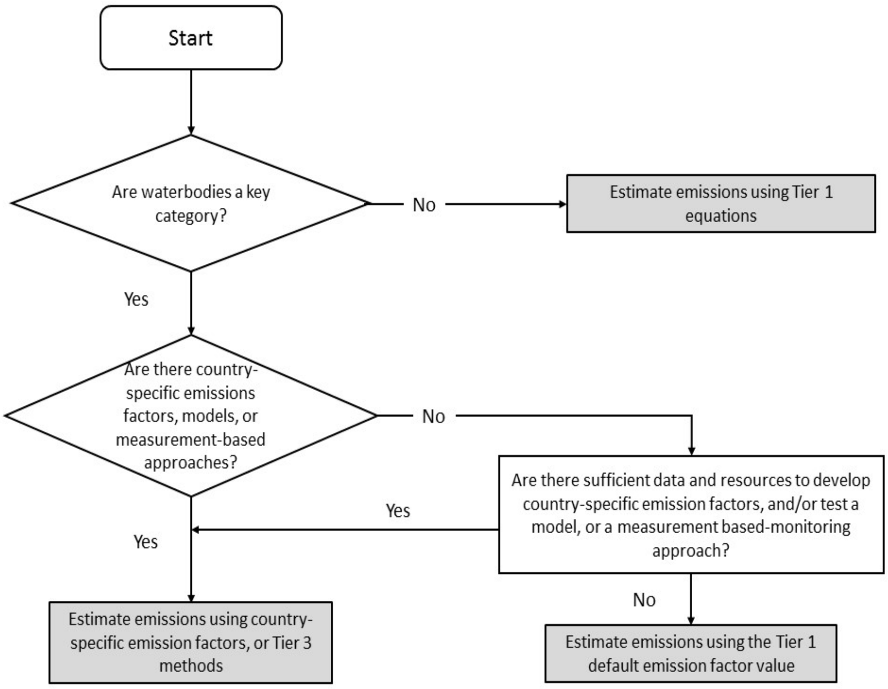
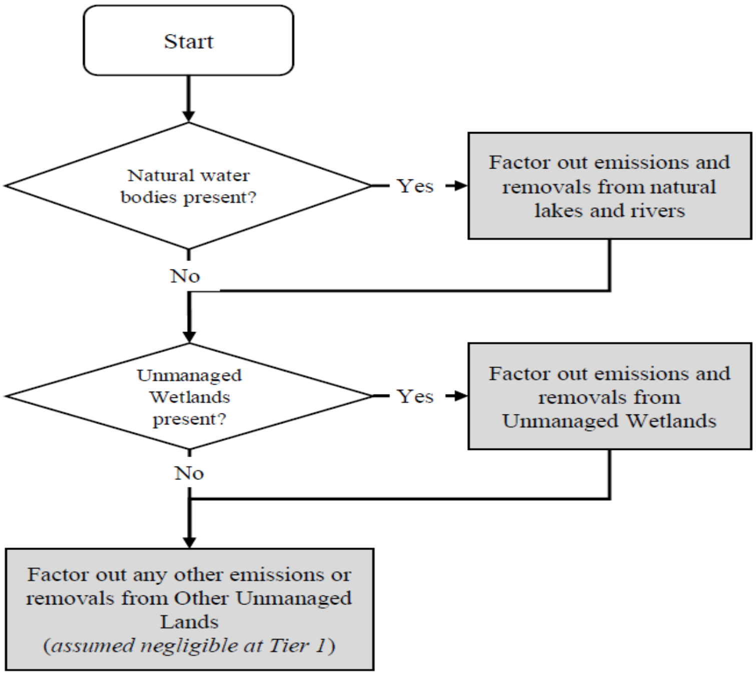


Figure 7.4 (New) Decision tree for factoring out emissions and removals from Unmanaged Land converted to Managed Flooded Land, for use in countries that choose to factor out emissions and removals that would otherwise occur if the land remained unmanaged



7.3.1 Flooded Land Remaining Flooded Land

7.3.1.1 CO_2 EMISSIONS FROM FLOODED LAND REMAINING FLOODED LAND

Total Flooded Land Emissions based on Managed Land Proxy

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 estimated as emissions from other managed land categories, and not addressed in this category to avoid double-counting of emissions (i.e., Volume 4, Chapter 4 Forest Land, Chapter 5 Cropland, Chapter 6 Grassland, Chapter 8 Settlements and the *2013 Wetland Supplement*). Therefore, no methodologies (Choice of Methods, Emission Factors, or Activity Data) are provided to estimate total CO_2 emissions for *Flooded Land Remaining Flooded Land* based on the managed land proxy.

Factoring Out Emissions (Removals) that would otherwise occur if Land Remained Unmanaged

Unmanaged land would continue to generate emissions (removals) in the absence of flooding. Guidance is provided here on methodologies to estimate and factor out these emissions (removals). The methods are applicable to all forms of *Flooded Land Remaining Flooded Land*.

Choice of methods

Tier 1

Unmanaged Flooded Land, Forest Land, Grassland, and Other Land are assumed to be at long-term steady state with respect to CO_2 exchange with the atmosphere, and therefore there is no net CO_2 emission (removal) to factor out at the Tier 1 level. However, Unmanaged Wetlands, which are not continuously flooded but may become Flooded Land through management activity, do not reach steady state and can remove CO_2 from the atmosphere over the long term, for example via peat formation. In most cases, Unmanaged Wetlands act as sinks for CO_2 (i.e. the emission factor is negative) and factoring out these emissions will increase the net emission of CO_2 for a reservoir or other waterbody.

The procedure for factoring out emissions (removals) that would otherwise occur if the land remained unmanaged includes three steps:

1. Estimate the total CO_2 emissions (removals) from the flooded land based on the managed land proxy, F_{CO2tot}. As explained above, this is assumed to be zero for *Flooded Land Remaining Flooded Land.*
2. Estimate CO_2 emissions (removals) that would otherwise occur if the land remained unmanaged, $F_{CO2otherwise}$. (Eq. 7.11)
3. Estimate net CO_2 emissions (removals) from the flooded area (F_{CO2net}) by subtracting the emissions that would otherwise occur (step 2) from the total emissions and removals estimated in step 1.

Net emissions from flooded lands is estimated with the following equation by factoring out emissions that would otherwise occur from Unmanaged Flooded Land without conversion to Managed Flooded Land:

EQUATION 7.10 (NEW GUIDANCE)
ANNUAL NET CO_2 EMISSIONS/REMOVALS FROM *FLOODED LAND WITH FACTORING OUT*

$$F_{CO_2net} = F_{CO_2tot} - F_{CO_2otherwise}$$

Where:

F_{CO2net} Net annual emission (removal) of CO_2 from flooded land [tonnes CO_2-C yr^{-1}]

F_{CO2tot} Total annual emission (removal) of CO_2 from flooded land [tonnes CO_2-C yr^{-1}] (assumed to be zero for Flooded Land Remaining Flooded Land).

$F_{CO2otherwise}$ Total annual emission (removal) of CO_2 from all unmanaged wetlands that would have otherwise occurred if the land remained unmanaged [tonnes CO_2-C yr^{-1}] (See Eq. 7.11)

Emissions that would otherwise occur if the land remained unmanaged are estimated with the following equation:

EQUATION 7.11 (NEW GUIDANCE)
ANNUAL CO_2 EMISSIONS/REMOVALS THAT WOULD HAVE OTHERWISE OCCURRED IF THE LAND REMAINED UNMANAGED

$$F_{CO_2 otherwise} = \sum_{j=1}^{6} \sum_{k=1}^{n_{wb,j}} \sum_{r=1}^{5} \sum_{i=1}^{n\_luc_{k,r}} \left(EF_{CO2\_luc_{j,r}} \bullet A\_luc_{k,r,i} \right)$$

Where:

$F_{CO2otherwise}$ Total annual emission (removal) of CO_2 from all unmanaged wetland types that would have otherwise occurred if land remained unmanaged [tonnes CO_2-C yr^{-1}]

$A\_luc_{k,r,i}$ Area of previously existing unmanaged wetland element '*i*' of type '*r*' inundated as a result of reservoir/other waterbody construction for reservoir/other waterbody '*k*' located in climate zone 'j'. [ha]

$EF_{CO2\_luc\ j,r}$ Emission factor for CO_2 emitted from unmanaged wetland of type '*r*' located in climate zone '*j*' [tonnes CO_2-C ha^{-1} y^{-1}] (Table 7.9 - *Emissions factors table, negative values denote a sink*)

$n\_luc_{k,r}$ Number of unmanaged wetland elements of wetland type '*r*' inundated by reservoir/other waterbody '*k*' in climate zone '*j*'.

$n_{wb,j}$ Number of waterbodies of all types in climate zone 'j'

i Summation index for the number of unmanaged wetland elements of type 'r' inundated by waterbody 'k'

j Summation index for climate zones (*j* = 1-6, see Table 7.9)

k Summation index for total number of reservoirs/other waterbodies in climate zone '*j*'

r Summation index for unmanaged wetland types (r = 1-5, see Table 7.9) .

Tier 2 and 3

Compilers may apply higher-tier approaches to estimate CO_2 removals from Unmanaged Wetlands based on guidance provided in Chapter 3 and 4 of the *2013 Wetlands Supplement*. At Tier 2, empirical data could be derived from studies of undrained wetlands (i.e., unmanaged), excluding data from re-wetted areas.

If Unmanaged Inland Wetland Mineral Soils are not in steady state with respect to carbon pools, Tier 2 emission factors may be developed based on country-specific measurements. Similarly, if CO_2 emissions or removals from other types of unmanaged land, including Forest Land and Grassland, are not at steady-state, country-specific emission factors of models can be applied to factor out the associated emissions or removals.

At Tier 3, models of long-term soil and biomass carbon accumulation (e.g. peat formation, forest growth) or depletion could be used to derive estimates of CO_2 emissions or removal for unmanaged individual wetland types and other land areas.

Choice of Emission Factor

Tier 1

Carbon pools in *Unmanaged Inland Wetland Mineral Soils* can be assumed to be at steady state, and the relevant emission factors therefore are set to zero. For Unmanaged Wetlands on Organic Soil, Tier 1 emission factors are provided by climate zone and subcategory (nutrient-poor bog and nutrient-rich fen) in Table 3.1 of the *2013 Wetlands Supplement* (provided in Table 7.9 below). Emission factors for mangroves and tidal marshes are from Table 4.12, Chapter 4, *2013 Wetland Supplement*. These emission factors are partly based on empirical data from natural sites (see *2013 Wetland Supplement*, Annex 3A.1) as a proxy for re-wetted sites, and therefore provide a basis for deriving Tier 1 emission factors for natural wetlands.

Tier 2 and 3

Under Tier 2, country-specific emission factors may be developed that take into account national circumstances as well as specific properties of unmanaged wetlands, including type of wetland, species, sedimentation and sequestration of carbon and other environmental (e.g. seasonal variation, salinity) and management factors. Guidance for development of country specific emission factors at Tier 2 and 3 can be found in the *2013 Wetland Supplement*.

TABLE 7.9 (NEW GUIDANCE)
CO2 EMISSION FACTORS FOR EMISSIONS THAT WOULD OTHERWISE HAVE OCCURRED FROM UNMANAGED WETLANDS

Climate Zone		**CO_2 Emission Factors *EFCO2_luc* $_{j,r}$** and [95% confidence intervals] **(tonnes CO_2-C ha^{-1} yr^{-1})**				
		Organic soils nutrient poor (bog)	**Organic soils nutrient rich (fen)**	**Mangroves (all salinities)**	**Tidal marshes (all salinities)**	**Inland wetland mineral soils**
	j	**r = 1**	**r = 2**	**r = 3**	**r = 4**	**r = 5**
Boreal	1	-0.34 [-0.59 – -0.09]	-0.55 [-0.77 – -0.34]	-1.62 [-2.92 – +0.38]	-0.91 [-1.61 – + 0.19]	0
Cool Temperate	2	-0.23 [-0.59 – -0.09]	+0.50 [-0.71 – +1.71]			
Warm temperate/dry	3					
Warm temperate/moist	4					
Tropical dry/montane	5	0	0			
Tropical moist/wet	6					

Note: Emission factors are from the *2013 Wetland Supplement*: Organic soils nutrient poor (bog) Table 3.1; Organic soils nutrient rich (fen) Table 3.1; Tidal marshes and mangroves Table 4.12; Inland wetland mineral soils Table 5.3

Choice of Activity Data

Tier 1

Activity data needed include area of Unmanaged Wetlands for subcategories, e.g. nutrient-poor bog, nutrient-rich fen or coastal wetlands, that become a managed flooded land and the final flooded land area in the respective climate zone. Activity data required to support Tier 1 factoring out calculations are complete mapping for pre-flooding wetland cover area estimated from a land use survey, remotely sensed imagery (e.g. Landsat data) or other national maps and data bases.

Tiers 2 and 3

The activity data needed depends on the approach chosen. Tier 2 and 3 may include the proportions of different types of Unmanaged Wetlands present prior to flooding and stratification over climate zone, soil types, nutrient and water levels and other factors that influence CO_2 emissions and removals from Unmanaged Wetlands. Guidance can be found in the Chapter 3 and 4 of the *2013 Wetland Supplement*.

7.3.1.2 NON-CO_2 EMISSIONS FROM FLOODED LAND REMAINING FLOODED LAND

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 allows the estimation of the total diffusive, ebullitive and downstream CH_4 emissions (see Glossary), F_{CH4tot}, (Equation 7.12).

A method is provided to estimate net emissions, F_{CH4net}, (Eq. 7.14) by factoring out emissions (removals) that otherwise would have occurred if the Managed Flooded Land had remained Unmanaged Land, $F_{CH4otherwise}$, (Eq.

7.15). If factoring out approaches are not used or there is insufficient information to factor out emissions (removals) that otherwise would have occurred if the land remained unmanaged, then $F_{CH4otherwise}$ is set to zero and only the total emission (removal), F_{CH4tot}, is estimated.

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, *Land Converted to Flooded Lands*.

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

Total emissions from flooded land (F_{CH4tot}) can be estimated as:

EQUATION 7.12 (NEW GUIDANCE)
ANNUAL CH_4 EMISSIONS FOR RESERVOIRS >20 YEARS OLD (*FLOODED LAND REMAINING FLOODED LAND*)

$$F_{CH_4tot} = \sum_{j=1}^{6}\sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH4age>20,j} \left(1 + R_d\right) \bullet A_{total,j,i} \right)$$

Where:

F_{CH4tot} Total annual emission (removal) of methane from all reservoirs > 20 years old [kg CH_4 yr^{-1}]

$A_{total,j,i}$ Total area of reservoir water surface for reservoir > 20 years old '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} yr^{-1}] (Table 7.10 - *Emissions factors table*)

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 7.11). 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 7.13 for Tiers 2 & 3.

i Summation index for the number of reservoirs of same age class in climate zone 'j'

j Summation index for climate zones (j = 1-6, see table 7.10)

$nres_j$ Number of reservoirs > 20 years old in climate zone ‘j’

The equation for scaling CH4 emission factors for eutrophication is estimated as follows:

EQUATION 7.13 (NEW GUIDANCE)
EQUATION USED TO SCALE CH_4 EMISSION FACTORS FOR THE INFLUENCE OF EUTROPHICATION USING MEASURED VALUES OF CHLOROPHYLL A (MODIFIED FROM DEEMER ET AL (2016))

$$\alpha_i = 0.26 \bullet Chla_i$$

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. 7.13) can be estimated from other general assessments of reservoir trophic status (See Table 7.12).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Net emissions from flooded lands is estimated with the following equation (flooded > 20 years prior to inventory) by factoring out emissions (removals) that would otherwise occur from Unmanaged Land without conversion to Managed Flooded Land:

EQUATION 7.14 (NEW GUIDANCE)
ANNUAL NET CH_4 EMISSIONS/REMOVALS FROM *FLOODED LAND REMAINING FLOODED LAND* *WITH FACTORING OUT*

$$F_{CH_4 net} = F_{CH_4 tot} - F_{CH_4 otherwise}$$

□

Where:

F_{CH4net} Net annual emission (removal) of methane from flooded land [kg CH_4 yr^{-1}]

F_{CH4tot} Total annual emission (removal) of methane from flooded land [kg CH_4 yr^{-1}]

$F_{CH4otherwise}$ Total annual emission (removal) of methane from all land use classes that would otherwise occur on the unmanaged land without conversion to Managed Flooded Land [kg CH_4 yr^{-1}]

Total emissions (removals) that would otherwise occur if the flooded land remained unmanaged may be estimated with the following equation:

EQUATION 7.15 (NEW GUIDANCE)
TOTAL ANNUAL CH_4 EMISSIONS/REMOVALS THAT WOULD HAVE OTHERWISE OCCURRED FROM UNMANAGED FLOODED LAND

$$F_{CH_4 otherwise} = \sum_{j=1}^{6} \sum_{k=1}^{n_{fl\_a\_j}} F_{CH_4 otherwise\_fl\_a_{k,j}}$$

Where:

$F_{CH4otherwise}$ Total annual emission (removal) of methane from all waterbody classes that otherwise would have occurred if these lands remained unmanaged [kg CH_4 yr^{-1}]

$F_{CH4otherwise\_fl\_a,k,j}$ Total annual emission (removal) of methane from a single flooded area 'k' (e.g. a single reservoir) in climate zone 'j' that otherwise would have occurred if the land remained unmanaged [kg CH_4 yr^{-1}]

$n_{fl\_a,j}$ Number of flooded areas of all types in climate zone 'j'

j Summation index for climate zones (j = 1-6, see Table 7.14)

k Summation index for total number of reservoirs/other waterbodies in climate zone '*j*'

The $F_{CH4otherwise\_fl\_a}$ for an individual flooded land area (e.g. element 'k' in climate zone 'j' where 'element' refers to the reservoir or other waterbody) is calculated using Equations 7.16-7.18:

EQUATION 7.16 (NEW GUIDANCE)
ANNUAL CH_4 EMISSIONS/REMOVALS THAT WOULD HAVE OTHERWISE OCCURRED FROM UNMANAGED WATERBODIES AND OTHER UNMANAGED LAND

$$F_{CH_4 otherwise\_fl\_a} = F_{CH_4 otherwb} + F_{CH_4 otherland}$$

Where:

$F_{CH4otherwise\_fl\_a}$ Total annual emission (removal) of methane that would otherwise occur if the land remained unmanaged [kg CH_4 yr^{-1}]

$F_{CH4otherwb}$ Total annual emission (removal) of methane from waterbodies, including lakes, rivers, and streams, that would otherwise occur if the land remained unmanaged [kg CH_4 yr^{-1}]

$F_{CH4otherland}$ Total annual emission (removal) of methane from other unmanaged land, including unmanaged wetland, mangroves, and tidal marshes that would otherwise occur if the land remained unmanaged [kg CH_4 yr^{-1}]

Emissions (removals) that would otherwise occur from unmanaged lakes, rivers and streams are estimated using equation 7.17. A scaling factor, α_i, is included to allow adjustment for their trophic state using Eq. 7.13 or Table 7.12.

EQUATION 7.17 (NEW GUIDANCE)
ANNUAL CH_4 EMISSIONS/REMOVALS THAT WOULD HAVE OTHERWISE OCCURRED FROM UNMANAGED WATERBODIES (LAKES, RIVERS AND STREAMS)

$$F_{CH_4otherwb} = \sum_{r=1}^{2} \sum_{i=1}^{n\_wb_r} \alpha_i \left(EF_{CH4wb_{j,r}} \bullet Awb_{r,i} \right)$$

Where:

$F_{CH4otherwb}$ Total annual emission (removal) of methane from unmanaged waterbodies (lakes, rivers and streams) that would otherwise occur if the land remained unmanaged [kg CH_4 yr^{-1}]

$Awb_{r,i}$ Area of unmanaged waterbody, element '*i*' of class '*r*' inundated as a result of reservoir/other waterbody construction for reservoir/other waterbody. [ha]

$EF_{CH4wb\ j,r}$ Emission factor for methane emitted from waterbody class of type '*r*' located in climate zone '*j*' [kg CH_4 ha^{-1} y^{-1}] (Table 7.13 - *Emissions factors table*)

α_i Emission factor adjustment for trophic state in waterbody '*i*' of class '*r*' located in climate zone '*j*'. [dimensionless] equals 1.0 by default for Tier 1 for all waterbody classes. See Equation 7.13 and Table 7.12 for Tiers 2 & 3.

n_wb_r Number of land elements of waterbody class type '*r*' inundated by reservoir/other waterbody.

i Summation index for the number of waterbody elements of class 'r' inundated by reservoir/waterbody

r Summation index for waterbody classes (r = 1 for streams and rivers, r = 2 for lakes).

Emissions (removals) that would otherwise occur from other unmanaged lands, including wetlands, mangroves and marshes are estimated using equation 7.18.

EQUATION 7.18 (NEW GUIDANCE)
ANNUAL CH_4 EMISSIONS/REMOVALS THAT WOULD HAVE OTHERWISE OCCURRED FROM OTHER UNMANAGED LANDS (WETLANDS, MANGROVES AND MARSHES)

$$F_{CH_4otherland} = \sum_{r=3}^{7} \sum_{i=1}^{n\_luc_r} \left(EF_{CH4\_luc_{j,r}} \bullet Alc_{r,i} \right)$$

Where:

$F_{CH4otherland}$ Total annual emission (removal) of methane from all wetland classes that would otherwise occur if the land remained unmanaged [kg CH_4 yr^{-1}]

$Alc_{r,i}$ Area of previously existing wetland element '*i*' of class '*r*' inundated by the flooded area [ha]

$EF_{CH4\_luc\ j,r}$ Emission factor for methane emitted from wetland class of type '*r*' located in climate zone '*j*' [kg CH_4 ha^{-1} y^{-1}] (Table 7.14 - *Emission factors table*)

n_luc_r Number of wetland elements of wetland class type '*r*' inundated by the flooded area.

i	Summation index for the number of wetland elements of class 'r' inundated by the flooded area
r	Summation index for wetland classes (r = 3-7, see Table 7.14) .

In general, other Unmanaged Lands, including forest land and grassland, are not considered a significant source of CH_4 emissions, and removals of CH_4 are not recognized as an anthropogenic source category in the AFOLU sector guidance. However some removal of CH_4 can occur through oxidation of atmospheric CH_4 by methanotrophic microorganisms in aerated soils, but this flux is typically small when expressed per unit land area (Oertel *et al.* 2016). Regardless, no guidance is provided to factor out CH_4 removal from unmanaged forest land and grassland.

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

At the Tier 2 level, downstream emissions can be estimated based on water withdrawal depths for individual reservoirs. If water is withdrawn from the oxic (upper) part of the water column, the CH_4 content of the water is expected to be relatively low, therefore downstream emissions can be assumed to be zero. If water is withdrawn from the anoxic (lower) part of the water column, where dissolved CH_4 can accumulate to high levels, downstream emissions should be estimated following equation 7.12 using the R_d factor found in Table 7.11 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 7.10) by a factor, α_i, either computed from measured mean annual chlorophyll-*a* (Chl-*a*) data using Equation 7.13, or taken from Table 7.12 where trophic state may be known but mean annual Chl-*a* data are lacking. Equation 7.13 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 7.12 rather than these global averages.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Compilers can factor out emissions (removals) that would otherwise occur in unmanaged land that is converted to managed flooded land following the methodology described in the Tier 1 approach. Where there are sufficient data compilers may also include the effect of carbon burial in the sediments in case there is a net removal of carbon in the managed flooded land (see Box 7.1).

BOX 7.1 (NEW GUIDANCE)
ADDITIONAL INFORMATION ON SEDIMENTATION AND CARBON BURIAL IN RESERVOIRS

Reservoirs are often sites of significant accumulation of sediments, and therefore carbon (Clow *et al.* 2015). 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.* 2017a). 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

Total Flooded Land Emissions based on Managed Land Proxy

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 GHG Measurement Guidelines for Freshwater Reservoirs 2010 (Goldenfum 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)).

Degassing can be estimated as the difference between the dissolved gas concentration at the water entering the dam and the dissolved gas concentration downstream of the dam, multiplied by the outlet discharge. Dissolved gas concentration of the water entering the dam can be estimated from water samples collected from the reservoir at the depth of the water intake or directly from the water conveyance structure, if possible. Diffusive emission from the downstream river can be directly measured or estimated using a mass balance approach. See (Goldenfum 2010) (UNESCO/IHA), section 2.4.1.2.3).

Accuracy is improved when measurements are undertaken across a full seasonal cycle because CH_4 dynamics are very temperature sensitive. The accuracy of CH_4 emissions can also be improved by considering atmospheric pressure that may strongly influence CH_4 ebullition. 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).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

A Tier 3 approach for factoring out emissions (removals) with conversion of unmanaged land to managed flooded land, estimating the effects of converting unmanaged flooded lands and wetlands to Flooded Land might use a process model to estimate emissions from unmanaged land, for example by taking account of variations in the attributes listed in the section above on total flooded land emissions for Tier 3. A Tier 3 approach might also take account of seasonal and inter-annual variations in CH_4 emissions, for example associated with the expansion of lake and wetland areas during wetter periods. If a Tier 3 approach is taken to factor out emissions from unmanaged flooded lands, a comparable approach should be taken to estimate emissions from the subsequent Flooded Land area.

Choice of Emission Factors

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

Emission factors for CH_4 via diffusion and ebullition from the reservoir surface, $EF_{CH4\ age>20,j}$ in the six aggregated climate zones are provided in Table 7.10. 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 and are averaged per climate zone. See Annex 7.1 for details of how default emissions factors were derived.

TABLE 7.10 (NEW GUIDANCE) CH_4 EMISSION FACTORS FOR RESERVOIRS OLDER THAN 20 YEARS (> 20 YEARS) – *FLOODED LAND REMAINING FLOODED LAND*				
Aggregated Climate Zone		**CH_4 Emission Factors $EF_{CH4\ age>20,j}$ (kg CH_4 ha^{-1} $year^{-1}$)**		
	j	**Average**	**Lower and upper 95% CI of mean**	**N**
Boreal	1	13.6	7.3-19.9	96
Cool Temperate	2	54.0	48.3-59.5	1879
Warm temperate/dry	3	150.9	133.3-168.1	578
Warm temperate/moist	4	80.3	74.0-86.0	1946
Tropical dry/montane	5	283.7	261.9-305.8	710
Tropical moist/wet	6	141.1	131.1-152.7	805
The emission factors are derived from the G-Res model outputs from N reservoirs in each climate zone. The aggregation into 6 climate zones is described in Annex 1, section A7.1.2.1. N is the number of modelled reservoirs used to estimate EF values and their 95% confidence intervals.				

Default values for the ratio of total downstream emission of methane to the total flux of methane from the reservoir surface are provided in Table 7.11.

TABLE 7.11 (NEW GUIDANCE) 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.* 2014a), (Bevelhimer *et al.* 2016), (Descloux *et al.* 2017), (DelSontro *et al.* 2011), (dos Santos *et al.* 2017), (Kumar & Sharma 2016), (Chanudet *et al.* 2011), (Abril *et al.* 2005), (Bastien & Demarty 2013), (Deshmukh *et al.* 2016), (Serça *et al.* 2016), (Guérin *et al.* 2006), (Kemenes *et al.* 2007).			

Trophic state adjustment factor (α_i, Eq. 7.13) can be estimated from other general assessments of reservoir trophic status, for example from trophic index, total phosphorus and nitrogen and Secchi depth, and alternative values are provided in Table 7.12

TABLE 7.12 (NEW GUIDANCE) RELATIONSHIPS BETWEEN TROPHIC INDEX (TI), SURFACE CONCENTRATIONS OF CHLOROPHYLL-A (Chl-*a*), TOTAL PHOSPHORUS (TP), TOTAL NITROGEN (TN), SECCHI DEPTH (SD), AND TROPHIC CLASS[1] AND TROPHIC STATE ADJUSTMENT FACTOR (α_i)						
TI	**Chl-*a* (µg/L)**	**TP (µg/L)**	**TN (µg/L)**	**SD (m)**	**Trophic Class**	**Trophic State Adjustment Factor α_i Range and (recommended value)**
<30 - 40	0 - 2.6	0 - 12	–<350	> 4	Oligotrophic	0.7 (0.7)
40 - 50	2.6 - 20	12 - 24	–350-650	2 - 4	Mesotrophic	0.7 - 5.3 (3)
50 - 70	20 - 56	24 - 96	650-1200	0.5 - 2	Eutrophic	5.3 - 14.5 (10)
70 - 100+	56 - >155	96 - >384	>1200	< 0.5	Hypereutrophic	14.5 - 39.4 (25)
[1] (Carlson 1977), (Smith *et al.* 1999)						

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Unmanaged lakes and rivers can act as significant sources of CH_4 emissions. Various forms of unmanaged wetland (wetlands on organic soil, inland wet mineral soils and low-salinity coastal wetlands) can also emit CH_4. At Tier 1, it may be assumed that the CH_4 emission factor of a natural waterbody (EF_{CH4wb}) is the same as the emission factor for *Flooded Land Remaining Flooded Land* ($EF_{CH4age>20,j}$). These emission factors are provided in Table 7.13. CH_4 emission factors for unmanaged rivers and streams is 0 (zero) under the assumption that these water bodies are fully aerobic environments.

TABLE 7.13 (NEW GUIDANCE)
CH_4 EMISSION FACTORS FOR EMISSIONS THAT WOULD OTHERWISE HAVE OCCURRED FROM FLOODED LANDS

Climate Zone		CH_4 Emission Factors $EF_{CH4wb\ j,r}$ [95% confidence intervals] (kg CH_4 ha^{-1} $year^{-1}$)	
		Streams/Rivers	**Lakes (same as for reservoirs with age > 20 years)**
	j	**r = 1**	**r = 2**
Boreal	1	0	13.6 [1.0 - 153.8]
Cool Temperate	2	0	54.0 [2.9 - 262.8]
Warm temperate/dry	3	0	150.9 [7.8 - 848.7]
Warm temperate/moist	4	0	80.3 [9.2 - 434.6]
Tropical dry/montane	5	0	283.7 [12.2 - 1188]
Tropical moist/wet	6	0	141.1 [9.2 - 608.3]

The emission factors are derived from the G-Res model outputs in each climate zone (see Table 7.10). The aggregation into 6 climate zones is described in Annex 1, section A7.1.2.1.

Tier 1 values for inundated wetland soils and tidal marshes, $EF_{CH4\_luc\ j,r}$ can be found for each wetland category in the *2013 Wetlands Supplement* and are reproduced for convenience in Table 7.14. For wetlands on organic soil, these emission factors were partly based on empirical data from natural sites (see *2013 Wetland Supplement*, Annex 3A.3) as a proxy for re-wetted sites, and are therefore appropriate for deriving Tier 1 emission factors for natural wetlands.

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

Under Tier 2, country-specific emission factors may be developed that take into account national circumstances as well as specific properties of individual reservoirs including: reservoir operation, size, and depth; relative locations of oxic/anoxic water and water intakes; trophic status; sedimentation and sequestration of carbon; and other environmental (e.g. seasonal ice cover) and management factors. CH_4 emissions due to wastewater inflow can be estimated and factored out of reservoir emissions (see Box 7.2).

BOX 7.2 (NEW GUIDANCE)
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). Allochthonous organic carbon from treated and/or untreated wastewater may reach the flooded land area and be converted to CH_4 (Deemer et al., 2016). At Tier 3 level it is a *good practice* to factor out CH_4 emission from wastewater treatment and discharge, (which is included in Volume 5, Chapter 6), to avoid double counting.

TABLE 7.14 (NEW GUIDANCE) **CH_4 EMISSION FACTORS FOR EMISSIONS THAT WOULD OTHERWISE HAVE OCCURRED FROM UNMANAGED WETLANDS**						
Climate Zone		**CH_4 Emission Factors $EF_{CH4\_luc\ j,r}$ and [95% confidence interval] (kg CH_4 ha^{-1} y^{-1})**				
		Organic soils nutrient poor (bog)	**Organic soils nutrient rich (fen)**	**Tidal marshes and mangroves (salinity) ≤ 18 ppt**	**Tidal marshes and mangroves (salinity) > 18 ppt**	**Inland wetland mineral soils**
	j	**r = 3**	**r = 4**	**r = 5**	**r = 6**	**r = 7**
Boreal	1	55 [0.7 - 328]	183 [0 - 657]	194 [99.8 - 358]	0	76 [0 - 152]
Cool Temperate	2	123 [4 - 593]	288 [0 - 1141]			235 [127 - 343]
Warm temperate/dry	3					
Warm temperate/moist	4					
Tropical dry/montane	5	55 [9.3 - 179]	55 [9.3 - 179]			900 [444 - 1356]
Tropical moist/wet	6					
Note: Emission factors are from the *2013 Wetland Supplement*: Organic soils nutrient poor (bog) Table 3.3; Organic soils nutrient rich (fen) Table 3.3; Tidal marshes and mangroves Table 4.14; Inland wetland mineral soils Table 5.4						

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Compilers may choose to estimate CH_4 emissions from unmanaged waterbodies converted to Flooded Lands based on additional country-specific information. This could include information about their mean depth, flow rates and water residence times, the extent of shallow (littoral) zones, trophic status and sediment loadings. Separate emission factors for lakes and rivers may also be developed. Information on average fluxes may be obtained from measurements made in lakes and rivers prior to reservoir construction, or from measurements made at natural waterbodies of the same type and within the same climate zone.

Compilers may apply Tier 2 approaches to factor out CH_4 emissions from unmanaged wetlands converted to *Flooded Land* based on guidance provided in Chapters 3, 4 and 5 of the *2013 Wetlands Supplement*. At Tier 2, emissions factors could be derived from studies of natural (undrained) wetlands, excluding data from re-wetted areas.

Tier 3

Total Flooded Land Emissions based on Managed Land Proxy

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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

A Tier 3 approach for *factoring emissions (removals) that otherwise would not have occurred in the absence of flooding*, estimating the effects of converting unmanaged waterbodies and wetlands to *Flooded Land* might use a process model to estimate natural emissions, for example by taking account of variations in the attributes listed above. A Tier 3 approach might also take account of seasonal and inter-annual variations in CH_4 emissions, for example associated with the expansion of lake and wetland areas during wetter periods. If a Tier 3 approach is taken to factor out emissions from unmanaged flooded lands, a comparable approach should be taken to estimate emissions from the subsequent Flooded Land area.

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

Total Flooded Land Emissions based on Managed Land Proxy

Country-specific data on the area of reservoirs within each climate zone are required to estimate CH_4 emissions from *Flooded Land*. 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.* 2011b). However, country-specific datasets are likely to be more complete.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Tier 1 country-specific data of the area of lakes, rivers, and unmanaged wetlands prior to flooding are needed. These data may be available from: maps of the pre-flooded land cover; land use surveys; project feasibility studies; environmental impact statements; remotely sensed imagery (e.g. Landsat data); or other national maps and data bases.

Tier 2 and 3

Total Flooded Land Emissions based on Managed Land Proxy

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 due to climatic and management activities, 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 water utilities responsible for dam operation and maintenance as well as from national dam operation databases. Tier 3 approaches can also include more detailed activity data on, for example, effects of climate variability on water surface area and reservoir management, but the exact requirements will depend upon the model or measurement design.

Data to directly calculate the trophic status adjustment, α_i, (Eq 7.13, 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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

At Tier 2 and 3, models of emissions pre-flooding of the landscape could be developed that include factors capturing seasonal and inter-annual variation in lake and river surface areas for different climate zones, eutrophication status, catchment hydrology and other factors similar to those recommended for estimation of total CH_4 emissions from reservoirs above. Estimates of eutrophication status could use dissolved and particulate sediment nutrient concentrations that facilitate use of water quality models for predicting trophic state; or direct measurement of chlorophyll-a with sufficient vertical and horizontal resolution to allow robust estimates of seasonally-averaged waterbody algal biomass under unmanaged conditions.

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 (e.g. recreation), and canals, drainage channels and ditches. This includes ponds within settlements, however, note that CH_4 emissions associated with wastewater are considered elsewhere (Volume 5, Chapter 6, *2019 Refinement*). For Managed Land categories on organic soils inventory compilers may choose to 'embed' emissions from small channels such as drainage ditches within their reporting of other Managed Land categories (using Equation 2.4, Section 2.2.2.1 of the *2013 Wetlands Supplement*[1] for drained organic soils). The same emissions should however not be included in Flooded Lands if they are included other Managed Land categories.

Choice of Method

1 Note that the approach described to account for ditch CH4 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.

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, incorporating variations in inundation regimes due to inter-annual and seasonal variation in water levels, management or other factors. All other constructed waterbodies are assumed to emit CH_4 at a constant average rate for as long as the land remains flooded. However, they may move between emission categories as a function of changes in site factors if higher tier approaches are applied. Compilers could use different tiers for subcategories within the *Other constructed waterbodies* category, depending on the importance of different waterbodies and the availability of activity data. Guidance on the development of country-specific factors or methods is provided below in Tier 2 and Tier 3 approaches.

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

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. At Tier 1, emission factors are not stratified by climate zone or trophic status, but this can be incorporated at Tier 2 and 3. See Annex 7.1 for details of how default emissions factors were derived.

Total emissions are calculated for a given waterbody type using Equation 7.19.

EQUATION 7.19 (NEW GUIDANCE)
ANNUAL CH_4 EMISSION FROM OTHER CONSTRUCTED WATERBODIES

$$F_{CH_4 other} = \sum_{j=1}^{6} \sum_{w=1}^{3} \sum_{i=1}^{nother_{w,j}} \left(A_{j,w,i} \bullet EF_{CH4,w} \bullet \alpha_{j,w,i} \right)$$

Where:

$F_{CH4other}$	Total annual flux of methane from ponds and channels [kg CH_4 yr^{-1}]
$A_{j,w,i}$	Area of other waterbody ‘i’ of type 'w' in climate zone 'j' [ha].
$\alpha_{j,w,i}$	Emission factor adjustment for trophic state other waterbody 'i' of type 'w' located in climate zone 'j'. Currently = 1 for all tiers. [dimensionless] Refer to Eq. 7.13, Table 7.12.
$EF_{CH4,w}$	Emission factor for other waterbody of type 'w' [kg CH_4 ha^{-1} y^{-1}]. Refer to Table 7.15.
$nother_{w,j}$	Number of other waterbodies of type 'w' in climate zone 'j'
i	Summation index for the number of other waterbodies of type 'w' in climate zone 'j'
j	Summation index for climate zones (j = 1-6, e.g. Table 7.14)
w	Summation index for waterbody classes (Table 7.15).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

The general approach of factoring-out emissions that would otherwise occur from Unmanaged Land without conversion to Managed Flooded Land for reservoirs may also be applied to Other constructed waterbodies, in which case Equation 7.19 would be substituted for Equation 7.12 (i.e. replace F_{CH4tot} in Eq. 7.14 with $F_{CH4other}$), and then apply Equations 7.16 - 7.18 as described in section 7.3.1.2. For example, if saltmarshes are converted to aquaculture ponds then the emissions and removals associated with saltmarsh could be factored using the appropriate CH_4 emissions factors Table 7.14).

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

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 7.19 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; inter-annual and seasonal variation in water levels; 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).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Compilers can factor out emissions (removals) that would otherwise occur in unmanaged land that is converted to managed flooded land following the methodology described in the Tier 2 approach for reservoirs.

Tier 3

Total Flooded Land Emissions based on Managed Land Proxy

A Tier 3 approach for constructed ponds and channels may specifically address the influence of different soils and land-uses 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 use of models that incorporate within-year and between-year variation in emissions as a function of climatic or land-management variability, water level variability or maintenance activities such as dredging and the duration of periodic drainage when sediments are exposed to air. 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 waterbodies 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).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Compilers can factor out emissions (removals) that would otherwise occur in unmanaged land that is converted to managed flooded land following the methodology described in the Tier 3 approach for reservoirs.

Choice of Emission Factors

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

Tier 1 emission factors for agriculture and aquaculture ponds, and from canals, drainage channels and ditches, are provided in Table 7.15. 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.

TABLE 7.15 (NEW GUIDANCE)
CH_4 EMISSION FACTORS FOR OTHER CONSTRUCTED WATERBODIES (FRESHWATER PONDS, SALINE PONDS, CANALS, DRAINAGE CHANNELS AND DITCHES)

Waterbody type	w	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	1	All	30	16-55	15
Freshwater and brackish ponds	2	All	183	118-228	68
Canals, drainage channels and ditches[c]	3	All	416	259-669	24[d]

[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] For Emission Factor for ditches in organic soils refer to Table 2.4, *2013 Wetlands Supplement*.

[d] 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.* 2016), (Castillo *et al.* 2017), (Chen *et al.* 2015), (Hai 2013), (Strangmann *et al.* 2008), (Vasanth *et al.* 2016), (Yang *et al.* 2015). Freshwater and brackish ponds: (Baker-Blocker *et al.* 1977), (Casper *et al.* 2000), (Grinham 2018), (Hu *et al.* 2016), (Huang 2016), (Liu *et al.* 2017), (Merbach *et al.* 1996), (Natchimuthu *et al.* 2014), (Selvam *et al.* 2014), (Stadmark & Leonardson 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 2006), (Evans *et al.* 2017), (Harrison 2003), (Hendriks *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.* 2011), (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).

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

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

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

Tier 3

Total Flooded Land Emissions based on Managed Land Proxy

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

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

Choice of Activity Data

Activity data consist of the total area of (non-reservoir) constructed waterbodies, stratified according to the waterbody type and any additional factors used to disaggregate emissions. Since flooded land area could change over time, countries should consider this in developing their time series of activity data, attributing land cover to the appropriate category. Countries may use older data sources to establish time series data as well as updated and recent data. Tier 2 and Tier 3 approaches are preferably based on national databases to track flooded land surface area in order to obtain more accurate emission estimates. For aquaculture ponds, additional data on product yields from ponds (FAO data) or management could be collected and related to CH_4 emissions to derive more accurate emission estimates.

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

Activity data required to support Tier 1 reporting are either complete mapping data for all constructed waterbodies, or alternatively a reliable estimate of the proportion of land area occupied by each waterbody type, such as estimated derived from a land use survey. For agricultural ponds, it may be possible to evaluate small representative areas within a larger land category in order to estimate the total proportion (and therefore total area) of ponds present (Lowe *et al.* 2005). The Ramsar Convention (Ramsar 2005) provides guidance on mapping of wetlands (Annex III) which can be used to determine the area of Other constructed waterbodies. Additional guidance for mapping agricultural ponds can be found in (Shaikh *et al.* 2011) and MDBC (2009) (Cunningham *et al.* 2009). The minimum recommended scale of mapping is 1:5000 (50m x 50m or 0.25 ha) which could be used if appropriate data are available, for example from Landsat remotely sensed imagery (Pekel *et al.* 2016) or other higher resolution satellite imagery. In many cases, drainage occurs at regular spacing within agricultural landscapes, such that the proportion of ditches in an area can be estimated from data on mean ditch width and spacing, as described in Section 2.2.2.1 of the *2013 Wetland Supplement* (the $Frac_{ditch}$ calculation). 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 may be available from remote sensing imagery (Ottinger *et al.* 2017) or national databases.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

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 to increase accuracy of CH_4 emission estimates.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

Tier 3

Total Flooded Land Emissions based on Managed Land Proxy

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 (which for drainage ditches could include high resolution aerial photography), waterbody type, nutrient status, flow rates, vegetation and other factors as described above. National level information capturing differing pond management (e.g. whether ponds are intensively managed or abandoned (Gusmawati *et al.* 2016), particularly where the effects of pond management influences CH_4 emissions (e.g. drainage, (Yang *et al.* 2015)) may also be appropriate to incorporate within a Tier 3 method.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to guidance for reservoirs provided earlier in this section (Section 7.3.1.2).

7.3.2 Land Converted to Flooded Land

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 guidance in other chapters (See 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.* 2004) (Huttunen *et al.* 2002; Huttunen *et al.* 2003). The rate of the post-flooding decrease in emissions may depend on the region in which a reservoir is located and can differ between CO_2 and CH_4, but seems to occur mainly during the initial decade following flooding (Delmas *et al.* 2005), (Abril *et al.* 2005), (Tremblay *et al.* 2005), (Teodoru *et al.* 2012).

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 input of organic material transferred into the flooded area from the watershed (Houel 2003), (Hélie 2004), (Cole & Caraco 2001), (Prairie *et al.* 2017a) and would have occurred in the absence of flooding, albeit displaced in space.

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*. 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 decay after flooding and the rate of decay diminishes over time following initial inundation. Therefore, it is not appropriate to report all C losses from 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 total CO_2 emissions during the 100-year lifespan of the reservoir from the flooded stock of organic matter are allocated to these 20 years (see below and Annex 7.1 Fig A4). C stocks are estimated using existing methodologies when possible (e.g., Volume 4, Chapter 2).

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 guidance in other chapters (See 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).

Annex 7.1 explains how the G-res model estimates 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

Total Flooded Land Emissions based on Managed Land Proxy

Emission factors for CO_2 from the reservoir surface, $EF_{CO2,j}$, in the six aggregated climate zones are provided in Table 7.16. 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 (Prairie *et al.* 2017a)) and are averaged per climate zone.

EQUATION 7.20 (NEW GUIDANCE)
ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM LAND CONVERTED TO FLOODED LAND

$$F_{CO_2tot} = \sum_{j=1}^{6} \sum_{i=1}^{nres_j} A_{total,j,i} \bullet EF_{CO_2 age\leq 20,j}$$

Where:

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

F_{CO2tot} Total annual emission (removal) of CO_2 from *Land Converted to Flooded Land* (Reservoirs ≤ 20 years old) [tonnes CO_2-C yr^{-1}].

$EF_{CO2\ age\leq 20,j}$ Emission factor for CO_2 for reservoir ≤ 20 years old in climate zone 'j' [tonnes CO_2-C ha^{-1} y^{-1}]. Refer to Table 7.16.

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

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

j Summation index for climate zones (j = 1-6, see Table 7.16)

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Net emissions of CO_2 from *Land Converted to Flooded Land* (i.e. Reservoirs ≤ 20 years old) are calculated following the method described in section 7.3.1.1 but using Eq. 7.20 to calculate F_{CO2tot}. Emissions and removals of CO_2 that would otherwise occur if the land remained unmanaged are estimated using Eq. 7.11 and Table 7.9.

Tier 2

Total Flooded Land Emissions based on Managed Land Proxy

The methodology for estimating Tier 2 annual carbon loss as CO_2 on recently flooded land (<20 years old) uses Equation 7.20 substituting in emission factor calculated in Equation 7.21. Tier 2 methods for determining annual CO_2 emissions/removals from newly flooded land use knowledge about climate zone and distribution of soil organic carbon stock of the land prior to flooding in order to develop country-specific factors.

EQUATION 7.21 (NEW GUIDANCE)
ANNUAL CO_2-C EMISSIONS/REMOVALS FROM *LAND CONVERTED TO FLOODED LAND* INCLUDING SOIL CARBON STOCKS

$$EF_{CO_{2\,j,i}} = \sum_{k=1}^{nsoil} \phi_{i,k} \bullet SOC_{j,k} \bullet M_j$$

Where:

$EF_{CO2\ j,i}$ Emission factor for CO_2 for reservoir 'i' climate zone 'j' [tonnes CO_2-C ha^{-1} y^{-1}].

$SOC_{j,k}$ Soil C stock (tonnes C ha^{-1} in 0-30 cm depth) values per climate zone (j) and mineral soil type (k) from Table 2.3 (Volume IV, Chapter 2), for undrained and drained peatlands using Table 2.6

		(*2013 Wetland Supplement*) with conversion from dry organic matter to organic carbon (see A7.1.2.2), 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 = 1-6, see Table 7.17)
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 7.17.
nsoil		Number of soil types (= 6, see Volume 2, Table 2.3)

Note that $\sum_{k=1}^{nsoil} \phi_{i,k} \leq 1$ will be nearly 1 if only a river existed prior to inundation of a large reservoir. In contrast, the value will be close to 0 if the reservoir is a small expansion of a natural lake.

Tier 2 may include: 1) a derivation of country-specific emission factors; 2) specification of climate sub-zones 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, and 5) a finer, more detailed classification of nutrient status or other water quality attributes, e.g. nitrogen, phosphorus, and chlorophyll.

For compatibility of approach, country-specific Tier 2 factors for CO_2 emissions and removals that are compiled using domestic flux data measured at the water-atmosphere boundary should follow a similar general concept to the G-res model, which is 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 waterbody. 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 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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged
Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

Tier 3

Total Flooded Land Emissions based on Managed Land Proxy
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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged
Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

Choice of Emission Factor

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

CO_2 emissions are calculated using the emission factors in Table 7.16.

TABLE 7.16 (NEW GUIDANCE) CO_2-C EMISSION FACTORS FOR RESERVOIRS ≤ 20 YEARS OLD – *LAND CONVERTED TO FLOODED LAND*			
Climate Zone		**CO_2-C Emission Factors $EF_{CO2\ age<20,j}$ (tonnes CO_2-C $ha^{-1}\ y^{-1}$)**	
	j	**Average**	**Lower and upper 95% CI**
Boreal	1	0.94	0.84 –1.05
Cool Temperate	2	1.02	1.00–1.04
Warm temperate dry	3	1.70	1.66 –1.75
Warm Temperate moist	4	1.46	1.44–1.48
Tropical dry/montane	5	2.95	2.86–3.04
Tropical moist/wet	6	2.77	2.71–2.84
The emission factors are derived from model outputs for each climate zone (Annex A7.1.2.1). The aggregation into 6 climate zones is described in Annex section A7.1.2.1.			

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

Tier 2 and 3

Total Flooded Land Emissions based on Managed Land Proxy

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-zones considered suitable for refinement of emission factors; 2) a finer, more detailed classification of management systems including estimation of emissions associated with drawdown zones during the time period of low water level in reservoirs; 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 that can be used in estimating the soil organic carbon stocks for 0-30 cm top soil layer within the flooded area using GIS tools. Table 7.17 provides scaling factor values that may be used with the Tier 2 method.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

Choice of Activity Data

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

Tiers 2 and 3

Total Flooded Land Emissions based on Managed Land Proxy

More detailed area information is needed for Tier 2 and 3 approaches, and can be found in geographic information products, reservoir statistics, or remote sensing products. Management systems for pre-impoundment land use characteristics of the flooded land could be derived from project-specific Environmental Impact Assessment documents, forest surveys from the pre-impoundment period, or remotely-sensed land cover assessments.

TABLE 7.17 (NEW GUIDANCE)
SCALING FACTOR VALUE M_J [y^{-1}] FOR EQUATION 7.21, ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM *LAND CONVERTED TO FLOODED LAND*.

IPCC climate zones	Aggregated climate zone		M		
		j	Average	Lower and upper 95% CI	Nb reservoir
Boreal dry Boreal moist Polar dry Polar moist	Boreal	1	0.0091	0.0075-0.0107	118
Cool temperate dry Cool temperate moist	Cool temperate	2	0.0146	0.0141-0.0151	2103
Warm temperate dry	Warm temperate dry	3	0.0568	0.0541-0.0595	679
Warm temperate moist	Warm temperate moist	4	0.0302	0.0291-0.0312	2095
Tropical dry Tropical montane	Tropical dry/montane	5	0.0900	0.0846-0.0954	902
Tropical moist	Tropical moist/wet	6	0.0668	0.0628-0.0708	920

Note: Scaling factors were derived from the integrated CO_2 emissions attributable to the reservoir estimated from the G-res model (see Annex 7.1 for details, (Prairie *et al.* 2017b) expressed as a fraction of soil organic carbon content (SOC) and applied to the first 20 years post-impoundment. The aggregation into 6 climate zones is described in Annex 1, section A7.1.2.1.

Countries could consider differentiating the fluxes from the drawdown zone. Estimation of drawdown zone areas can be done using remote sensing images taken during the time period of low water level in reservoirs or from reservoir managers.

Many countries also monitor water quality parameters from watercourses impacted by management activities. These include industrial effluent disposal, mining, land drainage, and wastewater treatment. 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.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Refer to section 7.3.1.1 for guidance on factoring-out CO_2 emissions.

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

RESERVOIRS

In reservoirs, high levels of CH_4 emissions can occur in the first 20 years following flooding (see Annex 7.1). No guidance on estimating N_2O emissions from flooded land is provided here because N_2O emissions from aquatic systems are indirect N_2O emissions from managed land that are addressed in other sections of this guidance (e.g. Volume 4, Chapter 11).

Choice of Method

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

For Tier 1, guidance can be found in 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 based on Equation 7.22, which differs from Equation 7.12 only in the values of the emission factors, $EF_{CH4\ age<20,j}$.

EQUATION 7.22 (NEW GUIDANCE)
ANNUAL CH_4 EMISSIONS FOR RESERVOIRS < 20 YEARS OLD FOR *LAND CONVERTED TO FLOODED LAND*

$$F_{CH_4 tot} = \sum_{j=1}^{6} \sum_{i=1}^{nres_j} \alpha_i \left(EF_{CH4\,age\leq 20,j} \left(1 + R_d\right) \bullet A_{total,j,i} \right)$$

Where:

F_{CH4tot}	Total annual emission(removal) of methane from all reservoirs ≤ 20 years old [kg CH_4 yr^{-1}]
$A_{total,j,i}$	Total area of reservoir water surface for reservoir ≤ 20 years old 'i' located in climate zone 'j' [ha]
$EF_{CH4\ age\leq 20,j}$	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 7.18)
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.
i	Summation index for the number of reservoirs of same age class in climate zone 'j'
j	Summation index for climate zones (j = 1-6, see table 7.14)
$nres_j$	Number of reservoirs ≤ 20 years old in climate zone ‘j’

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Emissions of CH_4 from unmanaged waterbodies and wetlands that would occur in the absence of their conversion to managed flooded land should be estimated using the methodology described above for *Land Remaining Flooded Land* (section 7.3.1.2, Equations 7.14 - 7.18 and Tables 7.13, 7.14).

Tiers 2 and 3

For Tiers 2 and 3, refer to guidance in section 7.3.1, Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Choice of Emission Factor

Tier 1

Total Flooded Land Emissions based on Managed Land Proxy

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 7.18. As for Flooded Land remaining Flooded Land (Table 7.10), 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 7.18 (NEW GUIDANCE)
CH_4 EMISSION FACTORS FOR RESERVOIRS ≤ 20 YEARS OLD – *LAND CONVERTED TO FLOODED LAND*

Aggregated Climate Zone		CH_4 Emission Factors $EF_{CH4\ age<20,j}$ (kg CH_4 ha^{-1} $year^{-1}$)		
	j	Average	Lower and upper 95% CI of the mean	N
Boreal	1	27.7	20.8–34.7	96
Cool Temperate	2	84.7	78.8-90.6	1879
Warm temperate dry	3	195.6	176.9-214.7	578
Warm Temperate moist	4	127.5	121.5-133.4	1946
Tropical dry/montane	5	392.3	366.5-417.7	710
Tropical moist/wet	6	251.6	236.6-266.7	805

Note: The Emission Factors are derived from model outputs from N reservoirs in each climate zone. The aggregation into 6 climate zones is described in Annex 1, section A7.1.2.1.

Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

Tier 1

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

Tiers 2 and 3

For Tiers 2 and 3, refer to guidance in section 7.3.1, Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

Choice of Activity Data

Tier 1

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

Tiers 2 and 3

For Tiers 2 and 3, refer to guidance in section 7.3.1, Non-CO_2 emissions from *Flooded Land Remaining Flooded Land*.

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

Refer to guidance in 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

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 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 waterbodies (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.

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 as 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.* 2014b), but can exceed emissions from the reservoir surface in thermally stratified systems with hypolimnetic withdrawal (Kemenes *et al.* 2007), (Abril *et al.* 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.* 2006). 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 (Goldenfum 2010) (UNESCO/IHA for measurement guidelines).

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

Uncertainties associated with Factoring Out Emissions that would otherwise occur if Land Remained Unmanaged

The suggested procedures for factoring out of emissions and removals from managed flooded lands that would otherwise occur if land remained unmanaged land are associated with several uncertainties:

The emission factors from >20 years old reservoirs are used for the unmanaged lake and river areas. The rationale is that CH_4 emission ranges for old reservoirs, lakes and rivers overlap, and are representative of the unmanaged condition. However, the emission range for large rivers is lower than ranges for lakes and reservoirs (Bastviken et al., 2011). Hence, the unmanaged river area CH_4 emissions may be overestimated with the suggested approach, resulting in underestimated flooded land emissions after applying the factoring out procedure. This may be addressed by developing Tier 2 or 3 methods that more accurately represent the emissions from river areas.

The unmanaged river and possibly lake area is a challenge to estimate if there is large intra- or inter-annual variability in river water level, resulting in a highly variable river area over time. To address this uncertainty, compilers may use the long-term mean river and lake area in the factoring out procedure, but it should be highlighted that there is a risk for higher uncertainty where the average area is challenging to assess.

7.4 INLAND WETLAND MINERAL SOILS

No refinement.

7.5 COMPLETENESS, TIMES SERIES CONSISTENCY, AND QA/QC

No refinement.

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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 temperature, anoxic conditions, and high sedimentation rates which provides organic matter and promotes anoxia. 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 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.

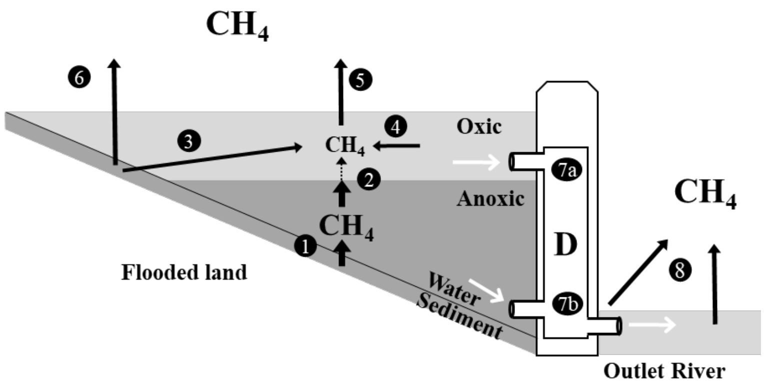
The transport of CH_4 through waterbodies

With reference to processes numbered in Figure A1, the transport of CH_4 through a reservoir can be described as follows (Bastviken 2009), 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 (Bussmann 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 (Camacho *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: estimation of emissions from coastal aquaculture ponds (Tier 1) is improved by consideration of salinity of the water as sulphides in seawater supress methanogenesis (Poffenbarger *et al.* 2011); 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 waterbody 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.* 2016). 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).

Factoring out emissions (removals) that would otherwise occur from Unmanaged Land without conversion to Managed Flooded Lands

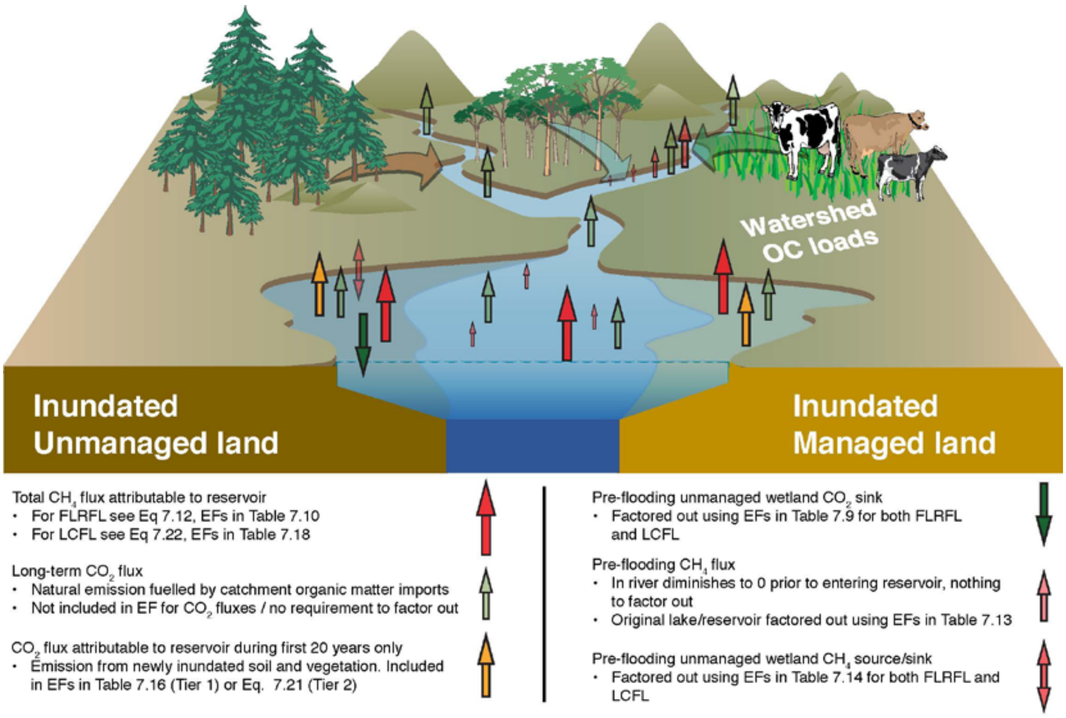
Factoring out emissions or removals that would otherwise occur from unmanaged lands, without their conversion to managed flooded lands reflects the net changes in greenhouse gas fluxes to the atmosphere resulting from the landscape transformation into a reservoir or other flooded lands. For example, unmanaged wetlands (e.g. peatlands) emit methane and sequester soil carbon and unmanaged lakes can also be a source of methane prior to their conversion to a reservoir. The factoring calculations allow for estimation of the net change in emissions when these unmanaged lands are converted to a reservoir. Box A7.1 describes the general approach used in factoring out in this Guidance.

BOX A7.1 (NEW GUIDANCE)

APPROACH FOR FACTORING OUT EMISSIONS AND REMOVALS THAT WOULD OTHERWISE OCCUR FORM UNMANAGED LAND WITHOUT CONVERSION TO MANAGED FLOODED LAND

The diagram below shows the rationale for factoring out using the example of CH_4 and CO_2 fluxes from a reservoir where land is either unmanaged (left) or managed (right) prior to flooding. CH_4 and CO_2 fluxes pre-flooding are shown compared to after flooding for *Flooded Land remaining Flooded Land* (FLRFL) and *Land converted to Flooded Land* (LCFL). Pre-flooding CH_4 emissions/removals from the original water surface area (pale red arrows) and from unmanaged wetlands (double-headed pale red arrow) are factored out by subtracting them from the total CH_4 flux emitted from the total surface area (bright red arrows) of the reservoir.

For factoring out CO_2 emissions/removals from the reservoir, CO_2 fluxes from unmanaged lands in both FLRFL and LCFL are assumed zero, with the exception of unmanaged wetlands, consistent with the *2013 Wetland Supplement* (dark green arrow). Changes in soil carbon stocks during the first 20 years after flooding (LCFL) are shown as yellow arrows. For both FLRFL and LCFL, long-term CO_2 fluxes arising from the decomposition of catchment-derived organic matter (pale green arrows) are considered natural in this guidance and are not incorporated into the CO_2 emission factors, hence do not require factoring out. For managed land (e.g. forest, croplands or grasslands), CO_2 and CH_4 fluxes prior to flooding, guidance is provided in other Chapters and not considered here.



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.* 2016).

The Emissions Factors from reservoirs presented for this methodology were derived from the application of the Greenhouse Gas Reservoir (G-res) model (Prairie *et al.* 2017b) which incorporates data from a large and diverse set of reservoirs (>6000 reservoirs with a global distribution). The G-res model is currently the only easily and widely applicable model and was developed to account for the potential biases described above. It uses empirical relationships between environmental drivers and emissions to estimate reservoir greenhouse gas fluxes. 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 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})

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

$$c_1 = 2.035 \pm 0.19$$

$$c_2 = 0.033 \pm 0.005$$

$$c_3 = 0.29 \pm 0.06$$

$$c_4 = 0.00178 \pm 0.006$$

$$c_5 = 0.076 \pm 0.03$$

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 [°C]

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 that corrects for the non-linearity in the temperature response of CH_4 emissions, and Q_{rad} is the mean daily solar irradiance averaged over a latitude-dependent period (see G-res documentation for details), and Ares is 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.* 2011a) 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.

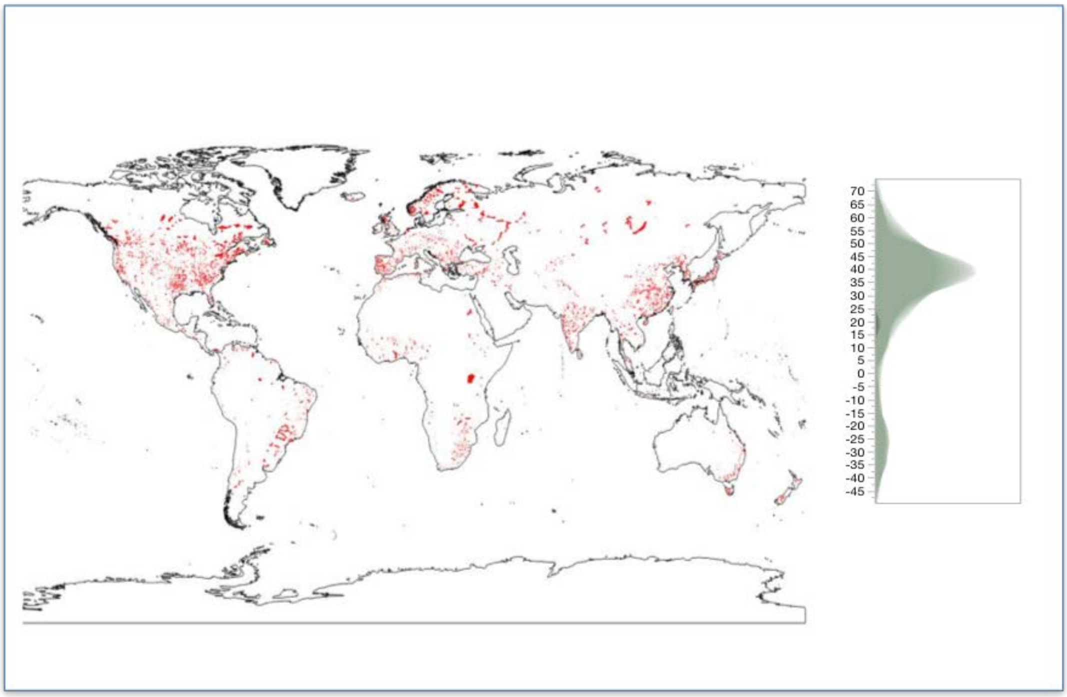


TABLE A1
NUMBER OF RESERVOIRS IN THE GRAND DATABASE IN EACH IPCC CLIMATE ZONE.

IPCC Climate zone	Number of Reservoirs
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 Methane Emissions Factors:

CH_4 emission is the sum of reservoir-wide 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*. The emission factor of CH_4 in this time interval can be derived with Equation A4. For *Flooded Land remaining Flooded Land*, the integration period was from 20 to 100 years post-impoundment. The emission factor of CH_4 in this time interval can be derived with Equation A5.

EQUATION A4
EMISSION FACTORS FOR *LAND CONVERTED TO FLOODED LAND*

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

EQUATION A5
EMISSION FACTORS FOR *FLOODED LAND REMAINING FLOODED LAND*

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

Where

EF Emission Factor

CH_{4_diff} Diffusive emission of CH4 [mg-C m^{-2} d^{-1}]

$CH_{4\_bubbling}$ Ebullitive (bubble) emission of CH_4 [mg-C m^{-2} d^{-1}]

Application of Equations A4 and A5 to the reservoirs described in Table A1 were averaged according the aggregated climate zones defined in Table A2 to produce the final Emission Factor (EF) tables for *Flooded Land Remaining Flooded Land* (Table 7.10) and *Land Converted to Flooded Land* (Table 7.18). Emissions factors (EFs) are expressed in kg CH_4 ha^{-1} yr^{-1}.

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}) downstream of 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.* 2014a), (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 waterbody 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 (see A7.1.2 “Validation of the data-model approach”). 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) and these were 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	

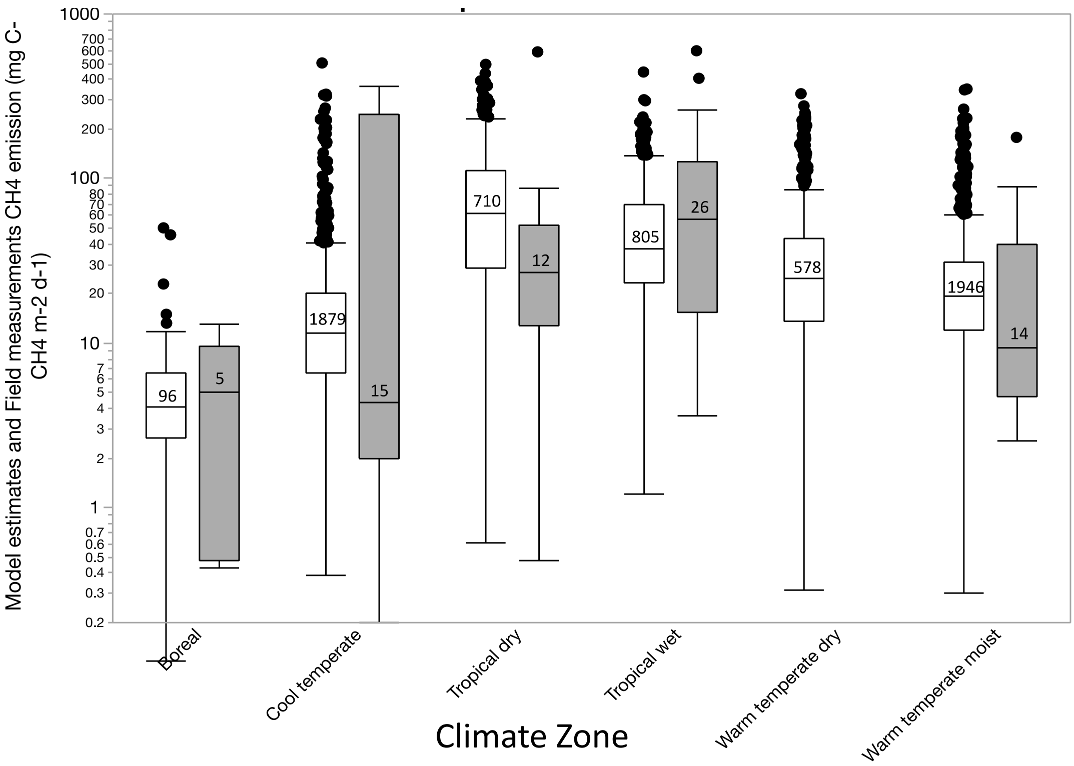
Validation of the data-model approach

Surface Emissions

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.

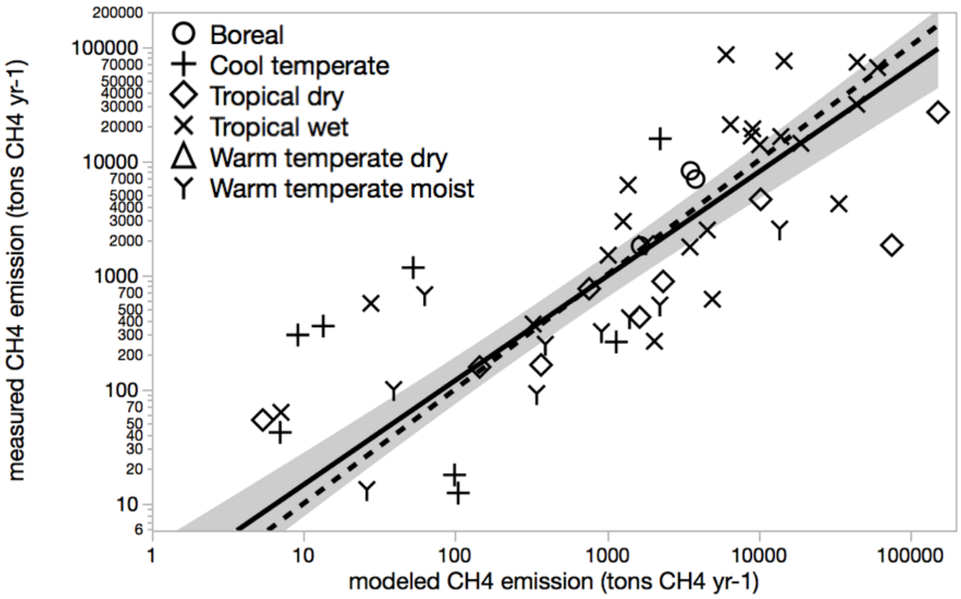
Field measurements are from (Deemer *et al.* 2016) while modelled estimates are derived from G-res model applied to about 6000 reservoirs worldwide. Exact correspondence between measured and modelled ranges is not expected given that the models were applied to a large number of reservoirs of different configurations. Numbers in box plots correspond to the number of observations in each climate zone.



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. Comparison of measure CH4 emissions with estimates based on the Emission Factors (EFs, Tables 7.10 and 7.18) of Tier 1 methodology.

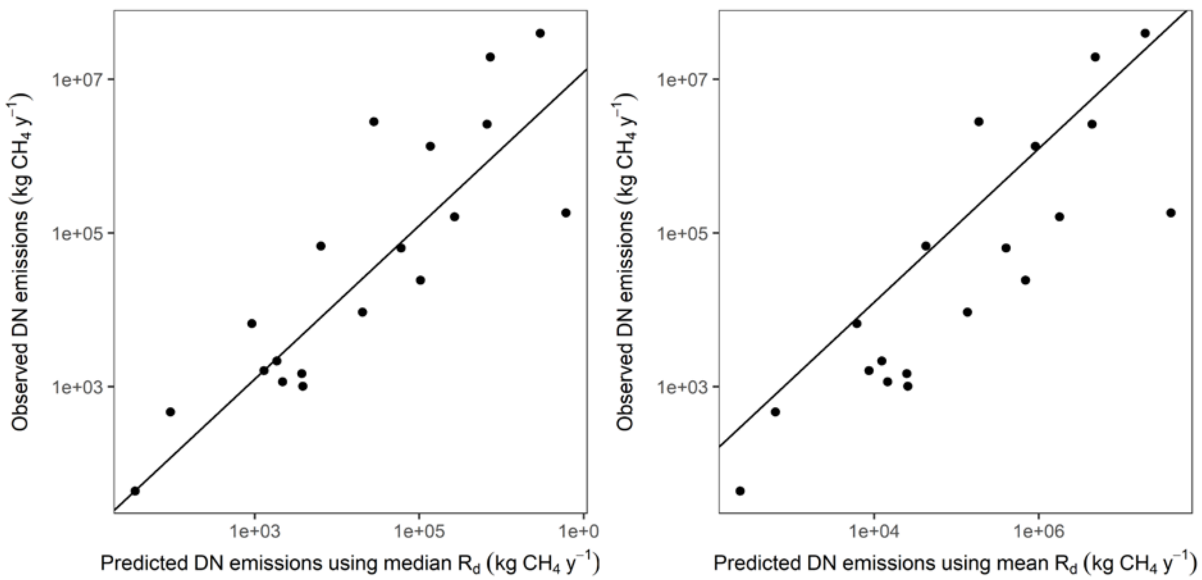
Solid line and shaded area correspond to least-squares regression line and 95% confidence interval respectively, while dashed line is 1:1 line. Estimates based on recommended EFs show no evidence of systematic bias. Different symbols represent the various aggregated climate zone (see Table A3).



Downstream Emissions

Downstream emissions estimated using the median of the literature Rd values (0.09), combined with model estimated surface emission rates, agree well with observed downstream emission rates (Figure A5). Downstream emissions estimated using the mean Rd literature value (0.60) systematically overestimate downstream emissions (Figure A5), lending additional support for the use of the median Rd value for estimating downstream emissions.

Figure A5. Measured downstream (DN) CH4 emissions compared to model estimates. The left and right panels model downstream emissions using the median and mean Rd values collected from the literature, respectively.



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.* 2017b). Meta-analyses of published emission studies (Barros *et al.* 2011), (Prairie *et al.* 2017b) suggest 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 *et al.* 2002). Over such a period, integration of the emissions above the modelled new equilibrium value at 100 years (upper panel of Figure A4) suggests 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.* 2017a).

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.

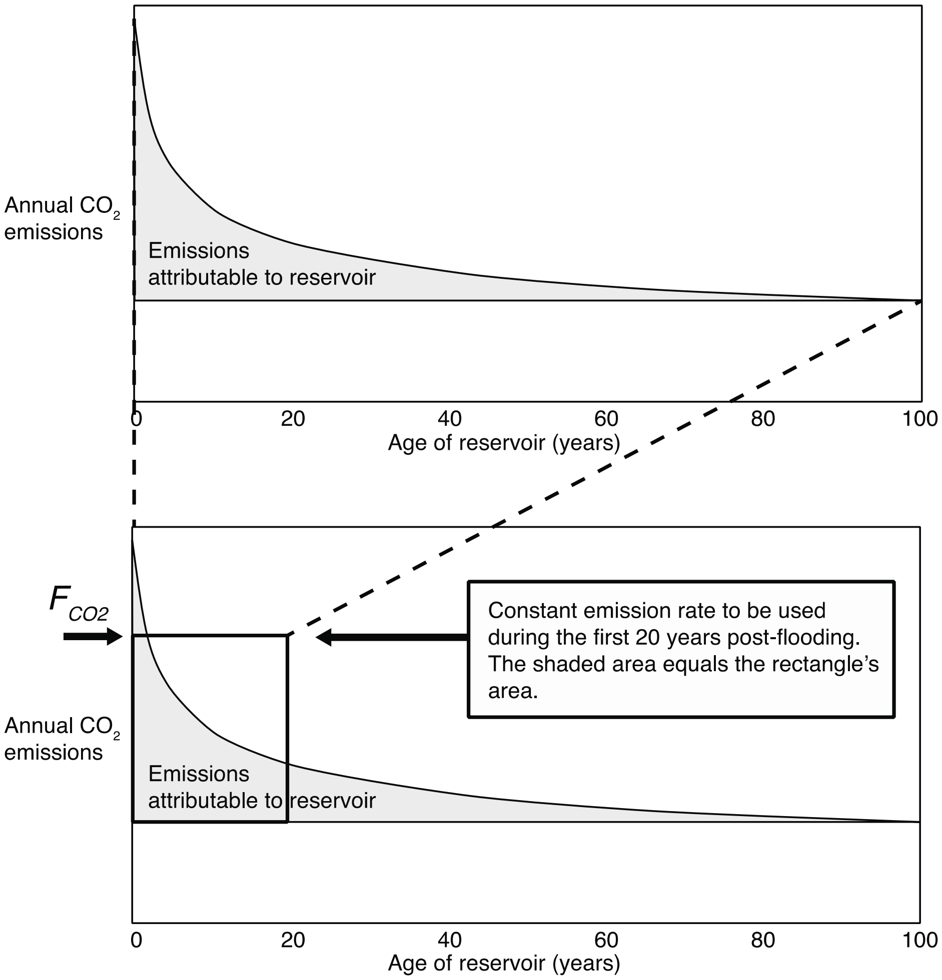
The easily decomposable organic matter fractions (litter, foliage, twigs, fine roots, organic soils) contribute to the post-flooding CO_2 pulse, while the more recalcitrant fractions (tree boles, mineral soils) are for the most part preserved. However, it is noteworthy that following flooding, the mineral 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 point 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, $CO_2 = C \cdot Age^{-b}$ 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. A6 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 7.21).

Figure A6. Relationship between CO_2 surge estimates from the newly flooded lands using the decay curve approach and the flooded soil organic carbon stock approach.



A7.1.2.4 DATA SOURCES

Data sources and range of emission values (mg C-CH_4 m^{-2} d^{-1}) for directly measured methane emissions are within Table A3. Data sources used to develop models (Equations A1, A2 and A3) are largely overlapping and are in Annex VI of (Prairie *et al.* 2017b) and were used in section 1.3 of Annex A1 to validate the Emission Factors provided in Tables 7.9 and 7.14.

Data sources (including systems assessed and citations) for estimating the multiplier (R_D, Table 7.10) which is the ratio of total CH_4 emissions (kg CH_4-C yr^{-1}) downstream of 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 yr^{-1}) are within Table A4.

TABLE A3
DATA SOURCES USED FOR MODELLING CH4 EMISSIONS FROM RESERVOIRS WITHIN DIFFERENT CLIMATE ZONES.

Grouped IPCC Climate Zone	Number of systems with CH_4 measurements in category	Range of reported emissions values (mg C-CH_4 m^{-2} d^{-1})	References
Polar moist, boreal dry and moist	6	0.4-13	(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 & Tremblay 2006), (Tadonléké *et al.* 2012), (Duchemin *et al.* 1995), (Huttunen *et al.* 2002), (Fedorov *et al.* 2015)
Cool temperate moist and dry*	16	0-360.7	(Harrison *et al.* 2017), (Matthews *et al.* 2005), (Hendzel *et al.* 2005), (Venkiteswaran Jason *et al.* 2013), (Kelly *et al.* 1997), (Deemer Bridget *et al.* 2011), (Maeck *et al.* 2013), (Huttunen *et al.* 2002), (Gruca-Rokosz *et al.* 2011), (Gruca-Rokosz *et al.* 2010), (Beaulieu *et al.* 2014a), (Beaulieu *et al.* 2014b)
Warm temperate moist	14	2.5-176.0	(Rosa *et al.* 2004), (dos Santos *et al.* 2006), (Harrison *et al.* 2017), (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	13	0.5-582.3	(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 2012), (Teodoru *et al.* 2015), (Almeida *et al.* 2016)
Tropical wet and moist	26	3.6-258.3	(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 & Stallard 1994), (Joyce & Jewell 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)

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.* 2014b), (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 & Sharma 2016)
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 & Demarty 2013), (Deshmukh *et al.* 2016), (Serça *et al.* 2016), (Guérin *et al.* 2006), (Kemenes *et al.* 2007)
*See references section for full citations.		

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

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

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

CH_4 emissions from small constructed waterbodies are primarily the result of new methanogenic production of CH_4 induced by anoxic conditions, which occurs when waterbodies have high organic matter loading and low oxygen status. These conditions often occur in small constructed waterbodies, such as slow-flowing ditches (Evans *et al.* 2016), agricultural ponds (Selvam *et al.* 2014) and aquaculture ponds (Robb *et al.* 2017), but may be lower where mixing or aeration occurs as part of aquaculture management (e.g. (Vasanth *et al.* 2016) and are sensitive to temperatures (Davidson Eric *et al.* 2011). Area-specific emissions from these constructed waterbodies may equal or exceed those observed in small lakes and reservoirs (Bastviken *et al.* 2010); see above). Furthermore, the CH_4 emissions from small constructed waterbodies are a direct consequence of the construction of the waterbody.

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