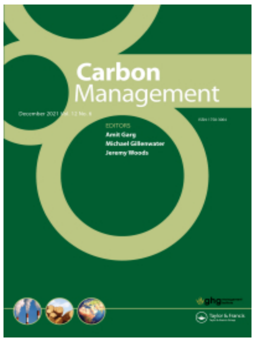

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CASE REPORT

An upscaling of methane emissions from Swedish flooded land

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ABSTRACT

The 2019 IPCC Refinement updated reporting guidelines for greenhouse gas (GHG) emissions (predominantly methane; CH_4) from "flooded land"; reservoirs, ponds, and drainage ditches/canals. These waterbodies are created by humans and thus their GHG emissions are considered anthropogenic. Here, we consider the implications of accounting for flooded land emissions in the Swedish national GHG inventory. We collate relevant Swedish GHG data for reservoirs, ponds and ditches, and combine these, and IPCC emission factors (EFs), with estimates of total waterbody surface area to upscale emissions. We find flooded lands emit a national total of 34,000 t CH_4 yr^{-1} using IPCC EFs, or 14,000 t CH_4 yr^{-1} when using EFs derived from Swedish data only, equivalent to 19% and 8% of national CH_4 emissions. Cumulatively, reservoirs cover the largest surface area (71% of total flooded land), followed by ditches (26%) and ponds (3%). However, using IPCC EFs, ditch emissions dominate the budget, emitting 28,700 t CH_4 yr^{-1} compared to ~1,700 t CH_4 yr^{-1} for ponds and 3,400 t CH_4 yr^{-1} for reservoirs. Our findings show that ditches may make outsized contributions to national emissions, and that default IPCC EFs may be inappropriately high for GHG accounting in Sweden, and presumably other northern nations.

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Introduction

Freshwaters emit globally large volumes of greenhouse gases (GHGs), particularly methane (CH_4), [1] and, when these emissions originate from human-constructed waterbodies, they should be accounted for in national GHG inventories. The Wetlands chapter of the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines included emissions from flooded land, defined as "water bodies where human activities have caused changes in the amount of surface area covered by water, typically through water level regulation." Specific examples given in these guidelines refer to reservoirs created for hydroelectricity production, irrigation, and navigation [2]. Due to a lack of data, CH_4 and nitrous oxide (N_2O) were excluded, and only emissions of carbon dioxide (CO_2) were included, and only for "land converted to flooded land," not "flooded land remaining flooded land." The Wetlands chapter of the 2019 IPCC Refinement significantly updated reporting guidelines for flooded land by including CH_4 as well as CO_2, and by extending the flooded land definition to "waterbodies where human activities have changed the hydrology of existing natural waterbodies" and "waterbodies that have been created by excavation" (i.e. ponds, ditches) [3]. These changes have implications for national GHG reporting, particularly for nations that have large numbers of reservoirs or extensive ditch networks. Here, we consider the 2019 Refinement guidelines for flooded land in Sweden, by doing the following:

1. Describe identified changes in the 2019 refinement that apply to Swedish flooded land.
2. Synthesize GHG emissions data from Swedish flooded land to generate national emission factors (EFs).
3. Assess the IPCC Refinement EFs for flooded land and assess their relevance for Swedish reporting.
4. Calculate national emissions based on 1–3.

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Identified changes to flooded land reporting

The relevant changes in the 2019 IPCC Refinement are found in the Wetlands chapter (chapter 7), specifically sections 7.3.1 ("flooded land remaining flooded land") and 7.3.2 ("land converted to flooded land"). Note that N_2O is excluded in order to avoid double-counting; it is assumed that N_2O emissions from flooded land are due to anthropogenic activity elsewhere in the catchment, and that these emissions are therefore captured in categories such as wastewater management and indirect emissions from managed soils. There are four relevant categories to consider.

Flooded land remaining flooded land: reservoirs

This category covers CH_4 emissions from reservoirs greater than twenty years old. Emissions of CO_2 are not included so as to avoid double-counting; these emissions are assumed to be due to carbon inputs from the catchment which are captured by other reporting categories such as forest land, cropland, and grassland according to the 2013 Wetlands Supplement [4]. The method for CH_4 allows estimation of diffusive and ebullitive emissions from the reservoir surface and downstream emissions (emissions originating from the reservoir but emitted downstream of the dam). The Tier 1 method uses reservoir surface emission factors EF that are disaggregated into six climate zones (greater emissions in warmer climate zones) with downstream emissions calculated as a fixed ratio to reservoir surface emissions. For Tier 2, the EF can be refined by adjusting to the trophic state of the reservoir. For Tier 3, direct measurements of diffusion and ebullition fluxes are required, or emissions can be modelled for individual reservoirs.

Flooded land remaining flooded land: other constructed waterbodies

This category includes freshwater and saline ponds, canals, and ditches in any land-use. However, note that CH_4 emissions from wastewater (which may include ponds) are covered elsewhere in the 2019 Refinement. Emissions from canals and ditches on organic soils may be covered under flooded lands reporting or under reporting of drained inland organic soils (in the 2013 Wetlands Supplement [4]) but should not be included in both. The Tier 1 approach uses a single EF for each waterbody category: saline ponds (salinity $>$ 18 ppt), freshwater and brackish ponds, canals and ditches. There is currently no disaggregation by climate zone, land use or nutrient status. A proposed Tier 2 approach could create and refine country-specific EFs using factors such as trophic state, soil type, flow rate, salinity, and presence of emergent vegetation. A proposed Tier 3 approach could go further for methods or models that include information on climate, catchment land uses and soils, and provide separate estimates of diffusive flux, ebullitive flux, and plant-mediated emissions for individual waterbodies. As for reservoirs greater than twenty years old, no CO_2 accounting takes place for ponds and canals in this category.

Land converted to flooded land: reservoirs

This category covers reservoirs under twenty years old. It is assumed that emissions from younger reservoirs are larger than those from older reservoirs, because formerly terrestrial organic matter rapidly decays upon flooding and causes the releases of GHGs. The Tier 1 method for CO_2 uses EFs that are disaggregated into six climate zones. The Tier 2 method refines the EF by adjusting for soil carbon stock (greater emissions from larger carbon stocks) and could also allow country-specific EFs to be developed according to climate sub-zones and nutrient status. A feasible Tier 3 method would use detailed data and/or models of soil carbon combined with time series of post-flooding CO_2 emissions (which will decline with time), from multiple reservoirs across a gradient of environmental conditions. Emissions of CH_4 from reservoirs under twenty years old are estimated using the same method as older reservoirs (see Flooded Land Remaining Flooded Land: Reservoirs section), with the single change that reservoir surface EFs are larger. As for CO_2, this is because larger emissions of CH_4 occur during the years immediately following inundation.

Land converted to flooded land: other constructed waterbodies

No specific guidance is given within the IPCC Refinement to account for GHG emissions from land converted to ponds, ditches or canals, apart from the notes that CO_2 emissions from ponds created by damming could be estimated as *Land converted to flooded land: reservoirs*, and CO_2 emissions from coastal wetlands converted to aquaculture could be estimated using the 2013 Wetlands Supplement. For CH_4, a lack of data means that the same EFs are used for flooded land remaining flooded land, and therefore no consideration is given in this paper to the age of other constructed waterbodies; i.e. all ponds, ditches and canals are grouped under the same EFs, regardless of age.

Relevant flooded land emissions data for Sweden

Emissions data were extracted from the scientific literature using a snowball approach, given our knowledge and familiarity of the Swedish situation (e.g. ML is an author on the national GHG inventory reports). We collated data that we were already aware of, as well as using Google Scholar and relevant search terms to find additional data. These emissions data are compared to the IPCC Refinement EFs to assess their applicability to Swedish reporting. Note that for ditch and pond emissions we follow the method that the IPCC Refinement used for ditch emissions: data are generally aggregated to study level, because studies often reported multiple measurements from the same ditch network or from sites in close proximity, therefore the total number of individual ditches and ponds used to derive the EF exceeds the number shown. Where EFs are disaggregated by climate zone, boreal and cool temperate EFs are presented. In line with the Swedish National Inventory Report [5] we split Sweden into two climate zones: "each county south of Värmland, Gävleborg, and Dalarna belongs to the temperate zone and the remaining counties belong to the boreal zone."

Flooded land remaining flooded land: reservoirs

The vast majority of Swedish hydropower reservoirs were completed before 1970. Somewhat surprisingly, very little CH_4 emissions data has been reported for Swedish reservoirs $>$ 20 years old. That which does exist is from hydropower on natural lakes in the south, where small dams (e.g. 50–100 m) have been built across river outflows. This is quite different from the northern boreal Swedish reservoirs that have been created either by flooding terrestrial land or by building very large dams (e.g. 1000 m +), and that make up the majority of Swedish "flooded land" reservoirs (see Flooded Land Remaining Flooded Land: Reservoirs section). When considering the small hydropower dams, in some cases these may not qualify as flooded land according to the IPCC: "lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed Flooded Land" [3]. Nevertheless, we briefly present the limited, southern CH_4 evidence base. [6] measured summer CH_4 fluxes from two dammed natural lakes during summer (note that whether these waterbodies technically count as flooded land is unclear due to a lack of contextual information; hydropower dams may not have raised water tables substantially, but may have altered residence times – or the damming may have made no difference). Using the weighting of the 2013 Wetlands Supplement with a growing season length of 190 days (see [4], expanded upon in [7]) gives annual emissions of 11.6 and 15.5 kg CH_4 $ha^{-1} yr^{-1}$. [8] also measured CH_4 emissions of $\sim$0.05 mmol m^{-2} d^{-1} from a small, created hydropower lake and a dammed natural lake, but only during springtime, making annual extrapolations impossible. Considering the limited data, and the unlikelihood that all of these waterbodies count as flooded land, emissions must therefore be calculated using the relevant default EFs (IPCC Refinement Table 7.9). This gives total CH_4 EFs (with 95% confidence intervals, CIs) of 14.8 (8 – 21.7) kg CH_4 $ha^{-1} yr^{-1}$ for boreal reservoirs and 58.9 (52.6 – 64.9) kg CH_4 $ha^{-1} yr^{-1}$ for cool temperate reservoirs.

Flooded land remaining flooded land: other constructed waterbodies

For the three waterbody types within this category, we assume that saline ponds are not relevant due to a low number/absence of this type of waterbody. For ditches and canals we extracted eleven CH_4 flux estimates (Table 1). These estimates were from 141 ditches on both organic and mineral soils, and flux measurements were made under flowing [9–12] and standing water conditions [9,13,14], and from dry ditches [9,13]. They captured the full range of drained land types, with approximately half from forest ditches (which represent $\sim$60% of the national ditch network [15]), and the remainder from urban, agricultural and peat extraction land covers. The dataset was biased towards the temperate ($n = 9$) zone, with few boreal studies ($n = 2$); this remains a knowledge gap but, if anything, a temperate bias would presumably result in a higher EF (because emissions decrease at higher latitudes). The mean from all ditches was 134 kg CH_4 $ha^{-2} yr^{-1}$, considerably lower than the default EF of 416 kg CH_4

Table 1. **Mean annual ditch CH_4 fluxes extracted from the literature, with climate zone, land use and soil type information for Swedish ditches. The mean EF for all ditches ± 95% CIs is shown, as is the IPCC Refinement EF.**

Climate zone	Land use	Soil	# ditches	Emission (kg CH_4 ha^{-2} yr^{-1})
Temperate	Settlement	Clay	2	45 [10]
Temperate	Forest	Sandy till	1	15.3 [10]
Temperate	Forest	Clay, sandy till	109	61 [11]
Temperate	Forest	Peat	8	10.0′ [10, 12]
Temperate	Forest	Peat	2	18.7 [13]
Temperate	Forest	Organic	2	127 [14]
Temperate	Cropland	Clay	2	146 [10]
Temperate	Cropland	Clay	4	45*
Temperate	Extraction	Peat	4	344 [16]
Boreal	Extraction	Peat	4	645 [16]
Boreal	Forest	Podzol	3	14.8 [17]

	EF (kg CH_4 ha^{-2} yr^{-1})	95% CIs (kg CH_4 ha^{-2} yr^{-1})
Swedish mean	134	23–244
IPCC EF	416	259–669

Note [13] and [14] are two papers that report data from the same site so are grouped. *Audet unpublished but reported in [11]. Refs [10,11,13,14]* made repeated measurements over an annual cycle (i.e. including non-growing season measurements). Refs [9,12,16,17] measured fluxes only during the growing season, and were upscaled to annual fluxes using the same approach as for the IPCC Wetlands Supplement [4,7] and IPCC Refinement [3] whereby fluxes were upscaled to the length of the growing season, and zero winter emissions were assumed which may lead to underestimates if ditches are not frozen (see [7]). Note that most studies measured diffusive fluxes and ignore ebullitive fluxes, but see [9,13] for some comparisons between flux pathways.

$ha^{-2} yr^{-1}$ (IPCC Refinement Table 7.12) and there was no overlap between the 95% confidence intervals (CIs) of the two EFs. It is also worth considering that the boreal/temperate EF for forest ditches on drained organic soils from the 2013 IPCC Wetlands Supplement is 217 (41–393) kg CH_4 $ha^{-2} yr^{-1}$, and the majority of ditches in Sweden drain forest land [15]. Thus, both the 2013 IPCC EFs for organic soils, and the new data collated here in Table 1, could suggest that the default EF in the IPCC Refinement may be inappropriately high for Sweden. In part, this could be because the IPCC Refinement EF is derived largely from ditches in agricultural land, which will have higher emissions than Swedish forestry ditches. However, the lack of overlap between CIs is also somewhat unsurprising given that the IPCC Refinement EF and associated CIs are derived from a mean of all global studies, without disaggregation into climate zones.

For freshwater ponds we extracted eight CH_4 flux estimates (Table 2). These estimates were from a total of 71 ponds on both organic and mineral soils, a range of land-uses and were all from the temperate zone. The dataset for ponds is therefore smaller and less-representative than the one for ditches. The mean from all ponds was 138 kg CH_4 $ha^{-2} yr^{-1}$, relatively similar to the IPCC EF of 183 kg CH_4 $ha^{-2} yr^{-1}$ and the 95% confidence intervals (CIs) of the two EFs overlap. This suggests that the IPCC EF may be suitable for Swedish ponds. However, no data are currently available from ponds in the Swedish boreal zone where emissions may be considerably lower.

Land converted to flooded land: reservoirs

Given the limited amount of reservoir construction in the twenty first century, it is not surprising that no CH_4 emissions data have been reported for Swedish reservoirs $<$ 20 years old. Emissions must therefore be calculated using the relevant default EFs from the IPCC Refinement (IPCC Refinement Table 7.15), adjusted to include downstream emissions (calculated as a set ratio of 0.09 to reservoir surface emissions). This gives total CH_4 EFs of 30.2 $(22.7 - 37.8)$ kg CH_4 $ha^{-1} yr^{-1}$ for boreal reservoirs and 92.3 $(85.9 - 98.8)$ kg CH_4 $ha^{-1} yr^{-1}$ for cool temperate reservoirs.

For CO_2, IPCC EFs are 0.94 $(0.84 - 1.05)$ t CO_2-C $ha^{-1} yr^{-1}$ for boreal reservoirs and 1.02 $(1.00 - 1.04)$ t CO_2-C $ha^{-1} yr^{-1}$ for cool temperate reservoirs (IPCC Refinement Table 7.13). We identified one relevant Swedish study [24] which reported CO_2 emissions from a 12-year-old oligotrophic hydropower reservoir in boreal Sweden. The reservoir flux was 0.6 t CO_2-C $ha^{-1} yr^{-1}$ which is low compared to the IPCC EF, and falls below the lower 95% CI of the mean. However, no robust conclusions can be drawn from a sample size of one, and it is entirely expected that some individual waterbodies will deviate from the globally-derived IPCC EFs Therefore, for reservoirs $<$ 20 years old the IPCC EFs should be used.

National emissions from flooded land

Flooded land remaining flooded land: reservoirs

The Swedish Agency for Marine and Water Management [25] state that dams and/or hydropower operations affect 4000 watercourses and 2000

Table 2. **Mean annual pond CH_4 fluxes extracted from the literature, with climate zone, land use and soil type information for Swedish ponds. The mean EF for all ponds ± 95% CIs is shown, as is the IPCC Refinement EF.**

Climate zone	Land use	Soil	# ponds	EF (kg CH_4 $ha^{-2}yr^{-1}$)
Temperate	Cropland	Mineral	3	347 [18]
Temperate	Urban	Clay	40	83.3 [19]
Temperate	Urban	Clay	6	137 [10]
Temperate	Urban	Mineral	1	257 [20]
Temperate	Forest	Peat	1	9.4 [10]
Temperate	Cropland	Clay	2	24 [10]
Temperate	Rewetting	Peat	1	166 [21]
Temperate	Cropland/grassland	Clay	17	81 [22]

	EF (kg CH_4 $ha^{-2}yr^{-1}$)	95% CIs (kg CH_4 $ha^{-2}yr^{-1}$)
Swedish mean	138	63–213
IPCC EF	183	118–228

Note [18] gives CH_4 concentrations only, which we converted to fluxes using piston velocities given in [19]. Refs [13,18,20] made repeated measurements over an annual cycle (i.e. including non-growing season measurements). Refs [21–23] measured fluxes only during the growing season, and were upscaled to annual fluxes using the same approach as for the Refinement [3] whereby fluxes were upscaled to the length of the growing season, and zero winter emissions were assumed. Note that most studies measured diffusive fluxes and ignore ebullitive fluxes, but see [13,22] for some comparisons between flux pathways.

lakes nationally. Cumulative emissions from these impoundments are therefore likely to be significant. However, a complete national upscaling of these emissions is non-trivial. Although the Swedish Meteorological and Hydrological Institute (SMHI) holds a lake register which contains waterbody surface areas, this does not disaggregate waterbodies into natural lakes and artificial ones (i.e. reservoirs). SMHI also holds a register of dams, but the associated data are incomplete and so waterbody surface area cannot be estimated using this register. The Global Reservoir and Dam Database (GRanD) [26] lists 49 reservoirs for Sweden, alongside surface areas and year of construction. However, this list includes large natural lakes such as Vänern (area 5,440 km^2) and Storsjön (464 km^2), presumably because these (and other lakes in GRanD) are regulated to some extent. The 2019 Refinement says that: “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.” Thus, the GRanD database is not suitable for a complete upscaling, even for the small subset of Swedish waterbodies it lists, because many of these waterbodies fall outside of the IPCC accounting remit. We therefore used the GRanD database to start a coarse and incomplete upscaling. Each individual waterbody in the database was checked using two approaches to assess which ones could be categorized as flooded land. After checking all waterbodies in the GRanD database, we performed further, untargeted searches to identify other large reservoirs. The approaches used to assess flooded land status were:

1. Comparing current and historic aerial imagery (using https://kartor.eniro.se/) to detect increases in waterbody area due to dam construction, or the presence of substantial unvegetated shorelines as indicators of significant anthropogenic fluctuations in water levels.
2. Literature searches (including scientific publications, grey literature, and popular websites) for information on dam construction, reservoir creation, changes to surface area, etc.

These approaches have limitations. Available historical aerial imagery dates from 1955–1967. Therefore, any waterbody appearing on modern aerial imagery but not historical aerial imagery *must* be anthropogenic flooded land. However, this method cannot be used to identify waterbodies that were created before 1955–1967. Categorizing flooded land is further complicated by the fact that the 2019 Refinement’s language is somewhat vague and says that to qualify as flooded land “substantial” changes to surface area and residence time must have occurred; this is suggested as increases $>$ 10% within the text for area and residence time (whilst an IPCC decision tree suggests surface area increases $\geq$10% or 0.25 ha qualify). Indeed, the 2019 Refinement acknowledges that “*reservoirs exist on a spectrum.*” Such vagueness is valuable in international guidelines, in that it allows for flexibility in interpretation depending on local conditions; e.g. some nations will have natural waterbodies (i.e. not flooded land) subject to huge seasonal variation in water level. As such, the presence of a dam cannot automatically be used to assign a waterbody as flooded land, because some smaller dams will only result in minor changes to waterbody area or retention time. Personal judgement is therefore necessary when categorizing waterbodies as flooded land, and there is some degree of uncertainty in whether all the listed waterbodies truly qualify as flooded land. Finally, these approaches preferentially target large waterbodies. Small reservoirs (see Flooded Land Remaining Flooded Land: Reservoirs section), which may occupy cumulatively large surface areas, will mostly be excluded. These small reservoirs will have altered residence times and surface areas but water level fluctuations, and thus unvegetated shorelines, may not feature. Other approaches will be required in future to map these waterbodies and their cumulative emissions may be large; e.g. global syntheses show that, on an areal basis, CH_4 emissions from lakes $< 0.001\,km^2$ are $\sim$3 times larger than emissions from lakes $> 1\,km^2$ [1].

Using the above methods, a list of thirty-five large ($> 8\,km^2$) reservoirs was produced, occupying a total area of 1,880 km^2 (Supplementary Table 1). The majority of waterbodies are in the boreal zone with just one in the temperate zone, and all are $>$ 20 years old. Upscaling using the proposed EFs from Flooded Land Remaining Flooded Land: Reservoirs section results in an emission of 3,368 (2,093–4,649) t CH_4 yr^{-1}.

Flooded land remaining flooded land: other constructed waterbodies

To upscale national ditch emissions, an estimate of total ditch area is required which can feasibly be estimated from ditch length and width. A first estimate of the total length of all ditches ($<$ 6 m wide), calculated using National Inventories of Landscapes in Sweden (NILS) data, was given as 890,000km [27], and later updated to 983,000 km [28]. An estimate using a high-resolution digital elevation model and an assumption that a catchment area of 2 ha is needed for stream initiation, gave the total length of all watercourses $<$ 6 m wide as 2,639,163 km [15]. According to the NILS data 63% of channels are ditches [15], resulting in a total ditch length of 1,660,000 km. Using digital elevation data only (i.e. no hydrological assumptions) and a deep neural network approach [29], gives 1,200,000 km of watercourses $<$ 6 m wide [30]. Using the NILS figure of 63% for the proportion of ditches to total watercourses therefore gives a ditch length of 756,000 km. This new estimate has a Matthews Correlation Coefficient of 0.72 (whereby 1 = perfect agreement with field data), whereas the map from [15] has a value of 0.46. For upscaling, we therefore use the more accurate mapped length of 756,000 km.

For ditch width, an average value must be assumed. Historically, medieval law decreed that agricultural ditches should be 1.2–2.1 m wide, and in the 1700s the law decreed that main agricultural ditches should be 1.2–1.5 m wide, and cross-ditches 0.9 m [31]. Mean ditch widths for Sweden have been reported from various areas as 1.3 m (forest ditches on mineral soils, Uppsala County [9]), "larger than 0.5 m" (forest ditches, Krycklan catchment, Västerbotten County [32]), 0.8 m (upland mire, Örebro County [33]) 0.5 m (harvested peatlands [17]), and 0.2 m (guideline for roadside ditches [34]). NILS data shows that, for ditches $<$ 6 m wide, 56% are 0.1–1 m wide, 13% are 1.1–2 m wide, 5% are 2.1–6 m wide, and no width is recorded for 26% of ditches [28]. However, wider ditches, not included in the NILS data, also exist in the landscape, with diameters up to 25 m in some cases [35]. Because no data exists on the distribution of these large ditches, we excluded them from our upscaling, but note that they could nevertheless have important cumulative effects on total areas and therefore emissions.

For upscaling, we first took the middle values from the three NILS width classes (0.5, 1.5, 4 m). We then took the associated proportions of the total ditch network for the three width classes (56, 13, 5%) and converted these to represent the total network; i.e. we assumed that the 26% of ditches where no width was recorded were distributed the same way. Thus, 76% of ditches (= 572,108 km) were assumed to be 0.5 m wide, 18% (= 132,811 km) were 1.5 m, and 7% (= 51,081 km) were 4 m. When these lengths are multiplied by their respective width classes, the total ditch network occupies an area of 68,959 ha. Using the 2019 IPCC EF (Table 1) gives a national emission of 28,687 (17,861 – 46,134) t CH_4 yr^{-1}. Using the considerably lower mean emission for Swedish ditches (Table 1) results in an emission of 9,227 (1,617 – 16,837) t CH_4 yr^{-1}. Note that these estimates include ditches on both organic/peatland and mineral soils. Double-counting of emissions will occur if emissions from drained peatlands are also accounted for, using the methodology of the 2013 IPCC Wetlands Supplement. Currently, emissions from ditches on peat soils are reported in the Swedish GHG inventory for forest, cropland, grassland and peat extraction land, with total emissions of 12,156 t CH_4 yr^{-1} [36]. The Wetlands Supplement method assumes a fraction of the total drained peatland area is ditch surface area ("$Frac_{ditch}$"; 5% for grassland and cropland, and

2.5% for forests). For Sweden, the total peatland ditch area corresponds to 88,074 ha [36], which is higher than our total (peat + mineral soil) ditch area of 68,959 ha, indicating that the $Frac_{ditch}$ method may be considerably overestimating ditch surface area.

A national upscaling of CH_4 emissions from freshwater ponds is not straightforward. These waterbodies are small, and missed by conventional mapping, and so accurate inventories of their number and areal size are lacking. It has been previously estimated that urban ponds occupy a total area of 17 km^2 [21]. Upscaling to this area results in a total urban pond emission of 311 t CH_4 yr^{-1} using the 2019 IPCC EF, or a slightly lower value of 235 t CH_4 yr^{-1} if using the Swedish mean EF from Table 2 (Table 3).

There are large numbers of ponds, occupying cumulatively large areas, in agricultural areas. However, here there arises a possible issue of double counting. These small, constructed ecosystems may be interchangeably called "ponds" or "wetlands." Partly this arises from the difficulty in defining ponds; see [37] who collate varied and sometimes contradictory pond definitions and state that "it is difficult (if not impossible) to define a pond." Some definitions suggest that ponds can be separated from wetlands according to the percentage of emergent vegetation, though we make no such distinction here. Finally, these waterbodies may be defined as ponds *and* wetlands; for example the Ramsar Convention notes that "it is also worth emphasizing that lakes and rivers are understood to be covered by the Ramsar definition of wetlands in their entirety, regardless of their depth" [38]. Although constructed wetlands are included in the 2013 IPCC Wetlands Supplement (as created inland wetlands on mineral soils), they are not currently included in Swedish accounting. Regardless of definitions, some effort can be made towards accounting for emissions from these ecosystems. SMHI's Anlagda Våtmarker database (https://vattenwebb.smhi.se/wetlands/) contains information from Jordbruksverket (Swedish Board of Agriculture) and the county administrative boards on constructed wetlands, yet does not cover all constructed wetlands in Sweden. These wetlands and waterbodies have an array of morphologies, depending on their purpose (primarily biodiversity provision and nutrient removal), but may feature large expanses of open water. There are 3,551 wetlands in the database occupying a total area of 10,920 ha, with a mean area of 3.1 ha ($n = 3{,}536$) and a mean water depth of 0.57 m ($n = 285$). Another assessment suggests 12,000–15,000 ha of wetlands have been constructed since 1990 [39]. However, the reported area is, in the majority of cases, construction area, that includes shores, embankments and all affected land, as well as water surface area. Data from 233 constructed Swedish wetlands/waterbodies shows that water surface can occupy 33–71% of construction area, with a mean of 55% [40]. Here, we use 12,000 ha and 15,000 ha as the lower and upper construction area bounds for upscaling, but weight these by 55% to calculate surface area bounds as 6,600–8,250 ha. For completeness and comparison, we use EFs from the 2019 IPCC Refinement, the Swedish mean EF from Table 2, and the temperate EF (235 ± 108 kg CH_4 $ha^{-2}yr^{-1}$) for created inland wetlands on mineral soils from the 2013 IPCC Wetlands Supplement [4]. Note that SMHI's Anlagda Våtmarker database shows the overwhelming majority of constructed wetlands are in southern and central Sweden, with ~20 wetlands north of Gävle, so for simplicity no disaggregation of boreal vs. temperate is made. The overall mean emission from all ponds/wetlands is calculated as 1,376 t CH_4 yr^{-1} (Table 3). Summing this with the mean of the two urban pond emission estimates gives a national pond emission of 1,649 t CH_4 yr^{-1}. Note that this estimate only includes urban and agricultural ponds; it is feasible that ponds in other ecosystems (e.g. sedimentation ponds in forestry on drained peatlands [41]) could occupy cumulatively significant areas and therefore contribute to emissions.

Table 3. National emissions from agricultural and urban ponds, calculated using three sets of EFs: those from 2019 IPCC Refinement, those from 2013 IPCC Wetlands Supplement (for created inland wetlands on mineral soils), and the Swedish mean EF from Table 2.

Waterbody type	EF origin	EF (kg CH_4 $ha^{-2}yr^{-1}$)	Emission (t CH_4 yr^{-1})
Urban Ponds	Swedish mean, ponds	138 (63–213)	235 (107–362)
Urban Ponds	2019 IPCC Refinement, ponds	183 (118–228)	311 (201–388)
Constructed agricultural ponds/wetlands	Swedish mean, ponds	138 (63–213)	1,025 (416–1,757)
Constructed agricultural ponds/wetlands	2019 IPCC Refinement, ponds	183 (118–228)	1,359 (779–1,881)
Constructed agricultural ponds/wetlands	2013 Wetlands Supplement, temperate IWMS	235 (127–343)	1,745 (838–2,830)

Note: here urban ponds occupy a total area of 1,700 ha [19] and agricultural ponds/wetlands occupy 6,600–8,250 ha (see main text).

Land converted to flooded land: reservoirs

All reservoirs identified as flooded land using the methodology of Flooded Land Remaining Flooded Land: Reservoirs section were older than 20 years. As there appears to be no inventory of reservoirs $<$ 20 years old, no accounting can take place under this category. However, the main phase of hydropower development took place many decades ago, and therefore the contribution to national emissions under this category can be considered negligible.

Summary and implications

In total, our estimate of national flooded land extent is 266,000 ha, although this is an incomplete and uncertain assessment. Incomplete, due to a lack of reservoir and pond inventories, and uncertain, due to an absence of detailed maps of ditch widths and water surface areas of ponds. Large reservoirs comprise 71% of this total area but, because their IPCC EFs are relatively low, they contribute only 10% of total flooded land emissions (total $=$ 34,000 t CH_4 yr^{-1}) (Table 4). Ponds occupy 3% of flooded land area and contribute 5% of all flooded land emissions. Ditches occupy cumulatively large areas (26% of all flooded land) and emit 85% of flooded land emissions, because the 2019 IPCC Refinement EF for ditches is high: 416 kg CH_4 $ha^{-2}yr^{-1}$, compared to 183 kg CH_4 $ha^{-2}yr^{-1}$ for ponds, and 14.8 kg CH_4 $ha^{-2}yr^{-1}$ (boreal) or 58.9 kg CH_4 $ha^{-2}yr^{-1}$ (temperate) for reservoirs $>$ 20 years old. However, using measurements of CH_4 emissions solely from Swedish ditches produces an EF that is just 32% of the IPCC EF, and total emissions from flooded land decrease accordingly by more than 50%. Including LULUCF, national CH_4 emissions from all sources are 177,000 t CH_4 yr^{-1} [36]. Emissions from flooded land are therefore equivalent to 19% of this figure using IPCC EFs, or 8% when using EFs generated from national CH_4 measurements only.

Other research has pointed to the potential importance of ditches in national GHG budgets. For instance, an assessment of traditional Spanish irrigation showed that ditch CH_4 made a substantial contribution to total budgets [42], whilst in the Netherlands ditches contribute ~10% of national CH4 emissions [43]. Some nations have also submitted National Inventory Reports that include flooded land accounting, allowing comparisons to be made. For the USA, reservoirs emit 1033 kt CH_4 yr^{-1}, compared to 509 and 90 kt CH_4 yr^{-1} for ponds and ditches respectively. This dominance by reservoirs is due to large cumulative reservoir surface areas in tropical states where EFs are high [44]. In Australia (who do not report ditch emissions), reservoirs again dominate the total flooded land budget compared to ponds, with respective emissions of 46 and 29 kt CH_4 yr^{-1}, despite reservoirs occupying only slightly more surface area (352,000 vs 313,000 ha) [45].

Table 4. National CH4 emissions from Swedish flooded land, calculated using EFs from both the 2019 IPCC Refinement and the national means generated in this paper. Note that no emissions of CH_4 or CO_2 are reported for reservoirs $<$ 20 years old due to a lack of data on the cumulative area of this waterbody category.

		Emission (t CH_4 yr^{-1})	
Waterbody type	Area (ha)	IPCC 2019 Refinement EF	Swedish EF
Reservoirs $>$ 20 years old	187,930	3,368	3,368*
Ditches	68,959	28,687	9,227
Ponds	9,125	1,670	1,259
Total	266,014	33,725	13,854

**Note:* there is no data from Swedish reservoirs $>$ 20 years old, so the IPCC 2019 Refinement EF is used instead.

Our findings highlight some clear knowledge gaps. Firstly, there are apparently no CH_4 measurements from any large, northern Swedish reservoirs, of any age. Measurements from reservoirs should therefore be a priority to determine whether the IPCC EFs are appropriate for national accounting. In tandem with this, a detailed inventory of reservoirs, along with their ages and surface areas is needed, because the upscaling here only includes the largest reservoirs. A cumulatively large surface area from small- and medium-sized reservoirs could lead to a significant increase in total emissions. A second knowledge gap is the absence of detailed maps of constructed pond/wetland surface area in agricultural landscapes. Furthermore, more emission measurements from these ponds are needed, including measurements of plant-mediated fluxes, as many studies focus on open water fluxes. Ditch emissions are relatively well measured but, as for ponds, there is a lack of data from boreal forests where ditch networks are extensive. Although the national ditch network is now well-mapped, detailed information on ditch width would help to improve the confidence behind the estimate of total ditch surface area. Additionally, total ditch emissions may be lower than our estimate, as many Swedish ditches dry out during summer [9] or never carry flow [46]. Dry ditches continue to emit CO_2, but CH_4 fluxes become close to zero, or even negative [9]. Additionally, Finnish research has shown that ditch CH_4 emissions can be significantly reduced if forest ditches become colonised by *Sphagnum* and

Polytrichum mosses [47]. Considering this, maps of ditch networks combined with wide-scale information flow/water level and ditch vegetation would significantly improve upscaling accuracy.

Finally, we note recent discussions highlighting the potential magnitude of GHG emissions from Swedish lakes, rivers and natural wetlands, and how these emissions could offset, to some extent, net removals in the Land Use, Land-Use Change and Forestry sector [48]. Whilst these natural waterbodies do contribute to GHG budgets they are currently not part of national inventory reporting or national climate targets, as they are either assumed to be captured within the carbon stock change for other land categories or not considered as anthropogenic emissions. However, considering that emissions from natural freshwaters will likely increase due to anthropogenic activity (e.g. eutrophication [49]), future IPCC EFs could aim to account for the anthropogenic component of these emissions to further refine inventories.

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Authors' contributions

MP wrote the first draft of the paper. MNF, WL, ML and PG refined this into the final version by contributing ideas, comments, text and additional data. All authors read and approved the final manuscript.

Disclosure statement

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Data availability statement

All data to recreate the analyses is contained within the main text and supplementary materials.

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