



Progress in the studies on the greenhouse gas emissions from reservoirs



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ABSTRACT

The green credentials of hydroelectricity in terms of greenhouse-gas (GHG) emissions have been tarnished with the finding of the researches on GHG emissions from hydroelectric reservoirs in the last two decades. Substantial amounts of GHGs release from the tropical reservoirs, especially methane (CH₄) from Brazil's Amazonian areas. CH₄ contributes strongly to climate change because it has a global warming potential (GWP) 24 times higher than carbon dioxide (CO₂) on a per molecule basis over a 100-year time horizon. GHGs may emit from reservoirs through four different pathways to the atmosphere: (1) diffusive flux at the reservoir surface, (2) gas bubble flux in the shallow zones of a reservoir, (3) water degassing flux at the outlet of the powerhouse downstream of turbines and spillways, and (4) flux across the air–water interface in the rivers downstream of the dams. This paper reviewed the productions and emissions of CH₄, CO₂, and N₂O in reservoirs, and the environmental variables influencing CH₄ and CO₂ emissions were also summarized. Moreover, the paper combined with the progress of GHG emissions from Three Gorges Reservoir and proposed three crucial problems to be resolved on GHG emissions from reservoirs at present, which would be benefit to estimate the total GHG emissions from Three Gorges Reservoir accurately.

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1. Introduction

Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are the three principal greenhouse gases (GHGs) in the atmosphere, and continuously increases in atmospheric concentrations of three GHGs are closely related to global climate change [1]. The studies on the GHG emissions from reservoirs in the last two decades indicated that hydroelectricity was not a green and clean energy as expected that no GHG is emitted from the reservoir surface [2–4]. In fact, reservoirs are also an important GHG source in the terrestrial ecosystems [5,6]. According to the natural belts that reservoirs located, the global reservoirs could be divided into tropical reservoirs (e.g., reservoirs in Brazil, French Guiana, and Laos) and temperate reservoirs (e.g., reservoirs in Canada, Switzerland, and China). The global warming potential (GWP) of the GHG emissions from Brazil's reservoirs are amazing, which are even higher than that from thermal power plants with similar installed capacity [2]. For example, Curuá-Una Reservoir in Brazil emitted 3.6 times more GHGs than those would have been emitted by generating the same amount of electricity from oil [7]. However,

GHG emissions from Canadian reservoirs are relatively low [8], which are lower than the GHG emissions compared with GHGs emitted by fossil-fuelled electricity generation. Therefore, it cannot be generalized to determine whether the development of hydroelectricity could reduce GHG emissions, which should depend on the specific situation of reservoirs. The geographic locations of reservoirs have an impact on the organic matter storage and water temperature, and influence on CO₂ and CH₄ emissions subsequently [6]. However, CH₄ emission fluxes from Lake Wohlen, a temperate reservoir in Switzerland, are even higher than those from tropical reservoirs [9], which cause the controversy on the development of hydroelectricity in the middle Europe region [3]. Beside latitudes, CO₂ emissions from reservoirs are also influenced by reservoir ages [6], wind speeds [10], pH values [11], precipitation [12], chlorophyll-a concentrations [12,13], and dissolved organic carbon in the water body [12,14], while CH₄ emissions from reservoirs are influenced by water depths [15], water level fluctuations [16], DO concentrations [17], water velocities [16], and wind speeds [10].

GHG emissions from reservoirs are different from the natural water bodies, such as lakes and rivers, because the impoundment of the reservoir has resulted in flooding of large areas of terrestrial and natural aquatic ecosystems. CO₂ and CH₄ are the major end

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products of the microbial decomposition of flooded organic matter [17], which are transported to the atmosphere from the reservoir surface by diffusion or bubbles. Turbines and spillways are unique to the dams, and turbines are used to generate electricity by transforming potential energy of the storage water into electric energy by the rotation of vane wheel; spillways are the drainage channels to control the floods in the reservoirs. When the deep water passes through the turbines and spillways, the dissolved gas (especially CH₄) in the hypolimnion before the dams would release into the atmosphere, becoming a huge CH₄ source, because of the abrupt change in temperature and pressure, which is called “degassing” [18]. Besides, downstream fluxes are often higher than upstream ones because of the strong disturbance to the water passing through the dams [19]; thus, the downstream emission fluxes should be paid attention. In conclusion, there are 4 pathways for GHG emissions from reservoirs, i.e., diffusive emission, ebullitive emission, degassing emission at turbines and spillways, and downstream emission [20].

The CO₂ emission from reservoirs is the largest, the second is CH₄ emission, and N₂O emission is the smallest. However, the GWP of the three gases is different. CH₄ has a GWP 24 times higher than carbon dioxide (CO₂) on a per molecule basis over a 100-year time horizon [3], and nitrous oxide (N₂O) has a GWP 298 times that of CO₂ [21]. Based on the studies on GHG emissions from reservoirs available, this paper reviewed the 3 GHG emissions from the tropical and temperate reservoirs through diffusion, ebullition, degassing, and downstream river. In addition, the environmental variables influencing GHG emissions were also summarized.

2. CO₂ emissions from reservoirs

2.1. CO₂ production in reservoirs

In a broad sense, CO₂ production in a reservoir includes the carbon footprint of emissions from the use of fossil fuel, steel, and cement during the construction phase of a dam [21], which is related to the size of dam and the duration of creation. The Three Gorges Dam (TGD) is a good example, with a length of 3035 m and a height of 185 m, which lasted for 18 years to construct (1992–2009). Although there is no study on CO₂ emission during the construction phase of the TGD, CO₂ emission during the process cannot be ignored. Besides, CO₂ production in a reservoir also includes the CO₂ emission when the dam operated normally, e.g., CO₂ emission from the fossil fuel combustion by shipping,

and CO₂ emission from the turbines. Navigation and electricity generation are two important functions of the Three Gorges Reservoir (TGR), but CO₂ emission has not been quantified during the two processes by far.

CO₂ discussed in the paper is produced from the decomposition of the flooded organic matter under the aerobic or anaerobic conditions after the impoundment. Carbon sources in the reservoirs included the flooded organic matter in the original forests, soils, vegetations, allochthonous input from terrestrial ecosystems or the upstream rivers nearby, and photosynthetic fixation by phytoplankton at the reservoir's surface or vegetations in the drawdown areas [21–23]. The flooded organic matter would decompose into CO₂ and CH₄ by methanogens under the anaerobic conditions at the reservoir bottom [23,24]. In fact, CO₂ could also be produced at the aerobic conditions, e.g., the decomposition of dead trees left above the water surfaces [24].

2.2. CO₂ transport in reservoirs

CO₂ emission fluxes in the reservoirs mainly include the two ways, i.e., diffusion and ebullition [24]. Diffusion is the dominate way for CO₂ emission from reservoirs [25], while bubbles have little contribution to CO₂ emission from reservoir's surface, because the solubility of CO₂ is large, i.e., 1 L water could dissolve 1 L CO₂ at the conditions of 1 atm and 25 °C; thus, CO₂ is easily absorbed by water during the transport from the reservoir's bottom. For example, bubbles contributed less than 1% of CO₂ emission from diffusion during the first years after the impoundment for Petit Saut Reservoir, French Guiana [23]; the CO₂ diffusive emission from Brazil's Balbina Reservoir is 2450 Gg C a⁻¹, while the CO₂ ebullitive emission is only about 0.02 Gg C a⁻¹ [26]. According to Table 1, bubbles are not the important way to transport CO₂ in tropical reservoirs, and only the CO₂ diffusive fluxes are studied in temperate reservoirs (Table 2), probably because the frequency of bubbles and CO₂ concentrations in bubbles are low and even could be ignored in temperate reservoirs.

2.3. Influences of turbines and spillways on CO₂ emission

The intakes of turbines and spillways often locate in the dozens of meters depth below the water surface, where have remarkable higher pressure than the atmospheric pressure. The dissolved CO₂ in the hypolimnion would be released into the atmosphere when the water passes through the turbines and spillways because

Table 1
CH₄ and CO₂ emissions from the tropical reservoirs.

| Location | Reservoir name | Age (a) | Diffusive flux (mg m ⁻² d ⁻¹) | | Bubbling flux (mg m ⁻² d ⁻¹) | | Degassing (Tg C y ⁻¹) | | Downstream river (mg m ⁻² d ⁻¹) | | Reference |
|---------------|----------------|---------|--|-----------------|---|-----------------|-----------------------------------|-----------------|--|-----------------|------------|
| | | | CO ₂ | CH ₄ | CO ₂ | CH ₄ | CO ₂ | CH ₄ | CO ₂ | CH ₄ | |
| French Guiana | Petit Saut | 1–10 | –440 to 16280 | 10–3200 | Ignore | 11.2–800 | 5–30 | 5–40 | 41,800 | 1440 | [23] |
| Panama | Gatun Lake | 84 | | 10.7 | | 526.3 | | | | | [27] |
| Brazil | Miranda | | 4389 | 130.35 | 0.25 | 23.85 | | | | | [28] |
| | Três Marias | | 1117 | 31.85 | 3.76 | 164.5 | | | | | [28] |
| | Barra Bonita | | 3986 | 16.95 | 0.13 | 3.95 | | | | | [28] |
| | Segredo | | 2695 | 7 | 0.07 | 1.8 | | | | | [28] |
| | Xingó | | 6138 | 29.3 | 0.05 | 10.75 | | | | | [28] |
| | Samuel | 4–5 | 7448 | 87.55 | 0.5 | 16.5 | 0.052–0.076 | 65,700 | 192 | | [19,24,28] |
| | Tucuruí | 8–9 | 8475 | 101.55 | 0.1 to 0.2 | 7.85 | 1.67 | | | | [25,28,29] |
| | Itaipu | 8 | 171 | 10.15 | | 0.55 | 0.31 | | | | [28,29] |
| | Serra da Mesa | | 2645 | 24.6 | 1.7 | 88.65 | 0.21 | | | | [28,29] |
| | Balbina | 18 | 13,845 | 193 | 0 | 13 | 0.081 | 0.065 | 18,000 | 28.4 | [26,30] |
| | Curuá-Una | 13 | | 36 | 77 | 0.022 | | | | [7] | |
| Laos | Nam Ngum | 28 | –38.9 to –5.0 | 0.07–0.4 | | | 0 | | | | [31] |
| | Nam Leuk | 10 | –19.4 to 70.0 | 0.5–7.9 | | | 7 × 10 ⁻⁵ | | | | [31] |
| | Nam Theun 2 | 1 | 22.1 | 19.2 | | 40 | | | | | [32] |

Table 2
CH₄ and CO₂ emissions from the temperate reservoirs.

| Location | Reservoir name | Age (a) | Diffusive flux (mg m ⁻² d ⁻¹) | | Bubbling flux (mg m ⁻² d ⁻¹) | References |
|------------------|--|---------|--|-----------------|---|------------|
| | | | CO ₂ | CH ₄ | CH ₄ | |
| Québec, Canada | Laforge-1 | 1–2 | 2300 | 8 | 57 | [37] |
| | La Grande-2 | 28 | 661 | 0.14 | | [8] |
| | Eastmain-1 | 3 | 2426 | 0.77 | | [8] |
| | Rivière-des-Prairies | 77 | 665 | 0.49 | | [8] |
| | Robertson | 5–7 | 1131 | | | [41] |
| | Sainte-Marguerite | 2–4 | 4399 | | | [41] |
| | Old Québec reservoirs | >10 | 1500–1600 | 8.8 | | [38,41] |
| Manitoba, Canada | Grand Rapids | | 624 | 0.58 | | [8] |
| | Jenpeg | | 316 | 1.11 | | [8] |
| | Kettle | | 514 | –0.01 | | [8] |
| | MaArthur | | 367 | 0.04 | | [8] |
| | 6 old reservoirs | >10 | 3350 | | | [41] |
| | | | | | | |
| Southeast Poland | Solina | 41 | –914–648 | 0 | | [42] |
| | Rzeszów | 36 | 2042–7150 | 736–3850 | | [42] |
| | Wilcza Wola | 21 | 3893–4161 | 32–451 | | [42] |
| Finland | Lokka | 27 | 1070 | 22.9 | | [43] |
| | Porttipahta | 25 | 1754 | 3.5 | | [43] |
| Switzerland | Lake Wohlen | 90 | 962 | 15 | 480 | [9,44] |
| | Lake Gruyere | 59 | 979 | 0.15 | | [44] |
| | Lake Lungern | 86 | 242 | 0.13 | | [44] |
| | Lake Sihl | 70 | 1100 | 0.21 | | [44] |
| | Lake Luzzone | 43 | 1414 | 0.13 | | [44] |
| West America | F.D. Roosevelt | 59 | –462 | 3.2 | | [11] |
| | Dworshak | 28 | –1195 | 4.4 | | [11] |
| | Wallula | 47 | –349 | 9 | | [11] |
| | Shasta | 57 | 1247 | 9.5 | | [11] |
| | Oroville | 33 | 1026 | 4.2 | | [11] |
| | New Melones | 22 | –1186 | 7.1 | | [11] |
| | 46 reservoirs in Utah, Arizona, New Mexico | >10 | 664 | | | [39] |
| China | Three Gorges Reservoir | 7 | 3919 | 6.2 | | [4,34] |
| | Xiangxi River | 7 | 1836 | 5.88 | | [13] |
| | Pengxi River | 7 | 3542 | 23.5 | | [45] |
| | Shuibuya | 4 | 3740 | 1.2 | | [46] |
| | Ertan | 10 | | 2.8 | | [15] |
| | Hongfeng | 49 | 240 | | | [47] |
| | Baihua | 47 | 384 | | | [47] |
| | Hongyan | 36 | 368 | | | [47] |
| | Xiuwen | 47 | 752 | | | [47] |

of the abrupt decrease in pressure and the increase in water temperature [18]. Compared with the CO₂ diffusive emission from the reservoir surface, the CO₂ degassing fluxes at the turbines and spillways have relatively small contribution to the total CO₂ emission of a reservoir. Based on the literatures available [23,26,31,33], CO₂ degassing at the turbines and spillways contribute 0–16% to the total emission. Specifically, CO₂ degassing emissions from the turbines and spillways of Petit Saut Dam account for 7–16% of the total CO₂ emissions during 1994 to 2003 [23], which is called “degassing proportion” hereafter. The degassing proportion for CO₂ emission is about 1.67% at the Balbina Dam [26], 0.4–5% at the La Grande-2 Dam, Canada, and 0.1–7% at the La Grande-2 Dam [33], but the CO₂ degassing proportion is close to 0 at the Nam Ngum Dam and Nam Leuk Dam, Laos (Table 1) [31]. Up to now, no measurement has conducted on the degassing emission in China because of the limitations in the measurement technique and the military supervision for Chinese dams. However, the part of degassing emission is crucial to the total GHG emissions from reservoirs, especially for CH₄ degassing fluxes.

2.4. CO₂ emission from the downstream rivers

Based on all the studies available [19,23,26], CO₂ emission from the downstream rivers contributed to 1.63–32% of the total CO₂ emissions from the reservoirs. Specifically, CO₂ emissions from

the Uatumã River, the downstream of the Balbina Dam, account for 1.63–7% of the total CO₂ emissions from the Balbina hydroelectric system [19,26]; CO₂ emissions from the Sinnamary River, the downstream of the Petit Saut Dam, contribute to 22–31% of the total CO₂ emissions from the Petit Saut hydroelectric system [19,23]; CO₂ emissions from the Jamari River, the downstream of the Samuel Dam, account for 32% of the total CO₂ emissions from the Samuel hydroelectric system [19]. CO₂ and CH₄ emissions at Sandouping, a downstream site of the TGD, are significantly higher than these emissions at Zigui, a site just upstream the TGD. The difference in the CO₂ and CH₄ emissions between the two sides of the TGD are probably related with the strong disturbance by the water passing through the turbines and spillways and the faster water velocity in the downstream rivers [34].

2.5. Environmental factors and their effects on CO₂ emission from reservoirs

2.5.1. Organic matter and temperature

CO₂ and CH₄ emissions from the reservoir's surface are related with the amount of easily decomposable organic matter that is flooded after the filling of the reservoirs [35]. A large amount of organic carbon is stored in peatlands and forests; thus CO₂ and CH₄ emission fluxes are very high when such two land use types are flooded, such as Eastmain-1 Reservoir [36], La Grande 2

Reservoir [37], Laforge-1 Reservoir in Canada [37], and Brazil's Balbina Reservoir [26]. CO₂ and CH₄ emissions from reservoirs are very low if barren soils are flooded in the canyons, such as Ertan Reservoir [15], TGR [34]. Therefore, intensity clearing activities are often carried out before the impoundment of hydroelectric reservoirs in China, which could prevent the water quality after the water storage, and reduce GHG emissions as well.

Fluctuation in the water temperature has an impact on the CO₂ solubility [22], primary production [12], and the decomposition in organic carbon. [12]. Elevation in the water temperature promotes CO₂ emissions by increasing the decomposition rate of organic carbon, which could be seen in the positive correlations between CO₂ emissions and water temperatures in Canadian reservoirs [38,39]. However, if there are algae distributed in the water surface, the elevation in the water temperature would promote CO₂ absorption because of the increase the primary production of aquatic plants [12].

2.5.2. Latitude and reservoir age

CO₂ emission fluxes are exponentially negative correlated with the latitudes of the geographic location of hydroelectric reservoirs [6]. Most of CO₂ emission fluxes in the tropical reservoirs are higher than those in the temperate reservoirs (Tables 1 and 2), because a large amount of organic carbon is stored in the tropical flooded areas, and the high water temperature is beneficial for the decomposition of organic matter [35].

CO₂ emission fluxes decrease with the increase of reservoir ages because of the gradual decrease in the storage of organic carbon in the reservoirs [35]. GHG emissions are mainly released at the initial periods after the impoundment due to the abrupt release of the nutrient substances in the flooded lands, the elevation of microbe activities, and the decomposition of unstable carbon matters, such as soils, litters, swigs, and leaves [39]. However, CO₂ emission fluxes gradually decrease in the reservoirs with the decrease of organic matter and the increase of CO₂ absorption through photosynthesis by various aquatic plants. Specifically, CO₂ emission fluxes reached up to 8000 mg CO₂ m⁻² d⁻¹ at the surface of Eastmain-1 Reservoir in 2006, the first year after impoundment [40], while decreased to 2426 mg CO₂ m⁻² d⁻¹ in 2009 (Table 2) [8]; the average CO₂ emissions from Petit Saut Reservoir were about 200 × 10³ t a⁻¹ in the first 3 years after impoundment (1994–1996), but decreased until less than 70 × 10³ t a⁻¹ after 2000 [23].

2.5.3. pH value

CO₂ emissions or CO₂ partial pressure are significantly negative related with pH values in the reservoir's surface, as were seen in the five reservoirs in Wujiang River in China [48], the reservoirs in the western United States [11], and the reservoirs in eastern Canada [38]. The pH critical values are often reported to be 7.9–8.5 between CO₂ absorption and emission [11,38,39]. PH level influences the CO₂ concentrations in the water by favoring the formation of bicarbonate at the alkaline conditions, which leads to an undersaturation of dissolved CO₂, promoting the absorption of atmospheric CO₂ [38].

2.5.4. Vegetation

Whether there are vegetations distributed in the reservoir's surface determines that the reservoir is CO₂ source or CO₂ sink. When aquatic plants are distributed in the reservoir's surface, such as alga, CO₂ would be absorbed from the air and water nearby by photosynthesis. For example, CO₂ sink during the low water level periods is related with algal blooms in Xiangxi River and Pengxi River in summer [13,45]. If there is no vegetation distributed in the water surface, it would be possibly CO₂ source to the atmosphere, because the CO₂ partial pressure in the water is higher than that in the atmosphere.

2.5.5. Wind speed

The gas transfer velocity is influenced by wind speeds at the air–water interface [49]. It is considered that the strong wind (larger than 3 m s⁻¹) would promote the dissolved gases to release from the water surface, and the thin boundary layer model is appropriate to measure the gas fluxes under the conditions of strong winds [50,51]. When wind speed is less than 2–3 m s⁻¹, the gas transfer coefficient (*k*), an important parameter in the boundary layer model, is independent on wind speed [50], thus the error would be large if the empirical model is used to calculate CO₂ flux. Floating chambers are good estimates of CO₂ diffusive fluxes under the conditions of low wind speeds ranging from 0 to 3 m s⁻¹, because gas fluxes are not easily influenced by the walls of chambers at such conditions [11].

2.6. Summary

CO₂ diffusive emissions are predominant in the upstream before a dam. CO₂ degassing emission from the turbines and spillways accounts for 0–16% of the total CO₂ emission from a hydroelectric system, and the downstream emission accounts for 1.63–32% of the total. To estimate the total CO₂ emission from a reservoir accurately, it needs to measure upstream CO₂ emission, degassing emission from turbines and spillways, and the downstream river. In addition, CO₂ emissions from reservoirs are influenced by the flooded organic carbon, water temperature, geographic location of reservoirs, reservoir age, pH value, vegetation, and wind speed.

3. CH₄ emission from reservoirs

3.1. CH₄ production in reservoirs

Damming for hydroelectric production involves the flooding of vegetations and soils containing significant amounts of organic matter. CH₄, N₂, and a small amount of CO₂ are released from the decomposition of various complicated organic matter under anaerobic conditions, while only CO₂ and N₂ are released under aerobic conditions [28]. Organic carbon is decomposed into CH₄ undergoing microbial fermentation, which could be divided into two steps as follows. Firstly, carbohydrate, fatty acid, and protein in the sediments of the flooded lands are decomposed into the simple organic acid (i.e., formate, acetate), small molecular alcohols (i.e., methanol, ethanol, isopropanol), methylamine, and dimethyl sulfide by hydrolyzation and fermentation, and these simple organic matter could be decomposed further by methanogenesis [52]. Secondly, CH₄ and CO₂ would be released from the decomposition of these substances by methanogens under the anaerobic conditions, and the following reaction equation reflects the decomposition process from acetic acid to CH₄: CH₃COOH → CH₄ + CO₂. The two processes happened synchronously [25,53].

3.2. CH₄ transport in reservoirs

Ebullition is a dominant way for CH₄ emission, while molecular diffusion is a secondary way for CH₄ emission from tropical reservoirs (Table 1). Bubble emissions are independent on reservoir ages. For examples, CH₄ emission by bubbles is about 1–3 times as high as that by diffusion in Petit Saut Reservoir in the first 6 years (1994–1999) after filling [23]; CH₄ emission by ebullition is 3 times higher than that by diffusion in Curuá-Una Reservoir (20–21 years old) in the wet season [7]; 98% of CH₄ is released by bubbles in Gatun Lake, Panama, which is an old reservoir with 84 years old [27]. However, molecular diffusion is a dominant way for CH₄ emission from temperate reservoirs (Table 2), but sometimes bubbles also have remarkable contribution to the total CH₄ emissions from some temperate reservoirs, and Lake Wholen in Switzerland, an old

reservoir with ages of 90 years, is a representative example. CH₄ ebullitive fluxes are up to 480 mg CH₄ m⁻² d⁻¹, and CH₄ diffusive fluxes are only about 15 mg CH₄ m⁻² d⁻¹ from Lake Wholen, which is by far the highest CH₄ emission rate ever documented for a mid-latitude reservoir, even higher than that in tropical reservoirs (Tables 1 and 2) [9]. Inundated forests provide a large supply of nutrients for microbes in the Lake Wholen. Thus, the water in Lake Wholen sometimes looks like champagne in the summer, with masses of gas bubbles rising to the surface [54]. In addition, recently studied indicated that the high sedimentation rate supplies reactive organic matter to deep, anoxic sediment strata at a very high burial rate (1100 g C m⁻² a⁻¹), which would fuel methanogenesis and ebullition of CH₄ at a warm water temperature (17 °C) [55].

3.3. Influences of turbines and spillways on CH₄ emission

The DO concentrations decrease with the water depths, while the dissolved CH₄ concentrations increase with the water depths in a reservoir [17,19,23,56]. The dissolved CH₄ concentrations reach 7.5 mg L⁻¹ at a depth of 30 m in Brazil's Tucuruí Reservoir [18]. When the water in the hypolimnion emerges from the turbines and spillways, the pressure instantly drops to a level of 1 atm, and the water temperature increases near to the temperature in the epilimnion; thus the great majority of the dissolved gas is released into the atmosphere of the downstream river because the solubility of CH₄ is only 0.035 mg L⁻¹ at the normal pressure and temperature (1 atm, 25 °C) [18]. CH₄ degassing emissions from the turbines and spillways are the dominant part of the total CH₄ emissions from a hydroelectric system. For examples, 64.9% and 34.5% of the total CH₄ emissions release from the turbines and spillways of the Tucuruí Dam, respectively, while CH₄ emissions from the reservoir's surface, including bubbles and diffusion, only account for 0.6% of the total CH₄ emissions [29]; CH₄ degassing emissions from the turbines contribute to 42.4–46.6% of the total CH₄ emissions from the Balbina Reservoir [30,57]; CH₄ degassing emissions from the turbines and spillways exceed 50% of the total CH₄ emissions from the Petit Saut Reservoir during the first 10 years after impoundment except for 1994, because CH₄ ebullitive emissions account for a large proportion of the total CH₄ emission in 1994, the first year after filling of the Petit Saut Reservoir [23]. In Brazil's other reservoirs, CH₄ degassing emissions from the turbines and spillways exceed the half of the total CH₄ emissions. For examples, 95% of the total CH₄ emission occurs at the turbines and spillways of the Curuá-Una Dam [7], 99% of the total CH₄ emission is degassing at the turbines and spillways of the Itaipu Dam [29], and 80.8% of the total CH₄ emission originates from the degassing emission from the turbines and spillways of at the Serra da Mesa Dam [29]. The turbine intakes of TGD are located at 80 m depth, and the pressure is about 8 atm there, but there is no report on the degassing emission from the turbines and spillways of the TGD by far.

3.4. CH₄ emission from the downstream river

Downstream CH₄ emission cannot be ignored in a hydroelectric system, because CH₄ diffusive flux is higher in the downstream river than the upstream. For example, the average CH₄ emission flux is (60 ± 38) mmol m⁻² d⁻¹ at the downstream rivers of Petit Saut, Balbina, and Samuel dams, which is significantly higher than the average upstream CH₄ emission flux ((3 ± 2) mmol m⁻² d⁻¹). However, rivers downstream of dams account for 9–33% of the total CH₄ emissions across the reservoir surfaces because of the relatively small areas of downstream rivers [19].

3.5. Environmental variables and their effects on CH₄ emissions from reservoirs

3.5.1. Temperature

CH₄ is the end product of the anaerobic decomposition of organic matter by multiple microbes, and CH₄ emissions from the reservoirs are influenced by temperatures [38]. Elevation of temperature can increase the activities of microbes. Methanogenic bacteria are much more responsive to temperature than methanotrophic bacteria [52], and the optimum temperatures for CH₄ production and oxidation is about 25 °C [58]. Therefore, when the temperature fluctuated at the range that two kinds of bacteria could bear, more CH₄ would be produced when temperature rises, and CH₄ production rate would decrease remarkable when temperature falls [58]. Therefore, CH₄ emissions are often reported to be linear or exponential relationships with soil temperatures or water temperatures [9,59–61].

3.5.2. Water depth

Most of CH₄ would be oxidized by methanotrophic bacteria when the water passes through the O₂ rich epilimnion waters by bubbles or molecular diffusion from reservoir sediments, and only a small amount of CH₄ could release into the atmosphere ultimately. CH₄ is more easily emitted from the shallow-water areas compared with the deep-water areas, because less CH₄ would be oxidized through a short distance between the surface and the reservoir bottom [60]. Although the occurrence of bubbles is episodic [6], bubbles often occur in the areas with a depth less than 10 m [17,23,27,37]. The shallower the water is, the more CH₄ ebullitive flux emits. For examples, CH₄ ebullitive fluxes are only 10–200 mg CH₄ m⁻² d⁻¹ in the areas deeper than 7 m in Gatun Lake, Panama, while the values reach 300–2000 mg CH₄ m⁻² d⁻¹ in the areas less than 2 m [27]; the average CH₄ ebullitive flux was (164 ± 50) mg CH₄ m⁻² d⁻¹ in the areas with depths of 0–3 m, while the CH₄ bubble flux was 0 in the areas deeper than 8 m in Petit Saut Reservoir in 1997 [56]. Moreover, the CH₄ diffusive fluxes are also influenced by water depths. For examples, the CH₄ diffusive emissions from the water surface at the 1 m and 5 m depths are higher than those at the 10 m and 50 m depths in Ertan Reservoir [15]; the CH₄ diffusive fluxes in the areas less than 3.5 m are significantly higher than those in the areas deeper than 7 m in the La Grande-2 Reservoir and Laforge-1 Reservoir, Canada [37].

3.5.3. Water level fluctuation

Water level fluctuation in a reservoir changes the water depths of the permanently flooded lands, which influences on CH₄ emissions from the reservoir's surface subsequently. The drawdown areas are caused by the fluctuation in water levels in the edge of a reservoir [62], and the vegetations in the drawdown area are served as "methane factory" [21]. The vegetations grow and absorb CO₂ from the atmosphere by photosynthesis when the drawdown areas are exposed each year, but the new fixed carbon would be decomposed into CH₄ under the anaerobic conditions in the bottom of reservoirs when the drawdown areas are inundated again [63]. The vegetations in the drawdown areas can continuously remove carbon from the atmosphere as CO₂ and return it as CH₄, with a much greater impact on global warming [63]. Such processes are repeated every year, but there is still lack of quantitative study in aboard. However, there are several studies available on CH₄ emission from the TGR drawdown areas [16,64,65]. After impoundment of the TGR, there is large drawdown areas distributed in the two sides of the TGR, with 30 m in height and 450 km² in area [34], which is seldom seen in the world. The difference is obvious in CH₄ emissions between drylands and wetlands during the drainage of the TGR drawdown areas. CH₄ emission fluxes in the natural wetland

(e.g., *Scirpus triquetus*) and man-made wetland (e.g., rice paddies) reach up to $14.9 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ [64] and $3.94 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ [16], respectively, while CH_4 emissions from the different types of drylands (i.e., fallow land, deforested land, cropland) are close to 0 during the drainage periods [16]. However, CH_4 emission fluxes are low both in the drylands and wetlands during the inundated periods ($0.1\text{--}0.3 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) [16].

3.5.4. Dissolved oxygen in the water

CH_4 emission fluxes at the air–water interface are positively related with the dissolved CH_4 concentrations in the surface layer [56], while the dissolved CH_4 concentrations are influenced by DO in the water. Thus, the DO concentrations in the surface layer have an effect on CH_4 emission from the water surface. The DO concentrations decrease with the water depths, which decreases the possibility of CH_4 oxidation in the hypolimnion. Besides, another reason why the CH_4 concentration is high in the hypolimnion is that the deep waters are closed to the sediments, the CH_4 source of production [66,67].

3.5.5. Other environmental variables

CH_4 emissions are also influenced by wind speed [49,68], water velocity [69,70], and air–water temperature difference [71,72], which causes the instability of the air–water interface. Such 3 variables have an effect on CH_4 emission by changing the gas transfer coefficient (k) at the air–water interface [10,49,69]. Besides, CH_4 emissions from the reservoirs are also influenced by the flooded organic carbon [35], the carbon input from the upstream rivers [23,73], the primary production of aquatic plants [23], the retention time of water [73], weather conditions (light, rainfall) [74], and water quality [43,74].

3.6. Summary

Ebullitive emissions are the dominant way for CH_4 emission from the surface of tropical reservoirs, while diffusive emissions are the main way for CH_4 emission at the air–water interface in the temperature reservoirs. Moreover, CH_4 degassing emissions from the turbines and spillways account for the major proportion of the total CH_4 emission from a reservoir. Furthermore, CH_4 fluxes are high in the downstream river, which cannot be ignored when estimate the total CH_4 emission from a reservoir. In addition, CH_4 emissions from reservoirs are influenced by temperature, water depth, water level, DO, organic carbon, and so on.

4. N_2O emission from reservoirs

4.1. N_2O production in reservoirs

N_2O could be released both in the aerobic or anaerobic conditions, but the substrates and bacteria are different between the two conditions. NO_3^- could reduce into NO_2^- and N_2 via microbial denitrification under anaerobic conditions [76], while NH_4^+ could oxidize into N_2O and N_2 by nitrifying bacteria under aerobic conditions [77]. N_2O , as the intermediate byproduct of two microbiological processes, could be produced in oxic epilimnion, in anoxic hypolimnion, at oxic-anoxic boundaries, either at the sediment–water interface [78].

4.2. N_2O emission flux in reservoirs

Diffusion flux is the main way for N_2O emission from the reservoir surface, while bubbles have little contribution to N_2O emission because of the high solubility of N_2O . For example, only about $0\text{--}0.7 \mu\text{g m}^{-2} \text{ d}^{-1}$ of N_2O is emitted by bubbles in Lokka Reservoir of Finland, which could be ignored [43]. Moreover, upstream N_2O

emission flux at the reservoir surface is higher than that in the downstream rivers. For example, normalized N_2O fluxes are 3–4 times higher at the upstream of Petit Saut Dam than those in its downstream river [79].

The impoundment of reservoirs may have little effect of adding additional N_2O emission, while may even decrease N_2O emission, because N_2O emission from lakes is significantly lower than that from croplands [78]. The original soils before filling, especially croplands, are an important N_2O source [76], but N_2O emission fluxes decrease even become a weak N_2O sink when the soils are flooded after impoundment [77]. However, it is not uniform for N_2O sink or source at various land use types before impoundment. Therefore, only if N_2O emission fluxes were measured at different land uses before and after impoundment in details, the net N_2O emission could be calculated accurately.

4.3. Influences of turbines and spillways on N_2O emission

The distribution of dissolved N_2O concentrations at the vertical profiles is different from that of dissolved CH_4 concentration. The dissolved N_2O concentrations increase with the decrease in DO, but the dissolved N_2O concentrations are undersaturated in completely anaerobic layers, which is consumed due to microbial denitrification in the reservoir sediments [78]. However, there is no report on N_2O degassing emission when the water passes through turbines and spillways.

4.4. Summary

There are a few studies available on N_2O emissions from temperature and tropical reservoirs (Table 3), but it is difficult to find a literature could include the N_2O ebullitive flux, the N_2O diffusive flux, the N_2O degassing flux at the turbines and spillways, and the N_2O emission flux in the downstream river. Compared with N_2O emissions from croplands, N_2O emissions from reservoirs are limited and unimportant. N_2O emissions from the agricultural soils are an important anthropogenic source, which cause the increase in N_2O concentration in the atmosphere [80].

5. Outlook

Several studies on GHG emissions from reservoirs are undertaken by Chinese scholars. Among these studies, GHG emissions from the TGR have drawn many attentions, and experts and scholars were organized to discuss several times in the past 5 years. The TGR is a typical valley-type reservoir, and the surface area of the TGR is up to 1084 km^2 , with 660 km in length and $1\text{--}2 \text{ km}$ in width when the water level reached 175 m . Spatial variations in GHG emissions from the TGR are significant due to the heterogeneity in hydrological conditions [81–83]; thus, to avoid mistaking GHG emissions from the TGR, different research teams should strengthen the cooperation to reveal the patterns of GHG emissions from the TGR correctly.

GHG emissions from the TGR have been studied for over 5 years since the CH_4 emissions from the TGR drawdown areas aroused attention at home and abroad in 2009 [64,84]. Much progress has been achieved on CH_4 emissions from the open water areas and the drawdown areas in the TGR by far [16,34,64,65]. However, there are 3 main defects on the present research. Firstly, no study is conducted on the degassing fluxes at the turbines and spillways of the TGD, especially substantial amounts of CH_4 emission when the hypolimnion passes through the turbines and spillways. Secondly, the dissolved gases in the water could reflect the potential abilities of gases storage and emission from a reservoir, but there is no study on the dissolved concentrations of CO_2 , CH_4 , and N_2O in

Table 3
N₂O emission from the temperate and tropical reservoirs.

| Location | Reservoir name | Area (km ²) | Age (a) | Diffusive flux (μg m ⁻² d ⁻¹) | References |
|---------------|-----------------------------------|-------------------------|---------|--|------------|
| Finland | Lokka | 2280 | 27 | –299 to 462 | [43] |
| | | | 28 | –14 to 507 | [43] |
| Switzerland | Porttipahta | 2573 | 25 | –260 to 173 | [43] |
| | Lake Wohlen | 3.65 | 90 | 72 | [44] |
| | Lake Lungern | 2.01 | 86 | 50 | [44] |
| China | Drawdown area in Pengxi River | 1084 | 5 | 744 (–72 to 7536) | [75] |
| West Canada | 15 reservoirs in British–Columbia | | 21–91 | 50 | [38] |
| Middle Canada | 6 reservoirs in Manitoba/Ontario | | 50–74 | 70 | [38] |
| East Canada | 26 reservoirs in Ontario/Québec | | 3–75 | 100 | [38] |
| | ELARP in Ontario | 0.19 | 1–2 | –1.0 to –3.5 | [77] |
| French Guiana | Petit Saut | 300 | | 4268 | [79] |
| Panama | Fortuna | 10 | 21 | 308 | [79] |
| Brazil | Tucuruí | 2430 | 8–9 | 5500 | [79] |
| | Samuel | 559 | 4–5 | 6908 | [79] |
| | Serra de Mesa | 1784 | | 132 | [79] |
| | Manso | | | 132 | [79] |

the water of the TGR because of the limitation in technique. Thirdly, there are many tributaries distributed in the TGR region, and every tributary has different conditions in hydrology and water quality, but the studies on GHG emissions from tributaries are limited in Xiangxi River, Pengxi River, Longxi River, and Daning River [13,45,83]. Due to these defects, it is difficult to estimate the total GHG emissions from the TGR accurately based on the present data available.

Besides the TGR, China has many other large dams with height higher than 15 m. According to the International Commission on Large Dams, there are 22,000 large dams in China, which account for 46% of the reported dams in the world [85]. However, the studies on GHG emissions are limited in Chinese reservoirs [86]. To evaluate the GHG emissions from the Chinese reservoirs, we could firstly choose the representative reservoirs in the 13 largest hydroelectricity bases in China, measure the 4 main pathways for GHGs to estimate the total GHG emissions from these reservoirs, and estimate the total GHG emissions from Chinese reservoirs based on these results. In the future international negotiations, the results would provide new evidences about whether the development of hydroelectricity could reduce the carbon emission in China.

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