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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 (CH_4) from Brazil's Amazonian areas. CH_4 contributes strongly to climate change because it has a global warming potential (GWP) 24 times higher than carbon dioxide (CO_2) 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 CH_4, CO_2, and N_2O in reservoirs, and the environmental variables influencing CH_4 and CO_2 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.

1. Introduction

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) 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 CO_2 and CH_4 emissions subsequently [6]. However, CH_4 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, CO_2 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 CH_4 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. CO_2 and CH_4 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 CH_4) in the hypolimnion before the dams would release into the atmosphere, becoming a huge CH_4 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 CO_2 emission from reservoirs is the largest, the second is CH_4 emission, and N_2O emission is the smallest. However, the GWP of the three gases is different. CH_4 has a GWP 24 times higher than carbon dioxide (CO_2) on a per molecule basis over a 100-year time horizon [3], and nitrous oxide (N_2O) has a GWP 298 times that of CO_2 [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. CO_2 emissions from reservoirs

2.1. CO_2 production in reservoirs

In a broad sense, CO_2 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 CO_2 emission during the construction phase of the TGD, CO_2 emission during the process cannot be ignored. Besides, CO_2 production in a reservoir also includes the CO_2 emission when the dam operated normally, e.g., CO_2 emission from the fossil fuel combustion by shipping, and CO_2 emission from the turbines. Navigation and electricity generation are two important functions of the Three Gorges Reservoir (TGR), but CO_2 emission has not been quantified during the two processes by far.

CO_2 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 CO_2 and CH_4 by methanogens under the anaerobic conditions at the reservoir bottom [23,24]. In fact, CO_2 could also be produced at the aerobic conditions, e.g., the decomposition of dead trees left above the water surfaces [24].

2.2. CO_2 transport in reservoirs

CO_2 emission fluxes in the reservoirs mainly include the two ways, i.e., diffusion and ebullition [24]. Diffusion is the dominate way for CO_2 emission from reservoirs [25], while bubbles have little contribution to CO_2 emission from reservoir's surface, because the solubility of CO_2 is large, i.e., 1 L water could dissolve 1 L CO_2 at the conditions of 1 atm and 25 °C; thus, CO_2 is easily absorbed by water during the transport from the reservoir's bottom. For example, bubbles contributed less than 1% of CO_2 emission from diffusion during the first years after the impoundment for Petit Saut Reservoir, French Guiana [23]; the CO_2 diffusive emission from Brazil's Balbina Reservoir is 2450 Gg C a^{-1}, while the CO_2 ebullitive emission is only about 0.02 Gg C a^{-1} [26]. According to Table 1, bubbles are not the important way to transport CO_2 in tropical reservoirs, and only the CO_2 diffusive fluxes are studied in temperate reservoirs (Table 2), probably because the frequency of bubbles and CO_2 concentrations in bubbles are low and even could be ignored in temperate reservoirs.

2.3. Influences of turbines and spillways on CO_2 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 CO_2 in the hypolimnion would be released into the atmosphere when the water passes through the turbines and spillways because

Table 1
CH_4 and CO_2 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
CH_4 and CO_2 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 CO_2 diffusive emission from the reservoir surface, the CO_2 degassing fluxes at the turbines and spillways have relatively small contribution to the total CO_2 emission of a reservoir. Based on the literatures available [23,26,31,33], CO_2 degassing at the turbines and spillways contribute 0–16% to the total emission. Specifically, CO_2 degassing emissions from the turbines and spillways of Petit Saut Dam account for 7–16% of the total CO_2 emissions during 1994 to 2003 [23], which is called "degassing proportion" hereafter. The degassing proportion for CO_2 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 CO_2 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 CH_4 degassing fluxes.

2.4. CO_2 emission from the downstream rivers

Based on all the studies available [19,23,26], CO_2 emission from the downstream rivers contributed to 1.63–32% of the total CO_2 emissions from the reservoirs. Specifically, CO_2 emissions from the Uatumã River, the downstream of the Balbina Dam, account for 1.63–7% of the total CO_2 emissions from the Balbina hydroelectric system [19,26]; CO_2 emissions from the Sinnamary River, the downstream of the Petit Saut Dam, contribute to 22–31% of the total CO_2 emissions from the Petit Saut hydroelectric system [19,23]; CO_2 emissions from the Jamari River, the downstream of the Samuel Dam, account for 32% of the total CO_2 emissions from the Samuel hydroelectric system [19]. CO_2 and CH_4 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 CO_2 and CH_4 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 CO_2 emission from reservoirs

2.5.1. Organic matter and temperature

CO_2 and CH_4 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 CO_2 and CH_4 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]. CO_2 and CH_4 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 CO_2 solubility [22], primary production [12], and the decomposition in organic carbon. [12]. Elevation in the water temperature promotes CO_2 emissions by increasing the decomposition rate of organic carbon, which could be seen in the positive correlations between CO_2 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 CO_2 absorption because of the increase the primary production of aquatic plants [12].

2.5.2. Latitude and reservoir age

CO_2 emission fluxes are exponentially negative correlated with the latitudes of the geographic location of hydroelectric reservoirs [6]. Most of CO_2 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].

CO_2 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, CO_2 emission fluxes gradually decrease in the reservoirs with the decrease of organic matter and the increase of CO_2 absorption through photosynthesis by various aquatic plants. Specifically, CO_2 emission fluxes reached up to 8000 mg CO_2 m^{-2} d^{-1} at the surface of Eastmain-1 Reservoir in 2006, the first year after impoundment [40], while decreased to 2426 mg CO_2 m^{-2} d^{-1} in 2009 (Table 2) [8]; the average CO_2 emissions from Petit Saut Reservoir were about 200×10^3 t a^{-1} in the first 3 years after impoundment (1994–1996), but decreased until less than 70×10^3 t a^{-1} after 2000 [23].

2.5.3. pH value

CO_2 emissions or CO_2 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 CO_2 absorption and emission [11,38,39]. PH level influences the CO_2 concentrations in the water by favoring the formation of bicarbonate at the alkaline conditions, which leads to an undersaturation of dissolved CO_2, promoting the absorption of atmospheric CO_2 [38].

2.5.4. Vegetation

Whether there are vegetations distributed in the reservoir's surface determines that the reservoir is CO_2 source or CO_2 sink. When aquatic plants are distributed in the reservoir's surface, such as alga, CO_2 would be absorbed from the air and water nearby by photosynthesis. For example, CO_2 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 CO_2 source to the atmosphere, because the CO_2 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 CO_2 flux. Floating chambers are good estimates of CO_2 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

CO_2 diffusive emissions are predominant in the upstream before a dam. CO_2 degassing emission from the turbines and spillways accounts for 0–16% of the total CO_2 emission from a hydroelectric system, and the downstream emission accounts for 1.63–32% of the total. To estimate the total CO_2 emission from a reservoir accurately, it needs to measure upstream CO_2 emission, degassing emission from turbines and spillways, and the downstream river. In addition, CO_2 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. CH_4 emission from reservoirs

3.1. CH_4 production in reservoirs

Damming for hydroelectric production involves the flooding of vegetations and soils containing significant amounts of organic matter. CH_4, N_2, and a small amount of CO_2 are released from the decomposition of various complicated organic matter under anaerobic conditions, while only CO_2 and N_2 are released under aerobic conditions [28]. Organic carbon is decomposed into CH_4 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., farmate, 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, CH_4 and CO_2 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 CH_4:$CH_3COOH \rightarrow CH_4 + CO_2$. The two processes happened synchronously [25,53].

3.2. CH_4 transport in reservoirs

Ebullition is a dominant way for CH_4 emission, while molecular diffusion is a secondary way for CH_4 emission from tropical reservoirs (Table 1). Bubble emissions are independent on reservoir ages. For examples, CH_4 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]; CH_4 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 CH_4 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 CH_4 emission from temperate reservoirs (Table 2), but sometimes bubbles also have remarkable contribution to the total CH_4 emissions from some temperate reservoirs, and Lake Wholen in Switzerland, an old

reservoir with ages of 90 years, is a representative example. CH_4 ebullitive fluxes are up to 480 mg CH_4 m^{-2} d^{-1}, and CH_4 diffusive fluxes are only about 15 mg CH_4 m^{-2} d^{-1} from Lake Wholen, which is by far the highest CH_4 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 Wohlen 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 CH_4 at a warm water temperature (17 °C) [55].

3.3. Influences of turbines and spillways on CH_4 emission

The DO concentrations decrease with the water depths, while the dissolved CH_4 concentrations increase with the water depths in a reservoir [17,19,23,56]. The dissolved CH_4 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 CH_4 is only 0.035 mg L^{-1} at the normal pressure and temperature (1 atm, 25 °C) [18]. CH_4 degassing emissions from the turbines and spillways are the dominant part of the total CH_4 emissions from a hydroelectric system. For examples, 64.9% and 34.5% of the total CH_4 emissions release from the turbines and spillways of the Tucuruí Dam, respectively, while CH_4 emissions from the reservoir's surface, including bubbles and diffusion, only account for 0.6% of the total CH_4 emissions [29]; CH_4 degassing emissions from the turbines contribute to 42.4–46.6% of the total CH_4 emissions from the Balbina Reservoir [30,57]; CH_4 degassing emissions from the turbines and spillways exceed 50% of the total CH_4 emissions from the Petit Saut Reservoir during the first 10 years after impoundment except for 1994, because CH_4 ebullitive emissions account for a large proportion of the total CH_4 emission in 1994, the first year after filling of the Petit Saut Reservoir [23]. In Brazil's other reservoirs, CH_4 degassing emissions from the turbines and spillways exceed the half of the total CH_4 emissions. For examples, 95% of the total CH_4 emission occurs at the turbines and spillways of the Curuá-Una Dam [7], 99% of the total CH_4 emission is degassing at the turbines and spillways of the Itaipu Dam [29], and 80.8% of the total CH_4 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. CH_4 emission from the downstream river

Downstream CH_4 emission cannot be ignored in a hydroelectric system, because CH_4 diffusive flux is higher in the downstream river than the upstream. For example, the average CH_4 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 CH_4 emission flux ((3 ± 2) mmol m^{-2} d^{-1}). However, rivers downstream of dams account for 9–33% of the total CH_4 emissions across the reservoir surfaces because of the relatively small areas of downstream rivers [19].

3.5. Environmental variables and their effects on CH_4 emissions from reservoirs

3.5.1. Temperature

CH_4 is the end product of the anaerobic decomposition of organic matter by multiple microbes, and CH_4 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 CH_4 production and oxidation is about 25 °C [58]. Therefore, when the temperature fluctuated at the range that two kinds of bacteria could bear, more CH_4 would be produced when temperature rises, and CH_4 production rate would decrease remarkable when temperature falls [58]. Therefore, CH_4 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 CH_4 would be oxidized by methanotrophic bacteria when the water passes through the O_2 rich epilimnion waters by bubbles or molecular diffusion from reservoir sediments, and only a small amount of CH_4 could release into the atmosphere ultimately. CH_4 is more easily emitted from the shallow-water areas compared with the deep-water areas, because less CH_4 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 CH_4 ebullitive flux emits. For examples, CH_4 ebullitive fluxes are only 10–200 mg CH_4 m^{-2} d^{-1} in the areas deeper than 7 m in Gatun Lake, Panama, while the values reach 300–2000 mg CH_4 m^{-2} d^{-1} in the areas less than 2 m [27]; the average CH_4 ebullitive flux was (164 ± 50) mg CH_4 m^{-2} d^{-1} in the areas with depths of 0–3 m, while the CH_4 bubble flux was 0 in the areas deeper than 8 m in Petit Saut Reservoir in 1997 [56]. Moreover, the CH_4 diffusive fluxes are also influenced by water depths. For examples, the CH_4 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 CH_4 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 CH_4 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 CO_2 from the atmosphere by photosynthesis when the drawdown areas are exposed each year, but the new fixed carbon would be decomposed into CH_4 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 CO_2 and return it as CH_4, 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 CH_4 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 km^2 in area [34], which is seldom seen in the world. The difference is obvious in CH_4 emissions between drylands and wetlands during the drainage of the TGR drawdown areas. CH_4 emission fluxes in the natural wetland

(e.g., *Scirpus triqueter*) and man-made wetland (e.g., rice paddies) reach up to 14.9 mg CH_4 m^{-2} h^{-1} [64] and 3.94 mg CH_4 m^{-2} 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 (0.1–0.3 mg CH_4 m^{-2} 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 0–0.7 μg m^{-2} 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 1–2 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
N_2O emission from the temperate and tropical reservoirs.

Location	Reservoir name	Area (km^2)	Age (a)	Diffusive flux ($\mu g\ m^{-2}\ d^{-1}$)	References
Finland	Lokka	2280	27	−299 to 462	[43]
			28	−14 to 507	[43]
	Porttipahta	2573	25	−260 to 173	[43]
Switzerland	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	Tucurui	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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