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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]