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Methane Emissions from a Hydro Power Reservoir in India

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***Abstract*—Since the last two decades, a large number of scientific studies have shown that hydropower reservoirs are the sources of anthropogenic methane (CH_4) emission, especially in the tropical ecoregion [1]. Therefore, the present study aims to find out the detailed nature and extent of CH_4 emissions from a hydropower reservoir (Tehri) in India. Our results show that all the sampling locations at the reservoir surface and downstream of reservoir were the sources of CH_4 emissions to the atmosphere. At the reservoir surface, average CH_4 fluxes and bubbling emissions were 16.01 ± 6.1 mg m^{-2} d^{-1} and 4.7 ± 7.9 mg m^{-2} d^{-1} respectively, whereas downstream emissions in the form of degassing and diffusive fluxes were 7.1 ± 5.5 Mg d^{-1} and 23.01 ± 4.6 mg m^{-2} d^{-1} respectively. Similarly, diffusive fluxes at the drawdown area were in the range of -5.2 to 78 mg m^{-2} d^{-1}. These results are comparable to other reservoirs in the tropical ecoregion. Overall, the total emissions vary seasonally with 60% of diffusive fluxes and downstream emissions occurring during 3 to 4 months of summer season. This study also indicates spatiotemporal variation as measured fluxes were different from one location to another due to variability in depth, organic carbon present in the water column and the varying hydrological conditions among different parts of the reservoir. A major portion of total emissions was contributed by degassing at the downstream (70.24%) while only 16.52% of diffusive and 4.4% of bubbling fluxes came from reservoir surface. The tentative annual calculation indicates that Tehri reservoir is a source of CH_4 with an annual CH_4 emission of about 1.20 Gg yr^{-1}. The results revealed that the CH_4 emissions from Tehri hydropower system were lower than the other tropical hydropower systems, partly due to the higher depth and lower allochthonous organic carbon input from the reservoir catchment.**

Keywords*— *Greenhouse gases; Hydropower; Reservoirs; Tropical ecoregion; Methane emission

I. INTRODUCTION

According to IPCC, (2013) [2], methane (CH_4) concentration in the atmosphere has reached up to 1803 ppb which is about 150% higher than pre-industrial level. Currently, CH_4 emission from various sources accounting for 43% of anthropogenic radiative forcing [2]. Hence, the identification and quantification of natural and anthropogenic sources of CH_4 have become major environmental issue. Until the 90's, hydropower has been supported as green energy source. Since the last two decades, a large number of scientific studies conducted worldwide have shown that CH_4 emissions from large hydropower reservoirs are one of the biggest sources of CH_4 emission, annually emitting 4 to 64 TgC CH_4 yr^{-1} [3] [4] [5].

The degradation of impounded or allochthonous organic carbon in anaerobic conditions at the bottom of the reservoir favors the production of CH_4 and its possible emission into the atmosphere [1]. A major portion of the CH_4 produced is oxidized within the water column and never reaches to the atmosphere [6]. The remaining portion of produced CH_4 escapes to the atmosphere through several pathways: (a) diffusive emission occurs at the surface of reservoir and drawdown area [7] [8] [9]; (b) bubbling occurs mainly in the shallower part of the reservoir [10][11][12]); (c) degassing due to pressure drop at the downstream of reservoir when water passes through turbines [12] [13] [14] and (d) diffusion along the river at the downstream [6]. The contribution of CH_4 emission from hydropower reservoirs varies with temporal and spatial variation [3] [15] [10], diurnal variation [15] [16], seasonal variation [17] [14] and decreases with reservoir age [13]. Hence, there are lots of uncertainties associated with CH_4 emissions from hydropower reservoirs.

Due to high temperature and high amount of impounded organic carbon in the tropical reservoirs, the estimates shows high potential of CH_4 emissions in tropical ecoregion [3] [5]. However, these conclusions are drawn from the compilations of results from specific number of reservoirs but not all the studies have included all emission pathways or the spatial and temporal variation [13] [14] [18]. Most of the studies on CH_4 emission from hydropower reservoirs have been conducted in Europe [19], North America [20] [18] and South America [13] [14] and there is very little information from Asia [8] [9] [21] [22] [23] [24] [25] [26] [27]) where 60% of the total world hydropower potential remains (2795 GW) [28]. The objective of the study is to quantify the gross and net CH_4 emission in subtropical Tehri Reservoir in India. Quantification of CH_4 was done during four field campaigns conducted during the year 2011-2012. Result of the study discussed spatio-temporal variation and contribution of each emission pathways.

II. SITE DESCRIPTION, SAMPLING STRATEGY AND METHODOLOGY

A. Study Area

Tehri dam is situated in one of the deep gorges of the Himalaya at the confluence of the river Bhagirathi and Bhilangana in India. It was competed and commissioned in 2006, flooded over 42.5 km^2 area out of 7502 km^2 of catchment area with Determiner water storage capacity of 3.2 million m3. This mega project of 2000 MW installed capacity, envisaged construction in two stages. The stage I, is termed as Hydropower Plant and Stage II, a Pump Storage Plant, have an installed capacity of 1000 MW each. The project area experiences a sub-tropical monsoon climate with distinct monsoon (June – September), post-monsoon (October -

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December), winter (January - February) and summer (March - May) seasons. In summer, the temperature in the area is relatively high due to the low elevation and topographic features. Maximum temperature varies from 30°C to 36°C while minimum temperature varies between 0°C to 6°C. Since water input is directly related to rainfall, maximum depth (d) of water (240 m) was observed during monsoon season (reservoir area of 42.5 km^2) and minimum (140 m) during pre-monsoon season (reservoir area of 18 km^2). Annual river discharge of 60 cumec was measured in winter and 900 cumec in monsoon with the annual turbine discharge of 273.35 cumec [29].

B. Physico-chemical parameters in the reservoir

Thermal and chemical properties of Tehri reservoir were analyzed by collecting and analyzing water samples as well as onsite using Hydrolab multiparametric sonde (DS5X) at 18 different locations spread over the reservoir surface, upstream and downstream as shown in Fig. 1.

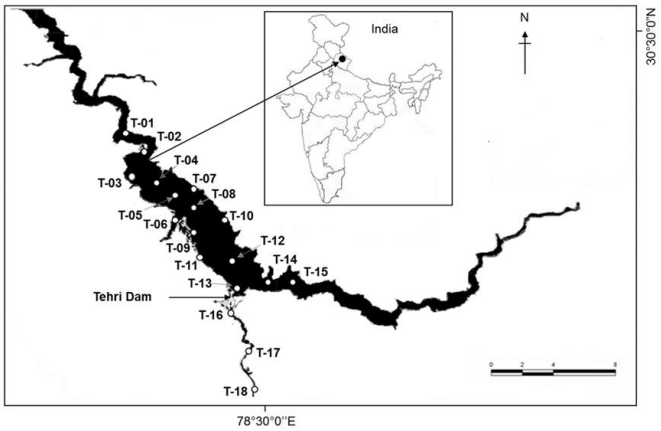

Fig1. Location map of Tehri reservoir and the sampling station

Sampling locations were chosen based on the spatial variability. Meteorological parameters viz. air temperature, wind velocity and rainfall were obtained from IMD (www.imd.gov.in) for the sampling period. Average annual wind speed and precipitation vary from 5.32 to 10.39 m s^{-1} and 1000 to 2000 mm respectively. Considering seasonal variations, sampling were done four times in year 2011–2012.

- *Vertical profile of dissolved CH_4*

Water samples were collected at fixed depth interval to measure dissolved CH_4 concentration and different forms of carbon content in the water column for entire volume of reservoir. Organic and inorganic carbon analysis were done using infrared spectrophotometry and automated carbon analyzer. Water samples for CH_4 concentrations were stored in 60 ml serum vials flushed with N_2 which were then sealed using butyl stoppers [6]. The headspace method were used to determine dissolved gas concentration by equilibrating equal volumes of water and air in the sampling syringe [30]. CH_4 concentration were determined using a Netel Michro 9100 gas chromatograph using flame ionization detector (FID). Methodology described by McNair and Miller (2009) [31] and Willard et al., (1998) [32] were used to prepare samples and run tests. Commercial standards at 2 to 1000 ppmv, air "Cristal "standards were used for calibration. The specific gas solubility for CH_4 [33] was used for calculation of total CH_4 concentrations dissolved in water.

- *CH_4 concentration at sediment water interface*

Sediment samples were taken from the bottom of the reservoir using a gravity sediment corer. Samples were stored into pre-weighted glass vials containing 20 ml of 1M NaOH. Glass vials were then closed with rubber stoppers and vigorously shaken to ensure equilibrium between gas and slurry phase before analysis [1]. The CH_4 concentrations in the headspace were determined using gas chromatograph. A sub-sample was taken immediately and sealed in a pre-weighted vial to determine water content and porosity.

C. Diffusive surface flux

Diffusive fluxes measurements were performed with floating chambers (surface area = 0.2 m^2; volume = 20 l) following the similar design as in Guerin et al. (2007) [6]. This method consists of enclosing air in a chamber that floats at the surface of the water. The chamber is equipped with a septum in order to take samples inside the chamber with a syringe. To avoid any artificial increase of turbulence in the floating chamber, the walls of vertical chamber were continuously submerged which was about 3 cm at the bottom and allowed to float freely with the water and air current [34]. During each flux measurement, three gas samples were collected at 15 min interval from the chamber. A 60 ml polyethylene syringes were used to collect the gas samples. Until the analysis, the collected samples were stored in 10 ml glass serum vials flushed with N_2 and covered with high density butyl rubber stoppers [35]. Collected gas samples were analyzed within 2 days using gas chromatography. A linear regression analysis were performed between gas concentration versus time and the slope of linear regression were used to compute CH_4 fluxes. The fluxes were accepted when the determination coefficient (R^2) of the linear regression was higher than 0.8.

D. Bubbling emission

Bubbling mainly occur in shallow parts of reservoirs where the hydrostatic pressure is not sufficiently high to dissolve gases in the interstitial water. The selection of sampling sites was decided on the basis of water depth and type of impounded ecosystem. An inverted funnel (30 cm diameter) initially filled with water and coupled to gas collectors were used, which captured the ascending bubbles [36]. Sets of funnels were placed above the water surface, at various depth ranging from 0.5 to 30 m and remained on the site for 12 to 24 hours. Samples were collected and stored in glass vials flushed with N_2 and analyzed by gas chromatography.

E. Emission at drawdown area

During the low water periods (early monsoon, summer and winter), diffusive fluxes were measured at 6 locations from the soils surrounding the Tehri reservoir. Soil moisture content and temperature were measured at each site. Sampling locations were chosen based on the representativeness of each impounded ecosystems. At each location, 3 zone were defined: the upper zone which was never flooded (soil moisture ~20%); the middle zone which was impounded during high water level (soil moisture <30%) and the lower

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zone which was close to the shoreline and water saturated (soil moisture ~40%).

F. Downstream Emission

Downstream emissions are those emissions observed below reservoir outlets. The intakes of turbine is located at 188 m depth below the water surface, where there is remarkable higher pressure than the atmospheric pressure. The dissolved CH_4 in the hypolimnion releases into the atmosphere when the water passes through the turbines because of the abrupt decrease in pressure and the increase in water temperature [37]. Downstream emissions are consisting of degassing and diffusive fluxes. Most of the dissolved CH_4 is released by degassing at the turbine outlet and remaining is transported downstream, and gradually released to the atmosphere by diffusion. The influence of emissions ranged from a few meters up to 50 km downstream in the river [13]. Degassing of CH_4 at the turbine outlet was estimated by multiplying the difference between average CH_4 concentration at the upstream near water intake (T-13) and turbine outlet (T-16), by the average discharge [12]. Diffusive fluxes at the downstream were computed by applying the gas concentration on thin boundary layer equation using formulation of k600 from study done by MacIntyre et al., (2010) [38]. As floating chamber measurement were not possible due to strong water current. K_{600} values were varied from 5.4 to 14.3 cm h^{-1} with varying wind velocity which is similar to the K_{600} value at the downstream of Petit Saut reservoir [6]. In four different seasons, 12 degassing emission measurement were done. However, 36 diffusive fluxes measurements were made at location T-16, T-17 and T-18 located at the 0 km, 5 km, and 10 km interval from downstream of water release from turbine respectively.

G. Statistical Analysis

Mean CH_4 fluxes were calculated by averaging all the replicates at each sampling site. To analyze the differences in GHG fluxes from different sites, one way analysis of variance (ANOVA) was used. Normal distribution of data was performed. Relation between the GHG fluxes and environmental variables were computed using the Pearson correlation analysis. The Kruskal–Wallis one-way analysis of variance was used for verifying whether samples originate from the same distribution and to compare more than two independent samples.

III. RESULTS AND DISCUSSION

A. Physico-chemical parameters in the reservoir

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 [39]. Therefore, vertical profile of temperature were measured. Thermal and chemical stratification was stronger during post-monsoon and summer season as shown in Fig. 2. Epilimnic water temperature was highest during summer (23.1 ± 3.7 °C) and post-monsoon (20.2 ± 3.6 °C) season, it rose up to 25°C whereas the hypolimnic temperature was observed in the range of 10 - 13 °C. During summer, the difference of 10 ± 2°C was observed between epilimnion and hypolimnion, however, in winter these temperature difference was 3 - 5°C. Dissolved oxygen (DO) play an important role in CH_4 oxidation in water column [40]. Throughout the year, epilimnion was oxic (7.0 to 8.5 mg l^{-1}) and DO level abruptly dropped to anoxic level in metalimnion (at 50 to 100 m depth) as well as in hypolimnion (at 100 to 200 m depth) (Fig. 2). Maximum DO at the surface was observed during monsoon, (8.2 ± 2.5 mg l^{-1}) and winter (8.5 ± 3.30 mg l^{-1}) season due to mixing of rain water during monsoon season and high solubility of oxygen (O_2) at low temperature in winter. At locations T-03, T-06, T-07, T-09, T-11 (at the rim, depth < 30), the reservoir was generally stratified with an anoxic hypolimnion and well-oxygenated epilimnion, although O_2 reach occasionally the hypolimnion during the sporadic destratification events during monsoon and post-monsoon seasons. The depth of oxycline was concomitant with the thermocline in all the seasons.

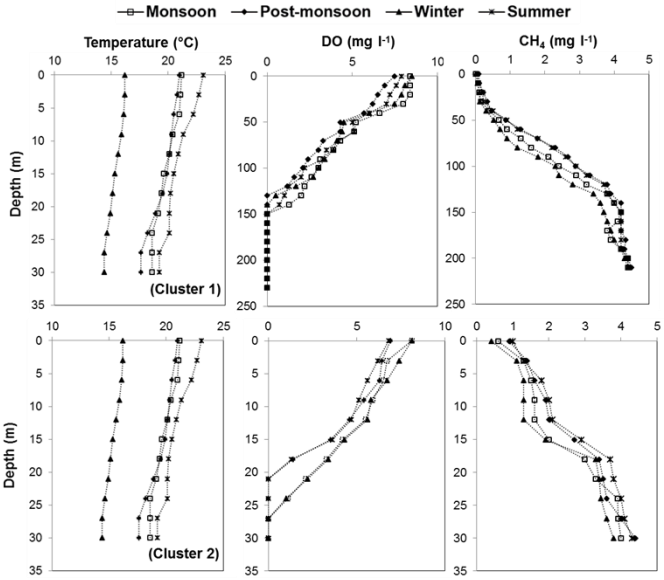

Fig 2. An example of vertical profile of temperature, dissolved oxygen and CH_4 concentration at cluster 1 (upper panel) and cluster 2 (lower panel).

B. Vertical profile of CH_4 concentration in reservoir water column

- *CH_4 concentration in reservoir water column*

CH_4 concentration in surface water at all sampling locations ranged from 0 to 2.4 mg l^{-1} (n = 120) with an average value 0.11 ± 0.9 mg l^{-1}. Vertical profile shows large variation due to physical and hydro dynamical conditions in water column (Fig. 2). Due to anoxic condition at the bottom of the reservoir, the decomposition of organic matter leads to high concentrations of CH_4 in the hypolimnion whereas oxidation of most of the produced CH_4 at oxi-anoxic interface leads to lower CH_4 concentration at the epilimnion. The regular decrease of CH_4 concentration from hypolimnion to the metalimnion and sharp decrease around metalimnion to epilimnion due to presence of oxygen is the typical characteristics of many lakes and reservoirs [6] [7] [11]. Distribution of CH_4 was exactly the opposite of DO. Such influence of DO was also observed in many tropical reservoirs [7] [12] [13].

Statistical analysis for the epilimnic CH_4 concentration suggested three cluster in sampling locations throughout the year ($p < 0.05$, one way ANOVA test), Cluster 1 : T-04, T-05, T-08, T-10, T-12, T-13 where water depth was high (> 30 m), cluster 2: T-03, T-06, T-07, T-09, T-11 at the rim of the reservoir (depth < 30 m) Cluster 3: T-01, T02, T-14, T-15 at the

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upstream of reservoir. Effect of depth on CH_4 emissions i.e. more emissions at shallow water locations compared to deep water locations due to less CH_4 oxidation was also observed by Dumestre et al., (1999) [41]; Guerin and Abril, (2007) [6]. This explains the importance of methanotrophic bacteria in regulating the CH_4 concentration at the epilimnion and metalimnion. At cluster 1, CH_4 concentration at the epilimnion (0.05 ± 0.5 mg l^{-1}) were about 88 times less than hypolimnion (4.4 ± 1.1 mg l^{-1}) concentration (Fig. 2). At cluster 2, due to lower standing water depth, epilimnic concentration (1.2 ± 0.5 mg l-1) was only 2 - 3 times lower than hypolimnic concentration (3.5 ± 1.2 mg CH_4 l^{-1}). In addition, T-06 was located in a small embayment preventing efficient water mixing with the rest of the reservoir, thereby not being part of the reservoir outflow or inflows and becoming more stagnant as a result higher CH_4 concentration at hypolimnion and epilimnion. At cluster 3, epilimnic concentration were very low compared to reservoir surface (0.03 to 0.4 mg l^{-1}) due to lower hypolimnic concentration and well oxygenated epilimnion. Variation of CH_4 concentration in the epilimnion with respect to DO and difference in surface and bottom temperature (Δt) is shown in Fig. 3.

At locations T-13 (at the water intake), when turbine were operated, homogeneous vertical CH_4 profile was observed due to mixing of water. Dissolved oxygen at the hypolimnion increases from 0 to 3.2 mg l^{-1} and CH_4 concentration decreases from 4.4 ± 1.1 to 2.12 ± 0.45 mg l^{-1}. Decrease in CH_4 concentration at the hypolimnion was concomitant with DO present into the water column and temperature difference at the epilimnion and hypolimnion.

On the seasonal basis, CH_4 concentration was significantly different (p = 0.034, one way ANOVA analysis). CH_4 concentration gradient were steeper during summer season due to higher temperature. As elevation of temperature increases the activities of microbes and methanogenic bacteria are much more responsive to temperature than methanotrophic bacteria [42]. During monsoon season, CH_4 concentration decreases sharply due mixing of freshwater inflows which increase penetration of oxygen and hence enhancement of aerobic CH_4 oxidation. However, it starts increasing slowly during post-monsoon due to inflow of organic carbon during monsoon season which leads to high degradation rate hence higher CH_4 production and again decreases during winter season due to lower degradation rate.

Due to stratification, after 150 m water depth, CH4 concentration was homogeneous till bottom in all the seasons (Fig. 2). Most of the high epilimnic CH4 concentrations were observed in summer (0.23 ± 0.56 mg l−1) and post-monsoon (0.19 ± 0.46 mg l−1) season where as in winter and monsoon season it was lesser i.e. 0.09 ± 0.23 mg l^{-1} and 0.12 ± 0.56 mg l^{-1} respectively. Similar pattern of seasonal variation in CH_4 profiles were often observed in stratified tropical reservoirs [7] [13] [21].

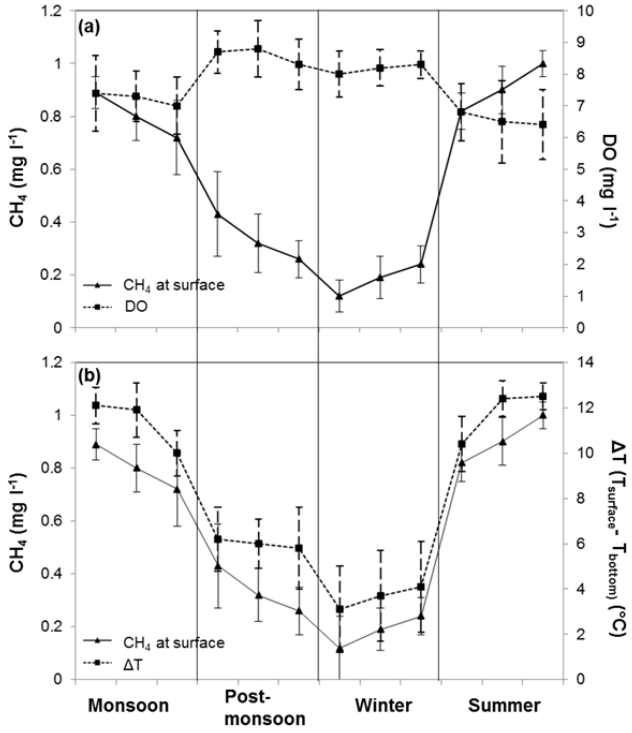

Fig 3. Variation in CH_4 concentration in surface water due to (a) dissolved oxygen and (b) ΔT (difference in surface and bottom temperature).

Average epilimnic CH_4 concentration (0.11 ± 0.17 mg l^{-1}) at Tehri reservoir was lower than CH_4 concentration at Petit Saut reservoir in March 2012 (0.16 ± 0.17 mg l^{-1}) [13], Balbina reservoir (0.14 ± 0.16 mg l^{-1}) [7], Nam Theun 2 (1.02 ± 0.9 mg l-1 in Feb - April, 2011) reservoir [22] as shown in Table 1. Similarly, hypolimnic concentration (4.35 ± 2.03 mg l^{-1}) was lower than CH_4 concentration at Petit Saut (4.8 mg l^{-1}), Balbina reservoir (6.7 ± 2.2 mg l^{-1}) and Nam Theun 2 reservoir (4.4 ± 3.4 mg l^{-1} in Feb - April, 2011) (Table 1).

- *CH_4 concentration at the downstream*

CH_4 concentration at the downstream locations T-16, T-17 and T-18 were not significant ($p < 0.05$). During winter and summer season, the DO saturation level was less than 8%. CH_4 concentration at T-16, which receives water from homogenized water column at T-13 varied from 0.04 to 2.62 mg l^{-1} (average 1.29 ± 0.39 mg l^{-1}). CH_4 concentration at the downstream was about 10 times higher than the natural river. Similar results of increase in CH_4 concentration due to creation of dam have been reported in Petit Saut reservoir [7]. Rivers are indeed ecosystems where oxic conditions generally prevail and where CH_4 production was rather limited. Maximum CH_4 concentrations at the downstream were observed during summer (2.62 ± 1.2 mg l^{-1}) and post-monsoon (2.63 ± 0.7 mg l^{-1}) as dissolved CH_4 concentration were higher at T-13 location during these seasons whereas lower concentrations were observed during monsoon (1.9 ± 0.34 mg l^{-1}) and winter (1.9 ± 0.12 mg l^{-1}) season. Concentration decreases from T-16 to T-18 during summer from 1.62 ± 1.2 to 0.06 ± 0.04 mg l^{-1}, post-monsoon from 1.34 ± 0.7 to 0.04 ± 0.03 mg l^{-1}, monsoon from 0.9 ± 0.34 to 0.04 ± 0.008 mg l^{-1} and winter from 0.2 ± 0.12 to 0.005 ± 0.003 mg l^{-1}. CH_4 concentrations at the water release from spillways was lower (0.006 to 1.6 mg l^{-1}) than at the full

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TABLE I. CONCENTRATION AND EMISSIONS OF CH_4 IN SOME TROPICAL RESERVOIRS (THE NUMBER IN PARENTHESIS INDICATES THE NUMBER OF MEASUREMENTS).

Reservoir	Location	Age	Date	Concentration (mg l^{-1})			Diffusive Flux (mg m^{-2} d^{-1})	Bubbling Fluxes (mg m^{-2} d^{-1})	Degassing fluxes (mg m^{-2} d^{-1})	Downstrea -m fluxes (Mg d^{-1})	Ref.
				Epilimnion	Hypolimnion	Downstream					
Tehri	India	6	04/10 to 05/11	0.11±0.9 [0-2.4] (120)	4.4±1.1 [0.9-5.2] (120)	1.29±0.39 [0.04-2.62] (48)	16.01±6.1 (216)	4.7±7.9 (60)	7.1±7.9 (60)	23.01±4.6 (36)	1
Nam Theun 2	Laos	1	02/11 to 04/11	0.024±0.008	4.4±3.4	1.5±1.2 [0.0004-3.5]	15.2±12.8 [2.56-51.2](32)	25			2
			05/10 to 09/10			1.05±1.2					
Nam Ngum		28	04/09 to 01/10	0.16±0.0014 (26)	0.21±0.45 (17)	0.033±0.054 (3)	3.2±3.2 (11)				3
Nam Leuk		10		0.12±0.019 (13)	1.1±1.7 (13)	0.056±0.043 (3)	40±64 (8)				3
Petit Saut	French Guiana	1-10	11/94 to 12/03	0.0016±4.4 (1521)	4.8 [0.004-20.8] (483)	1.16 [0.12-5.93](190)	[10-3200]	11.2-800	5-40	1440	4
			05/03	0.004±0.0016 (23)	3.5±0.4 (33)	1.02 (1)	123±140.8 (18)				4,5
			12/03	0.16±0.17 (22)	11.2±2.9 (20)	1.4 (1)	43.2±25.6 (17)				4,5
			03/05	0.038±0.046 (3)	1.9±0.049 (9)	0.76 (1)	1.6±1.6 (3)				4,5
			05/05	0.004±0.001 (3)	0.54±0.73 (11)	0.35 (1)	11.2±8 (6)				4,5
Balbina	Brazil	18	11/04	0.14±0.16 (12)	6.7±2.2 (15)	1.2±0.11 (3)	33.6±48 (6)	13	0.065	28.4	5
			01/05 to 11/05				48 [6.4-464] (80-140)				6
			09/04 to 02/06				193				6
Samuel		4 - 5	98-99				160 [4.8-2368]	16.5	65700		4,5
			11/04	0.03±0.003 (4)	4.1±1.1 (4)	0.64 (1)	87.55±95.4 (2)				7,8
Miranda		1	98-99				130.35 [19.2-4576]	23.85			7,8
Tres Marias		36	98-99				31.85 [0.8240]	164.5			7,8
Barra Bonita		35	98-99				16.95 [3.2-28.8]	3.95			7,8
Segredo		6	98-99				7 [0.016-64]	1.8			7,8
Xingo		4	98-99				29.3[1.2-142.4]	10.75			7,8
Tucurui		8 - 9	98-99				101.15 [0.32-2880]	7.85			7,8
Itaipu		8	98-99				10.15 [1.4-127.6]	0.55			7,8
							24.6 [3.2-94.4]	88.65			7,8
Serra da Messa		1	98-99				36	77			9
Cueua-Una		13									

1. Present study; 2. Deshmukh et al., 2014, 2015; 3. Chanudet et al., 2011 [20]; 4. Abril et al., 2005 [13]; 5. Guerin et al., 2006; 6. Kemenes et al., 2007 [14]; 7. dos Santos et al., 2005 [43]; 8. dos Santos et al., 2006 [44]; 9. Fearnside et al., 2005 [45].

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reservoir level (low epilimnic CH_4 concentration) and water release from the spillway happens only during monsoon season and flood events.

The average CH_4 concentration (1.11 ± 0.20 mg l^{-1}) at downstream of Tehri reservoir was similar to CH_4 concentration (1.16 mg l^{-1}) at downstream of Petit Saut reservoir [13], at Balbina reservoir (1.2 ± 0.11 mg l^{-1}) [7] and Nam Theun 2 reservoir (1.5 ± 1.2 to 0.02 ± 0.01 mg l^{-1} in March - April, 2011 [21]) as shown in Table 1.

- *CH_4 stored in sediment pore water*

For all the three cores of sediment (at surface, at 10 cm and at 30 cm) mean CH_4 concentration in pore water varied from 2.8 ± 0.5 mg l^{-1} to 8.9 ± 1.32 mg l^{-1}. The concentration in the first sediment layer (below soil water interface) ranged from 4.7 to 7.4 mg l^{-1} with high spatial variation. CH_4 in pore water of the core was 2 times higher than the average concentration at hypolimnic water which conforms the occurrence of methanogenesis in the flooded soils.

C. Pre-impoundment emissions

Pre-impounded emissions were computed on the basis of land use classification for Tehri reservoir before impoundment [46] and CH_4 emissions values for various type of ecosystem exist in the impounded land. Values of CH_4 emissions were obtained from literature [47] for sub-tropical ecoregion. CH_4 fluxes from the river channel were measured at the upstream of the river and is calculated as 6.2 ± 4.2 mg m^{-2} d^{-1}. Estimates of CH_4 emissions for different land use type were added together and average annual emission were estimated as 88.07 Mg yr^{-1}.

D. GHG Emissions

- *Diffusive fluxes*

During the different field campaigns, 216 floating chamber measurements were made (with three replicates at each location). CH_4 diffusive fluxes exhibit high spatial variability ($p = 0.03$) similar to the observations described for epilimnic CH_4 concentration (section CH_4 concentration in reservoir water column). Such variations in the measurements at different locations were often due to variation in the flooded ecosystem such as dense forest, open forest, agricultural land and more often during low water level periods during summer and early monsoon season. Among the validated data, diffusive measured fluxes at cluster 1 ranged from 6 to 17.1 mg m^{-2} d^{-1} with an average value of 12.08 ± 2.4 mg m^{-2} d^{-1} as shown in Fig. 4. Most of the diffusive fluxes at cluster 2 were rejected due to sudden entry of CH_4 bubble in the chamber and it varied from 9.4 to 22.7 mg m^{-2} d^{-1} with an average value of 17.66 ± 3.8 mg m^{-2} d^{-1}. Considering seasonal variations, CH_4 fluxes during monsoon, post-monsoon and summer were not significantly different with their average diffusive fluxes ($p = 0.67$) except during winter season ($p = 0.032$). CH_4 fluxes during monsoon (16.07 ± 6.1 mg m^{-2} d^{-1}), post-monsoon (17.52 ± 6.3 mg m^{-2} d^{-1}) and summer (17.8 ± 6.4 mg m^{-2} d^{-1}) season were maximum and minimum during winter season (12.6 ± 5.8 mg m^{-2} d^{-1}). Comparison of CH_4 fluxes from Tehri reservoir to other tropical reservoir is presented in Table 1. CH_4 fluxes at Tehri reservoir were in lower range than the measured CH_4 fluxes at other tropical reservoirs [7] [13] [14].

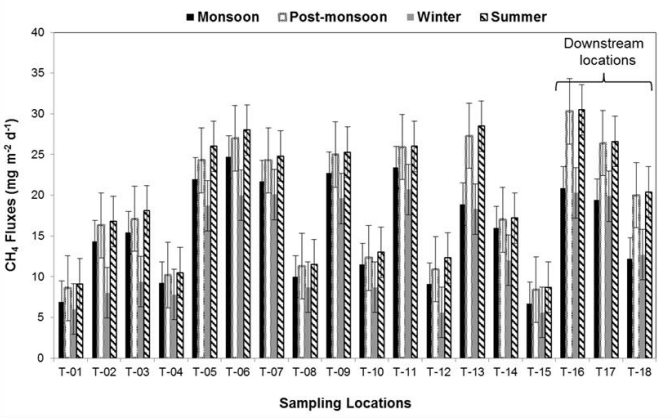

Fig 4. CH_4 emission fluxes at different sampling location

- *Bubbling emissions*

Bubbling fluxes were measured at different depths from 0.5 to 30 m at 5 locations spread over various parts of the reservoir and results are shown in Fig. 5. The average bubbling emissions was 4.7 ± 7.9 mg m^{-2} d+ from 60 individual measurements. A strong relationship ($R^2 = 0.82$) was observed between the second order polynomial function of 1-m binned average fluxes and water depth at the measurement site. Bubbling emission decreased from 27.8 to 0 mg m^{-2} d^{-1} for water depth ranging from 0.5 to 30 m and no bubbling was observed for water depth higher than 30 m

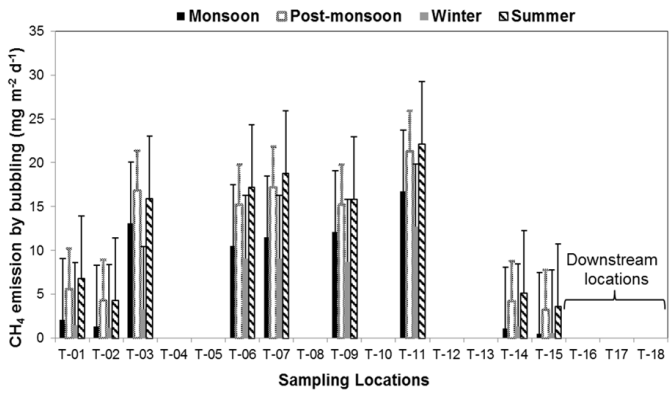

Fig 5. CH_4 emissions by bubbling at different sampling locations

(Fig. 6). The influence of depth on bubbling emissions was frequently documented in various aquatic environments like lakes 2004 [11] [48] and hydropower reservoirs [36] [49].

Bubbling emission exhibits large seasonal variation well correlated with water level variations (mainly decrease), fluxes were maximum during summer and post-monsoon season (27.6 ± 6.6 mg m^{-2} d^{-1} and 22.5 ± 8.7 mg m^{-2} d^{-1}). During this period, it contributed around 40 – 45 % of total annual bubbling emission even if the reservoir exhibits the lowest water surface area at that period. This suggests that the estimation of bubbling from an aquatic ecosystem with large water level variations requires high frequency measurements over the period of water level decrease, since the water level as well as its variations and the concomitant temperature variations have a strong impact on bubbling.

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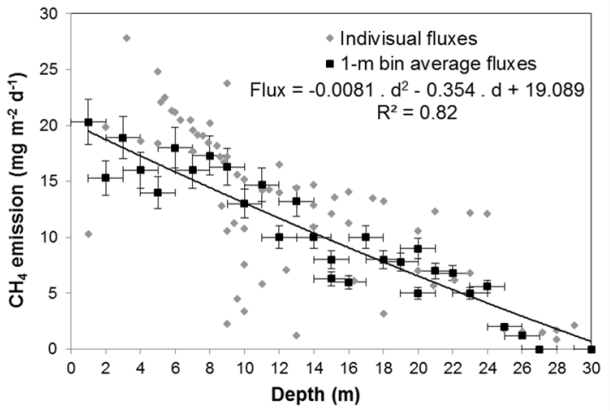

Fig 6. Second order polynomial relationship between average CH_4 bubbling emissions in 1-M binned area and water depth

Average bubbling emissions (4.7 ± 7.9 mg m^{-2} d^{-1}) at Tehri reservoir was much lower than average bubbling emission (44.8 ± 64 mg m^{-2} d^{-1}) in some Amazonian tropical reservoirs e.g. Petit Saut (11.2 ± 8 mg m^{-2} d^{-1}) [13] [12] [49]; Três Maria, Barra Bonita, Segredo, Samuel, Tucuruí and Itaipu [13] [44] [50]; Curuá-Una [45] and Gatun Lake [36] (Table 1). Emission range in these reservoirs varies from 0.48 (Itaipu and Tucuruí reservoirs) up to 2400 mg m^{-2} d^{-1} (Gatun Lake). The hydro acoustic measurements done by DelSontro et al., (2011) [10] showed that bubbling emission could vary over several orders of magnitude (up to ~ 96000 mg m^{-2} d^{-1}) for African reservoirs.

- *Diffusive fluxes from the drawdown area*

Drawdown area were observed during early monsoon, winter and summer season. Diffusive fluxes from the drawdown area ranged from -5.2 to 78 mg m^{-2} d^{-1} for soil temperature ranging from 23 to 35°C. Upper zone of soil sometimes acts as sink of CH_4 with the fluxes ranging from -0.9 to 0.87 mg $m^{-1}d^{-1}$ (average 0.4 ± 0.2 mg m^{-2} d^{-1}) with the moisture content was about 18 ± 7%. The middle zone (moisture content: 28 ± 5%) emitted 1.1 ± 0.8 mg m^{-2} d^{-1} and the lower layer (moisture content: 41 ± 6%) emitted 37 ± 46 mg m^{-2} d^{-1}. CH_4 emissions from soils with moisture content between 20 to 30% showed a shift between a sink and a source CH_4. However, CH_4 emissions from soils with moisture content 30 to 40% showed a shift between sources of low CH_4 to significantly higher source of CH_4. Hence, moisture content plays a key role to control the methanogenesis and the methanotrophic activities in the soil which was also observed by Le Mer and Roger, (2001) [51]. When moisture content of soil is low, oxygen penetrates deeper in the soil, enhancing CH_4 oxidation hence soil act as sink of CH_4 and vice versa when soil moisture content is high which leads to source of CH_4. Soil temperature has no effect on CH_4 fluxes (R^2 = 0.06) (data not shown). The range of fluxes observed was in lower range than the results reported for drawdown zone of Nam Theun 2 reservoir (-6.88 – 1984 mg m^{-2} d^{-1}) [23].

- *Degassing and diffusive emission at the downstream locations*

Throughout the year 48 measurements were made in four different seasons at downstream locations located at the 0 m, 5 km and 10 km interval from turbine outlet. Degassing efficiency was 30 – 45 % during summer and post-monsoon seasons. The degassing efficiency was similar to the Nam Theun 2 reservoir (32% during dry season) and lower compared to Balbina Reservoir (53%) [14]. Seasonal variation in diffusive fluxes at T-16, T-17 and T-18 is shown in Fig. 3. Degassing emissions at the downstream range from 0.17 to 14.4 Mg d^{-1} (average 7.1 ± 5.5 Mg d^{-1}) and diffusive fluxes range from 8.7 to 30.5 mg m^{-2} d^{-1} (average of 23.01 ± 4.6 mg m^{-2} d^{-1}). During occasional spillway release, degassing emissions was 0.03 – 1.2 Mg d^{-1}. Even if these emissions were occasional and generally occur within a few days, it needed to be accounted for when calculating the total CH_4 emissions from reservoir.

At the downstream, both degassing and diffusive CH_4 fluxes followed the same seasonal variation as those observed in the CH_4 concentrations and decreased with the distance from the turbines. Average diffusive fluxes at T-16 were 25.5 ± 5.6 mg m^{-2} d^{-1} which drops 16.32 ± 4.4 at T-18. Such decrease in diffusive fluxes as the distance increase from the turbine was also observed at Petit saut reservoir [6]. This estimates of diffusive flux at the downstream of Tehri dam along 10 km reach were far less than the estimate along 40 km reach downstream of Petit saut dam (1440 mg m^{-2} d^{-1}) [6] and 30 km reach downstream of Balbina dam (2240 mg m^{-2} d^{-1}) [14].

E. Annual gross and net CH_4 emission (Gg CH_4 yr^{-1})

Annual gross emissions from Tehri Reservoir through the different emission pathways were quantified by integrating detailed spatial and temporal variability. This includes area weighted average CH_4 emission for each pathway in four different seasons and respective reservoir water surface area and the results are shown in Table 2. Overall, total CH_4 emissions reach their maximum at the end of summer (722.87 Mg CH_4 yr^{-1}) and post-monsoon (280.05 Mg CH_4 yr^{-1}) season. This is because of higher temperature as well as decreasing water level in summer and presence of high amount of organic carbon in the water column during post-monsoon season.

Throughout the year, degassing at the downstream was the main pathway of CH_4 emission to the atmosphere contributing 71.82 % of the total CH_4 emission and reservoir surface contributed 16.54 % in the form of diffusive fluxes, 4.46% in the form of bubbling emission and 7.15% from the drawdown area. The contribution of degassing emission was similar to the tropical reservoir Petit Saut (70%) after 6 years of impoundment, however diffusive fluxes were in lower range (5.7%) and bubbling emissions were higher (15%) which may be due to lower water depth [13]. We hypothesize that the high contribution of degassing could result of rapid degradation of above ground vegetation and litter since this type of labile organic matter could produce very high amount of CH_4 during the initial phase of the mineralization in anoxic conditions [1]. However, low contribution of diffusive fluxes and bubbling fluxes was due to CH_4 oxidation through long distance between surface and bottom. Annual gross CH_4 emission after 6 years of impoundment through different pathways was estimated to be 1202.8 Mg CH_4 yr^{-1} which was 17 times lower than the gross CH_4 emissions estimated for Petit Saut reservoir (20,501 Mg yr^{-1}) after 6 years of impoundment [13]. However, even after 18 years of impoundment, Balbina reservoir shows 94,900 Mg yr^{-1} [14].

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As suggested by Abril et al., (2005) [13] and Guerin et al., (2008a) [1] the difference in the annual estimates is due to variation in reservoir area, topography, amount of carbon impounded and rate of inflowing organic matter from the catchment. Temperature might also influence methanogenesis

TABLE II. GHG EMISSIONS THROUGH DIFFERENT PATHWAYS IN THE YEAR 2011-2012

Season	Diffusive fluxes	Degassing	Diffusive fluxes at the downstream	Bubbling	Diffusive fluxes at the drawdown area	Total
			(Mg y^{-1})			
Monsoon	30.08	58.3	4.92	14.6	9.2	117.1
Post-monsoon	72.8	188.2	4.95	14.1	0	280.05
Winter	48.9	10.5	4.86	12.3	6.3	82.86
Summer	47.04	587.96	4.27	12.4	71.2	722.87
Total	198.82	844.96	19	53.4	86.7	1202.8
	16.54%	70.24%	1.58%	4.46%	7.15%	

and subsequent emissions, as suggested by Barros et al., (2011) [3] by showing the relationship between CH_4 emission and the latitude.

Net CH_4 emission for the year 2011-2012 was calculated to be 1114.73 Mg yr^{-1}. Net emissions were lower than the gross emission due to pre-impoundment emissions of 88.07 Mg yr^{-1}.

IV. CONCLUSIONS

From the present study, it was confirmed that the seasonal variation of the emissions is significant with 60% of diffusive fluxes and downstream emissions occurring during 3 to 4 months of summer season. Based on an original approach for the extrapolation of the diffusive and bubbling emissions at the reservoir scale, we evidenced a very low contribution of diffusive and bubbling emissions compared to previous studies in the tropics. This study has also explored the spatial–temporal patterns of CH_4 emissions at Tehri reservoir. The data indicate that fluxes from reservoir surface were different from one location to another due to variability in depth, organic carbon present in water column and the varying hydrological conditions among different parts of the reservoir. Major portion of total emissions were contributed by degassing at the downstream (71.82%) while only 16.54% of diffusive and 4.46% of bubbling fluxes came from reservoir surface. Although degassing fluxes were maximum in case of Tehri reservoir, it was lower compared to other tropical reservoirs.

Finally, gross CH_4 emission from Tehri reservoir for the year 2011-2012 was calculated to be 1202.8 Mg yr^{-1}. The results revealed that the CH_4 emissions from Tehri hydropower system were lower than the other tropical hydropower systems, partly due to the higher depth and lower allochthonous organic carbon input from the reservoir catchment. As Tehri reservoir area were source of CH_4 emission before impoundment, net emissions were lower than the gross emissions and the final value calculated to be 1114.73 Mg CH_4 yr^{-1}.

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VI. REFERENCES

[1] F. Guerin, G. Abril, A. de Junet, and M.P. Bonnet, “Anaerobic decomposition of tropical soils and plant material: implication for the CO2 and CH4 budget of the Petit Saut Reservoir”. Appl Geochem, vol. 23, pp. 2272-83, 2008a.

[2] IPCC, “Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [T.F. Stocker, D. Qin, G.-K. Plattner, M. TignorAllen, S.K. Boschung, J. Nauels, A. Xia, Y. Bex and P.M. Midgley (eds.)]”. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1535, 2013.

[3] N. Barros, J.J. Cole, L.J. Tranvik, Y.T. Prairie, D. Bastviken, and V.L.M. Huszar, “Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude”. Nat Geosci, vol. 4, pp. 593–6, 2011.

[4] S. Li, and Q. Zhang, “Carbon emission from global hydroelectric reservoirs revisited”. Environ Sci Pollut Res, vol. 21, pp. 13636–13641, 2014.

[5] V. L. St. Louis, C.A. Kelly, E. Duchemin, J.W.M. Rudd, D.M. Rosenberg, “Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate”. Bioscience, vol. 20, pp. 766-75, 2000.

[6] F. Guerin, and G. Abril, “Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir”. J Geophys Res Biogeosci, vol. 112 pp. G03006, 2007. doi:10.1029/2006JG000393.

[7] F. Guerin, G. Abril, S. Richard, B. Burban, C. Reynouard, and P. Seyler, “Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers”, Geophysical Research Letters, vol. 33, pp. L21407, 2006. doi:10.1029/2006GL027929.

[8] H. Chen, Y. Wu, X. Yuan, Y. Gao, N. Wu, and D. Zhu, “Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir”. Journal of Geophysical Research, vol. 114, pp. D18301, 2009. doi:10.1029/2009JD012410

[9] H. Chen, X. Yuan, Z. Chen, Y. Wu, X. Liu, and D. Zhu, “Methane emissions from the surface of the Three Gorges Reservoir”. Journal of Geophysical Research, vol. 9, pp. D21306, 2011. doi:10.1029/2011JD016244.

[10] T. DelSontro, M.J. Kunz, T. Kempter, A. Wüest, B. Wehrli, and D.B. Senn, “Spatial heterogeneity of methane ebullition in a large tropical reservoir”. Environ Sci Technol, vol.45, pp. 9866-9873, 2011.

[11] D. Bastviken, J.J. Cole, M. Pace, and L. Tranvik, “Methane emissions from lakes: dependence of lake characteristics, two regional assessments, and a global estimate”, Global Biogeochem Cycles, vol. 18, pp. GB4009, 2004. Doi: 10.1029/2004GB002238.

[12] C. Galy-Lacaux, R. Delmas, C. Jambert, J.F. Dumestre, L. Labroue, and S. Richard, “Gaseous emissions and oxygen consumption in hydroelectric dams: a case study in French Guyana”. Global Biogeochemical Cycles, vol. 11, pp. 471–83, 1997.

[13] G. Abril , F. Guerin, S. Richard, R. Delmas, C. Galy-Lacaux, and P. Gosse, “Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana)”. Global Biogeochem Cycles, vol. 19, GB4007, 2005. doi:10.1029/2005GB002457.

[14] A. Kemenes, B.R. Forsberg, J.M. Melack, “Methane release below a tropical hydroelectric dam”. Geophys Res Lett, vol. 34, pp. L12809, 2007. doi:10.1029/2007GL029479.

[15] D. Bastviken, L.J. Tranvik, J.A. Downing, P.M. Crill, and A. Enrich-Prast, “Freshwater methane emissions offset the continental carbon sink”. Science, vol. 7, pp. 3316013-50, 2011.

[16] E. Sahlee, A. Rutgersson, E. Podgrajsek, and H. Bergström, “In-fluence from surrounding land on the turbulence measurements above a lake, Boundary-Layer”. Meteorol, vol. 150, pp. 235–258, 2014.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 08, August-2019

[17] M. Demarty, J. Bastien, and A. Tremblay, "Annual follow-up of gross diffusive carbon dioxide and methane emissions from a boreal reservoir and two nearby lakes in Québec, Canada". Biogeosciences, vol. 8, pp. 41-53, 2011. doi:10.5194/bg-8-41-2011.

[18] C.R. Teodoru, J. Bastien, M-C. Bonneville, P.A. del Giorgio, M. Demarty, M. Garneau, J-F. Hélie, L. Pelletier, Y.T. Prairie, N. Roulet, I Strachan, and A. Tremblay, "The net carbon footprint of a newly-created boreal hydroelectric reservoir". Glob Biogeochem Cycles, vol. 26, pp. GB2016, 2012. doi:10.1029/2011GB004187.

[19] T. DelSontro, D.F. McGinnis, S. Sobek, I. Ostrovsky, and B. Wehrli, "Extreme methane emissions from a Swiss Hydropower Reservoir: Contribution from bubbling sediments". Environtal Science & Technology, vol. 447, pp. 2419-25, 2010.

[20] N. Soumis, E. Duchemin, R. Canuel and M. Lucotte, "Greenhouse gas emissions from reservoirs of the western United States". Global Biogeochem Cycles, vol.18, pp. GB3022, 2004. doi:10.1029/2003GB002197.

[21] V. Chanudet, S. Descloux, A. Harby, H. Sundt, B.H. Hansen, O. Brakstad, D. Serça, and F. Guérin, "Gross CO2 and CH4 emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR". Sci Total Environ, vol. 409, pp. 5382-5391, 2011.

[22] C. Deshmukh, D. Serça, C. Delon, R. Tardif, M. Demarty, C. Jarnot, Y. Meyerfeld, V. Chanudet, P. Guédant, W. Rode, S. Descloux, and F. Guérin, "Physical controls on CH4 emissions from a newly flooded subtropical freshwater hydroelectric reservoir: Nam Theun 2". Biogeosciences Discuss, vol. 11, pp. 3271–3317, 2014.

[23] C. Deshmukh, F. Guérin, S. Pighini, A Vongkhamsao, P. Guédant, W. Rode, A. Godon, V. Chanudet, S. Descloux, and D. Serça, "Low methane (CH4) emissions downstream of a monomictic subtropical hydroelectric reservoir (Nam Theun 2, Lao PDR)". Biogeosciences Discuss, vol. 12, pp. 11313–11347, 2015.

[24] S. Li, and R.T. Bush, "Revision of methane and carbon dioxide emissions from inland waters in India". Global Change Biology, vol. 21, pp. 6–8, 2015a.

[25] S. Li, Q. Zhang, R.T. Bush, and A. Leigh, "Sullivan Methane and CO2 emissions from China's hydroelectric reservoirs: a new quantitative synthesis". Environ Sci Pollut Res, vol. 22, pp. 5325–5339, 2015b.

[26] B. Panneer Selvam, S. Natchimuthu, L. Arunachalam and D. Bastviken, "Methane and carbon dioxide emissions from inland waters in India - implications for large scale greenhouse gas balances". Global Change Biology, vol. 20:11, pp. 3397-3407, 2014.

[27] Z. Zhao, B.F. Wu, and Y. Zeng, "Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China". Biogeosciences, vol. 10, pp. 1219–1230, 2013.

[28] A. Kumar, T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J-M. Devernay, M. Freitas, D. Hall, A. Killingtveit, and Z. Liu, "Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)". Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.

[29] S.K. Jain, P.K. Agrawal, and V.P. Singh, "Tehri dam project, Hydrology and water Resources in India". Water science and technology library, pp. 408-413, 2007.

[30] B. Kolb and L.S. Ettre, "Static Headspace-Gas Chromatography, Theory and Practice". Second Edition, John Wiley & Sons, pp. 349, 2006.

[31] H.M. McNair, and J.M. Miller, "Basic gas chromatography. 2nd edition". Published by John Wiley and Sons:233, 2009.

[32] H.H. Willard, Jr. L.L. Merritt, J.A. Dean, and Jr F.A. Settle, "Instrumental methods of analysis. 7th edition 1988". Wadsworth Publishing Company, pp. 895, 1988.

[33] S. Yamamoto, J.B. Alcauskas, and T.E. Crozier, "Solubility of methane in distilled water and seawater". J Chem Eng Data, vol. 21, pp. 78-80, 1976.

[34] P.A. Raymond, and J.J. Cole, "Gas exchange in rivers and estuaries: Choosing a gas transfer velocity". Estuaries, vol. 24, pp. 312–317, 2001.

[35] A.H. Devol, J.E. Richey, B.R. Forsberg, and L.A. Martinelli, "Seasonal dynamics in methane emissions from the Amazon River floodplain to the troposphere". J Geophys Res, vol. 95, pp. 16417-16426, 1990.

[36] M. Keller, and R.F. Stallard, "Methane emission by bubbling from Gatun lake panama". J Geophys Res, vol. 99 (D4), pp. 8307–8319, 1994.

[37] P.M. Fearnside, "Greenhouse Gas Emissions from Hydroelectric Dams: Controversies Provide a Springboard for Rethinking a Supposedly 'Clean' Energy Source". Climatic Change, vol. 66,(2-1), pp. 1-8, 2004.

[38] S.A. MacIntyre, M. Jonsson, J. Jansson, D.E. Aberg, Turney, S.D. Miller, "Vuoyancy flux, turbulence, and the gas transfer coefficient in a stratified lake". Geophys Res Lett, vol. 37, pp. 24:L24604, 2010.

[39] J. Tremblay, B. Therrien, E. Hamlin, L. Wichmann, and Le. Drew, "GHG emissions from boreal reservoirs and natural aquatic ecosystems". In: A. Tremblay, L. Varfalvy, C. Roehm, M. Garneau (Eds.), Greenhouse Gas Emission–Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments, Springer, New York, 209–232, 2005.

[40] Y.P. Xing, P. Xie, H. Yang, L.Y. Ni, Y.S. Wang, and K.W. Rong, "Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical lake in China". Atmos Environ, vol.39, 30, 5532–5540, 2005.

[41] J.F. Dumestre, J. Guezennec, C. Galy-Lacaux, R. Delmas, S. Richard, and L. Labroue, "Influence of light intensity on methanotrophic bacterial activity in the Petit Saut reservoir, French Guiana". Appl Environ Microbiol, vol. 65, pp. 534-539, 1999.

[42] E. Topp, and E. Pattey, "Soils as sources and sinks for atmospheric methane". Canadian Journal of Soil Science, vol. 77, 2, 167–178, 1997.

[43] M.A. dos Santos, B. Matvienko, L.P. Rosa, E. Sikar, E.O. dos Santos, "Gross greenhouse gas emissions from Brazilian hydro reservoirs. In: Tremblay A, Varfalvy L, Roehm C, Garneau M, editors. Greenhouse gas emissions — fluxes and processes". Hydroelectric reservoirs and natural environments, Berlin: Springer Verlag, pp.267–91, 2005.

[44] M.A. dos Santos, L.P. Rosa, B. Sikar, E. Sikar, E.O. dos Santos, "Gross greenhouse gasfluxes from hydro-power reservoir com-pared to thermo-power plants". Energy Policy, vol. 34, pp. 481–488, 2006. doi:10.1016/j.enpol.2004.06.015

[45] Fearnside, "Do hydroelectric dams mitigate global warming? The case of Brazil's Curná–Una dam". Mitig Adapt Strat Glob Change, vol. 10,4, pp. 675– 69, 2005.

[46] P. Rautela, R. Rakshit, V.K. Jha, R.K. Gupta, and A. Munshi, "GIS and remote sensing-based study of the reservoir-induced land-use/land-cover changes in the catchment of Tehri dam in Garhwal Himalaya, Uttaranchal (India)". Current Science, vol. 83:3, pp. 308-311, 2002.

[47] A.M. Blais S. Lorrain, and A. Trembley, "Greenhouse Gas Fluxes (CO2, CH4 and N2O) in Forests andWetlands of Boreal, Temperate and Tropical Regions, in Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments (Eds. Tremblay A, Varfalvy L, Roehm C, Garneau M)". Environmental Science Series, Springer, Berlin, 87, 2005.

[48] P. Casper, S.C. Maberly, G.H. Hall, and B.J. Finlay, "Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere". Biogeochemistry, vol. 49, pp. 1-19, 2000.

[49] C. Galy-Lacaux, R. Delmas, G. Kouadio, S. Richard, and P. Gosse. "Long term greenhouse gas emission from a hydroelectric reservoir in tropical forest regions". Global Biogeochemical Cycles, vol. 13, pp. 503-517, 1999.

[50] L.P. Rosa, M.A. Dos Santos, B. Matvienko, E. Sikar, R.S.M. Lourenço, and C.F. Menezes, "Biogenic gas production from major Amazon reservoirs". Brazil Hydrol Process, vol. 17, pp. 1443-1450, 2003.

[51] J. Le Mer, and P. Roger, "Production, oxidation, emissions and consumption of methane in soils: a review". Eur J Soil Biol, vol. 37, pp. 25-50, 2001.