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Carbon Dioxide Emission from a Reservoir in India

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Abstract

Large number of scientific studies have been conducted on hydropower reservoirs in last two decade which shows high carbon dioxide (CO_2) fluxes emissions from hydropower reservoirs especially in tropical region. There are very few studies conducted in India for this subject area, present study aims to find out the detailed nature and extent of CO_2 emissions from a Tehri hydropower reservoir in India. Gross CO_2 emission in the form of diffusive, bubbling and degassing were measured at multiple locations on the reservoir surface and at the downstream. Our results show that Tehri reservoir area was sink of atmospheric CO_2 before impoundment and all the sampling locations were the sources of CO_2 to the atmosphere after impoundment. At the reservoir surface, CO_2 fluxes and bubbling emissions were found in the range of −430 to 1482 mg m^{-2} d^{-1} and 8.2 to 21.2 mg m^{-2} d^{-1} respectively, whereas downstream emissions were consist of degassing emission (22 to 87 Mg d^{-1}) and diffusive fluxes (219 to 461 mg m^{-2} d^{-1}). These values are comparable to other tropical reservoirs. Sometimes, the reservoir surface acted as a sink for atmospheric CO_2 at shallow locations. While at the reservoir surface, higher temperature and allochthonous carbon inputs led to a relatively higher CO_2 emissions in pre-monsoon (982.8 ± 212 mg m^{-2} d^{-1}) and summer (1012.7 ± 203 mg m^{-2} d^{-1}) season compared to winter (737.1 ± 127 mg m^{-2} d^{-1}) and monsoon (702.3 ± 202 mg m^{-2} d^{-1}) season. This study has also explored the spatial variation of CO_2 emissions at Tehri reservoir where reservoir surface contributed 75% diffusive fluxes, 21% bubbling fluxes and downstream emission contributed 4% of the total CO_2 emission. The tentative annual calculation indicates that Tehri reservoir is a source of CO_2 with gross CO_2 emission of about 0.30 ± 0.15 Gg CO_2 km^{-2} yr^{-1} and net CO_2 emission of 26.89 Gg CO_2 yr^{-1}.

Keywords: Carbon dioxide, greenhouse gas, reservoir, emissions, tropical ecoregion

1 Introduction

One of the purpose for creation of reservoirs is hydropower generation by using stored water in the reservoir and was widely considered aa a clean and renewable source of energy, highly desirable in today's changing climate conditions. However, "climate neutrality" of hydropower in recent years has been questioned since knowledge on greenhouse gas emissions (GHG) from reservoirs has increased (Fearnside, 2004; Giles, 2006, St. Louis et al., 2000). Although, the process of carbon emission from inland water to the atmosphere is natural (Cole et al., 2007), hydropower reservoirs are considered as it produce and emit more carbon compared to natural systems, especially during the initial years (20 years) after submergence (Barros et al., 2011). Carbon dioxide (CO_2) is one of the main greenhouse gas emitted from both natural aquatic ecosystems and manmade reservoirs (Borges and Frankignoulle 2002; Gurney et al., 2002; Richey et al., 2002). CO_2 is produced from the decomposition of the flooded organic matter under aerobic (Fearnside et al., 2005) or anaerobic (Abril et al., 2005) conditions after the impoundment. The magnitude of the fluxes depends on the physico-chemical characteristics of the reservoir and the input of organic carbon from the catchment (Duchemin et al., 2000; Rosa et al., 2002; Huttunen et al., 2002). Carbon sources in the reservoirs included the flooded organic matter in the original forests, soils, vegetations, allochthonous input from terrestrial ecosystems and photosynthetic fixation by phytoplankton at the reservoir's surface (Abril et al., 2005; Zhao et al., 2008; Fearnside, 2012).

Once produced, CO_2 is emitted to the atmosphere via several pathways, i.e. diffusion, ebullition and degassing (Galy-Lacaux et al., 1997; Abril et al., 2005; Guerin et al., 2006; Kemenes et al., 2007). Diffusive and bubbling fluxes release at the surface of the reservoir and degassing emissions releases at the downstream of the dam. Emissions were reported in both boreal (Duchemin, et al., 1995; Demarty et al., 2009; 2011; Teodoru et al., 2011) and tropical (Abril et al., 2005; Guerin et al., 2008a; Roland et al., 2010) hydropower reservoirs. However, these datasets showed that CO_2 fluxes are significantly higher in tropical region than in the boreal region (Barros et al., 2011). Very few studies have considered all important parameter affecting the gas emissions from hydropower systems, and more data is necessary especially in the country like India where very few studies are done and most of the constructed dams fall in tropical to subtropical ecoregion (ICOLD, 2007). Present study discusses the results of a detailed investigation of CO_2 emissions from the Tehri hydropower system in India which include year-round measurements of CO_2 emission from multiple sampling stations on the reservoir surface, upstream and downstream of the dam.

2 Site description, sampling strategy and methodology

2.1 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 completed and commissioned in

2006, flooded over 42.5 km^2 area out of 7502 km^2 of catchment area with reservoir water storage capacity of 3.2 million m^3. 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 - December), winter (January - February) and summer (March - May) seasons (Kumar and Ram, 2005). In summer, the temperture 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 km^2) and minimum (140 m) at the pre-monsoon season (reservoir area of 18 km^2).

2.2 Physico-chemical parameters in the reservoir

Thermal and chemical properties of Tehri reservoir were analyzed by collecting and analyzing water samples at 18 different locations spread over the reservoir surface, upstream and downstream as shown in Figure I. 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 4.32 to 5.39 m s^{-1} and 1000 to 2000 mm respectively. Considering seasonal variations, sampling were done four times in year 2011–2012.

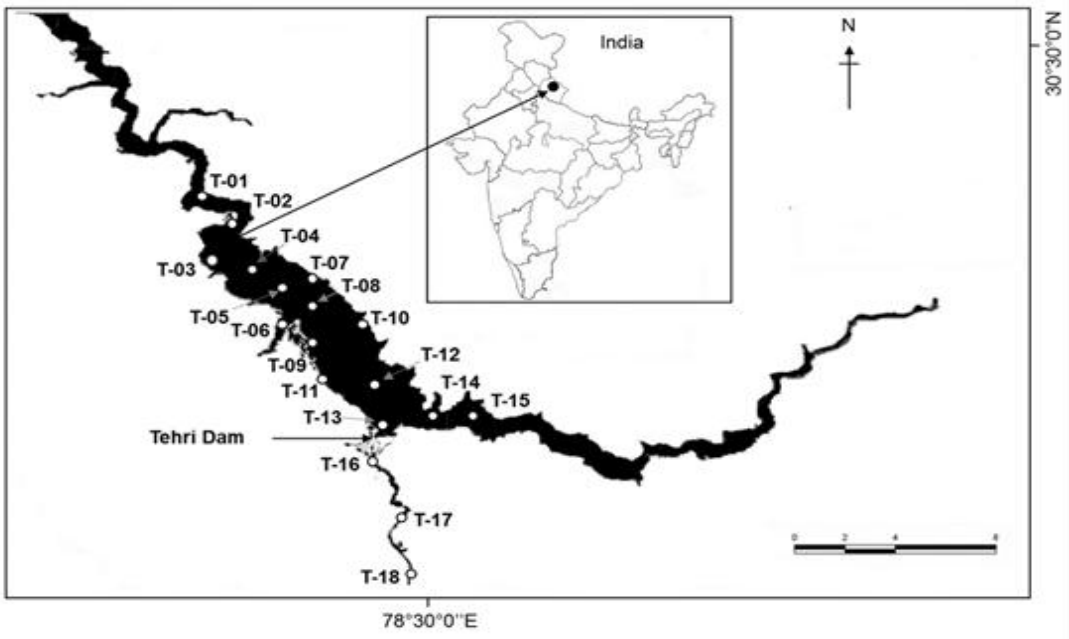

Fig I. Location map of Tehri reservoir and the sampling station

Vertical profiles of temperature, dissolved oxygen concentration (DO), conductivity and chlorophyll (Chl-a), pH were measured using a Hydrolab multiparametric sonde (DS5X). Water samples were collected at 10 m depth interval to measure dissolved CO_2 and other carbon species i.e. dissolved organic carbon (DOC), dissolved inorganic carbon (DIC). Water samples for organic and inorganic carbon analysis were stored in 150 ml HDPE bottles at 0 °C in a cool box and analyzed within 2 days using IR spectrophotometry and automated carbon analyzer. Water samples for CO_2 concentrations were stored in 60 ml serum bottles which were sealed and injected with $HgCl_2$ (Guerin and Abril., 2007). Dissolved gas concentrations were determined with the headspace method by equilibrating equal volumes of water and air in the sampling syringe (Kolb and Ettre, 2006). CO_2 concentration were determined using a Netel Michro 9100 gas chromatograph equipped with flame ionization detector (FID) and a FID methanizer. Methodology described by McNair and Miller (2009) and Willard et al., (1998) were used to prepare samples and run tests. Commercial standards at 2 to 1000 ppmv were used for calibration. Duplicate injection of samples showed reproducibility better than 5%. The specific gas solubility for CO_2 (Weiss, 1974) was used for calculation of total CO_2 concentrations dissolved in water. To determine CO_2 emissions from the Tehri hydropower reservoir, regular measurements of diffusive fluxes, bubbling and degassing emissions were made.

2.3 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). 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, it was allowed to drift freely during deployment (Raymond and Cole, 2001) and the lower 3 cm of the vertical chamber wall was submersed. During each flux measurement, three gas samples were collected from the chamber at 15 min intervals with 60 ml polyethylene syringes and stored in 10 ml glass serum vials flushed with N_2 and covered with high density butyl rubber stoppers until analysis (Devol et al., 1990). Collected gas samples were analyzed within 48 hours using gas chromatography. CO_2 fluxes were calculated from the slope of the linear regression of gas concentration in the chamber versus time. The fluxes were accepted when the determination coefficient (R^2) of the linear regression was higher than 0.8.

2.4 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 (Keller

and Stallard, 1994). Sets of funnels were placed above the water surface, at various depth ranging from 0 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.

2.5 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 CO_2 in the hypolimnion releases into the atmosphere when the water passes through the turbines due to the abrupt decrease in pressure and the increase in water temperature (Fearnside, 2004). These emissions are degassing and diffusive fluxes and their influence ranged from a few meters up to 50 km downstream in the river (Abril et al., 2005). Degassing at the downstream of the dam was calculated using the difference between the gas concentration upstream and downstream of the structure multiplied by discharge (Galy-Lacaux et al., 1997). Gas concentrations were computed by collecting water samples at turbine intake and downstream of the structure. Diffusive fluxes at the downstream were computed by applying the gas concentration on thin boundary layer equation using formulation of k_{600} from study done by MacIntyre et al., (2010). In four different seasons, 12 degassing emission values were computed. However, 36 diffusive fluxes measurements were made at location T-16, T-17 and T-18 located at the 500m 1000m, 1500m respectively from the turbine.

2.6 Statistical Analysis

Mean CO_2 fluxes were calculated by averaging all the replicates at each sampling site. One way analysis of variance (ANOVA) was used to analyze the differences in GHG fluxes from different sites. Normal distribution of data was performed. GHG fluxes were related to environmental variables by 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.

2.7 Estimate of annual GHG emissions

Due to the large spatial variation and temporal variation, there is high fluctuation in the CO_2 emission and averaging all the measured values at different location may give wrong estimate. For accurate estimate, reservoir area was divided into three sub region according to the depth and type of emissions i.e. rim area where the depth < 30 m, middle of the reservoir where depth > 30 m and downstream of the reservoir. Water surface areas at different water level were extracted using a 10-m resolution digital elevation map. Linear relationships between water level and surface water area for different water level were then established using a regression analysis and the surface area at different water levels were calculated. Area-weighted seasonal

average emissions from Tehri reservoir were calculated by multiplying water surface area for that period. GHG fluxes of unmeasured area were interpolated using the values of the two nearest measured location. Annual gross estimates were calculated by summing up all the estimates for diffusion, bubbling and degassing emission. Finally, net emissions were calculated by deducting pre-impoundment CO_2 emissions values from the gross emissions. Total average CO_2 fluxes were estimated by dividing the total CO_2 emissions by the total surface area of Tehri reservoir at full capacity; these results were compared to other reservoirs around the world.

3 Results and discussion

3.1 Physico-chemical parameters in the reservoir

Thermal and chemical stratification was stronger during summer and pre-monsoon season (Figure II). Fluctuation in the water temperature has an impact on the CO_2 solubility (Zhao et al., 2008), primary production (Lu et al., 2007) and the decomposition of organic carbon (Lu et al., 2007). Hence, verticle profile of water temperature were measured. Throughout the year water temperature varies from 10°C to 25°C. Epilimnic water temperature was highest during pre-monsoon (22.2 ± 3.6 °C) and summer (23.1 ± 3.7 °C), it rose up to 25°C whereas the hypolimnic temperature was observed in the range of 10 - 13 °C. The difference of 10 ± 2°C was observed between epilimnion and hypolimnion during pre-monsoon, monsoon and summer season, however, in winter these temperature difference was 3 - 5°C only. The epilimnion was oxic (7.0 to 8.5 mg l^{-1}) and DO level abruptly dropped to anoxic level in metalimnion (at 40 to 100 m depth) as well as in hypolimnion (at 100 to 240 m depth) (Figure II).

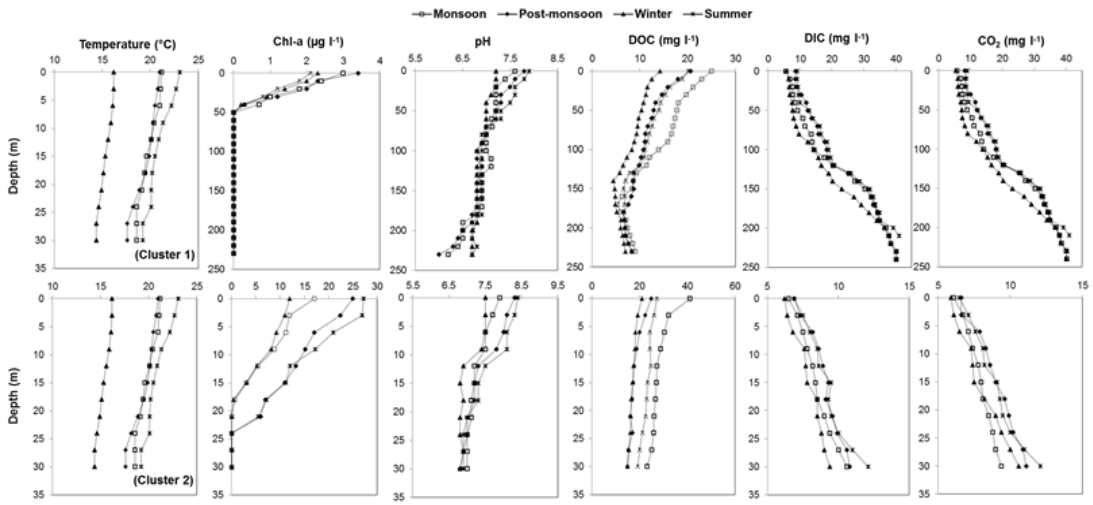

Fig II. An example of vertical profile of temperature, dissolved Oxygen, chlorophyll a, pH, dissolved organic carbon, dissolved inorganic carbon and CO_2 concentration at Cluster 1 (upper pannel) and Cluster 2 (lower pannel).

DOC concentrations were observed high in the inflowing rivers and reservoir surface (10.3 – 30.3 mg l^{-1}), due to the contribution of humic substances leaching from forest soils. This high-DOC background often masks some small changes due to internal biogeochemical processes in the reservoir. For instance, during the pre-monsoon and summer season, a significant trend of high DOC at the epilimnion was often observed due to the presence of particulate organic matter as well as high primary production. Intense releases of DOC during phytoplankton blooms have been reported in the ocean (Meon and Kirchman, 2001) and in reservoirs (Mash et al., 2004).

pH level influences the CO_2 concentrations in the water by favouring the formation of bicarbonate at the alkaline conditions, which leads to an undersaturation of dissolved CO_2, promoting the absorption of atmospheric CO_2 (Tremblay et al., 2005). The pH critical values are often reported to be 7.9 – 8.5 between CO_2 absorption and emission (Peng et al., 2012; Tremblay et al., 2005). At deep water locations, pH observed at the epilimnion varied from 6.7 to 7.9 and decreases gradually in metalimnion and hypolimnion (5.5 to 6.5). At shallow water locations, pH value at the epilimnion was more than 8 ± 0.5. Hence, reservoir surface was both source and sink of CO_2 especially at the shallow water locations. Notably, higher chl-a concentration at the shallow water locations (30 – 40 µg l^{-1}) support the higher rate of primary production compare to deep water location (2 to 3.5 µg l^{-1}). Such influence of pH on CO_2 emissions in the reservoir's surface was observed in the five reservoirs in Wujiang River in China (Peng et al., 2012), the reservoirs in the western United States (Soumis et al., 2004), and the reservoirs in eastern Canada (Tremblay et al., 2005). Turbidity at the surface water was observed varying from 6.4 - 46.3 NTU. Maximum turbidity was observed during monsoon season. This may be due to high silt flushed to the reservoir water with the inflow during monsoon. As secci depth is inversely praportional to turbidity, it was higher during winter season (1.2 m) and lower during monsoon season (0.8 m).

3.2 Vertical profile of dissolved CO_2

3.2.1 In water column

Vertical profile of CO_2 on the basis of CO_2 solubility at given temperature were measured at different locations and is shown in Figure II. Throughout the year, water column exhibited thermal and chemical stratification, resulting in the higher concentration of CO_2, in the hypolimnion (20 - 41 mg l^{-1}) than in the epilimnion (6 - 13 mg l^{-1} of CO_2). Notably, DOC concentration were higher in epilimnion than hypolimnion. Positive relationship between dissolved CO_2 and DIC suggests a dependency of hetertrohic pelagic or benthic respiration on availability of organic matter. Lower concentration at the epilimnion was due to evasion that occurs at the air-water interface (Wanninkhof, 1992) and photosynthetic activity in the upper water column of the reservoir. Photosynthetic activity was conformed by the presence of Chl-a (2 - 30 µg l^{-1}) in the upper water column.

Spatial heterogeneity in the epilimnic CO_2 concentrations was not significant as

opposed to the hypolimnic CO_2 concentration ($p = 0.024$, one way ANOVA test) due to physical and hydrodynamical condition in the water column. Statistical analysis for the epilimnic CO_2 concentration suggested three cluster in sampling locations throughout the year ($p = 0.04$, one way ANOVA test), Cluster 1 : T-04, T-05, T-08, T-10, T-12 and T-13 where water depth is high (> 30 m) and 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, T-02, T-14, and T-15 at the upstream of reservoir. The difference of CO_2 concentration in epilimnion and hypolimnion was higher in cluster 1 as compared to cluster 2. Similar pattern of CO_2 profiles were often observed in stratified tropical reservoirs (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007; 2011).

At cluster 1, epilimnic CO_2 concentration during pre-monsoon and summer season were significantly different compared to monsoon and winter season ($p = 0.032$, one way ANOVA analysis) due to strong thermal and chemical stratification during pre-monson and summer. Epilimnic CO_2 concentration was highest during pre-monsoon (8.0 ± 3.7 mg l^{-1}) and summer (8.6 ± 3.5 mg l^{-1}) season due to lower water level and higher temperature (16° C to 25° C). However, in the same cluster lower CO_2 concentrations were observed during monsoon (5.6 ± 3.6 mg l^{-1}) and winter (5.3 ± 4.7 mg l^{-1}) season as high inflow rate and regular mixing of rainwater in monsoon season dilute the CO_2 concentration. Lower temperature in winter affect the decomposition rate and create more homogenious vertical profile from epilimnion to hypolimnion. Epilimnic CO_2 concentration at cluster 2 were not significantly different ($p = 0.62$), and their values during pre-monsoon, monsoon, winter and summer season were 6.2 ± 3.9 mg l^{-1}, 5.9 ± 3.6 mg l^{-1}, 6 ± 2.5 mg l^{-1} and 6.1 ± 3.1 mg l^{-1} respectively. At the upstream of the reservoir, dissolved CO_2 concentration in the inflowing river varied from 3 to 7 mg l^{-1} (cluster 3). Turbine water intake is located at a depth of 188 m from surface therefore when turbines were operated, homogeneous vertical profile of CO_2 was observed at T-13 due to mixing epilimnic and hypolimnic water. This mixing of water creates destratification results into higher epilimnion concentration (9.6 ± 3.4) and lower hypolimnion concentration (16.32 ± 6.4 mg l^{-1}) compared to other locations.

At deep water locations (cluster 1) CO_2 concentration shows positive correlation with temperature. Tremblay et al., (2005) and Therrien et al., (2005) also showed positive correlation with temperature in boreal and semi-arid reservoirs. However, at shallow location (cluster 2) due to primary production, the elevation in the water temperature promotes CO_2 absorption (Lu et al., 2007). CO_2 absorption is confermed by presence of higher chl-a concentration (20 - 30 µg l^{-1}). Similiarly, CO_2 concentration shows positively correlation with DIC and negatively correlation with pH and Chl-a concentration in water column.

3.2.2 At the downstream

CH_4 concentration at the downstream locations T-16, T-17 and T-18 were not significant ($p < 0.05$). CO_2 concentration at the downstream location reflected the water composition at T-13 location (near to turbine water intake).

CO_2 concentration at the downstream varried from 3.5 – 9.1 mg l^{-1} with an average value of 8.04 ± 5.5 mg l^{-1} suggesting seasonality with maximum concentration during summer (8.7 ± 3.2 mg l^{-1}) and pre-monsson (8.3 ± 2.9 mg l^{-1}) whereas minimum during monsson (6.8 ± 2.2 mg l^{-1}) and winter season (6.7 ± 3.4 mg l^{-1}). However, CO_2 concentration decreases gradually from T-16 to T-18 during summer from 8.7 ± 3.2 to 6.7 ± 2.3 mg l^{-1}, pre-monsson from 8.3 ± 2.9 to 6.4 ± 2.8 mg l^{-1}), monsson from 6.8 ± 2.2 to 5.5 ± 1.2 mg l^{-1}, winter from 6.7 ± 3.4 to 5.4 ± 1.5 to mg l^{-1}). CO_2 conccentration at the downstream was about 10 times higher than the natural river. CO_2 concentrations at the water release from spillways was lower (2.5 – 5.3 mg l^{-1}) than at the turbine outlet as spillways outlet is located at the full reservoir level with lower CO_2 concentration and water release from the spillway happens only during monsoon season and flood events.

3.2.3 Comparison with other reservoirs

Similar seasonal pattern of CO_2 profiles are often observed in stratified tropical reservoirs (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007; 2011, Deshmukh et al., 2012). The average CO_2 concentrations in the hypolimnion of the Tehri reservoirs were in the lower range compared to other tropical reservoir (Table 1). However, average CO_2 concentration in the epilimnion was higher than all the previously published data except for Nam Theun 2 reservoir and Petit Saut reservoir in December 2003 (Table 1). Lower epilimnic CO_2 concentration in other reservoirs is likely to be a consequence of the age difference (Abril et al., 2005) as all the other reservoirs were older than Tehri reservoir.

3.3 Pre-impoundment emission

Pre-impounded emissions were computed on the basis of land use classification for Tehri reservoir before impoundment (Rautela et al., 2002) and CO_2 emissions values for various type of ecosystem exist in the impounded land. Values of CO_2 emissions for different ecosystem were obtained from literature (Blais, 2005) for the same ecoregion. CO_2 fluxes from the river channel were measured at the upstream of the river and is calculated to be 927 ± 120 mg m^{-2} d^{-1}. Estimates of CO_2 emissions for different land use type were added together and average annual emission were estimated to be –0.118 Gg CO_2 yr^{-1} .

3.4 Post-impoundment CO_2 Emissions

3.4.1 Diffusive CO_2 fluxes emission

During the different field campaigns, 216 floating chamber measurements were made (with three replicates at each location). CO_2 emission exhibit high temporal and spatial variability as shown in Figure III. Spatial variations in the diffusive fluxes were similiar to observations described in section 3.2.1 for epilimnic CO_2 concentration. One way ANOVA test ($p < 0.05$) suggest 3 clusters in sampling

locations. Negative CO_2 fluxes were observed at cluster 2 for some time during summer and pre-monsoon due to primary production, indicated by high Chl-a concentration, DO and pH. During primary production most of the dissolved CO_2 get utilized by phytoplankton and further uptake from atmosphere count as negative fluxes (Anesio and Graneli, 2003). Also, at these locations, continuous flushing of municipal waste from nearby civil area leads to the eutrophication indicated by higher nutrient availability (Total phosphorous 3.3 ± 1.3 mg l^{-1} and total nitrogen 2.1 ± 0.5 mg l^{-1}). Negative fluxes were also observed by dos Santos et al., 2006 and Chanudet et al., 2011 for tropical reservoirs Tres Marias in Brazil and Nam Ngum in Laos respectively (Table 1). However, diffusive fluxes values for upstream and downstream locations evidenced spatial heterogeneity compared to all the other sampling locations.

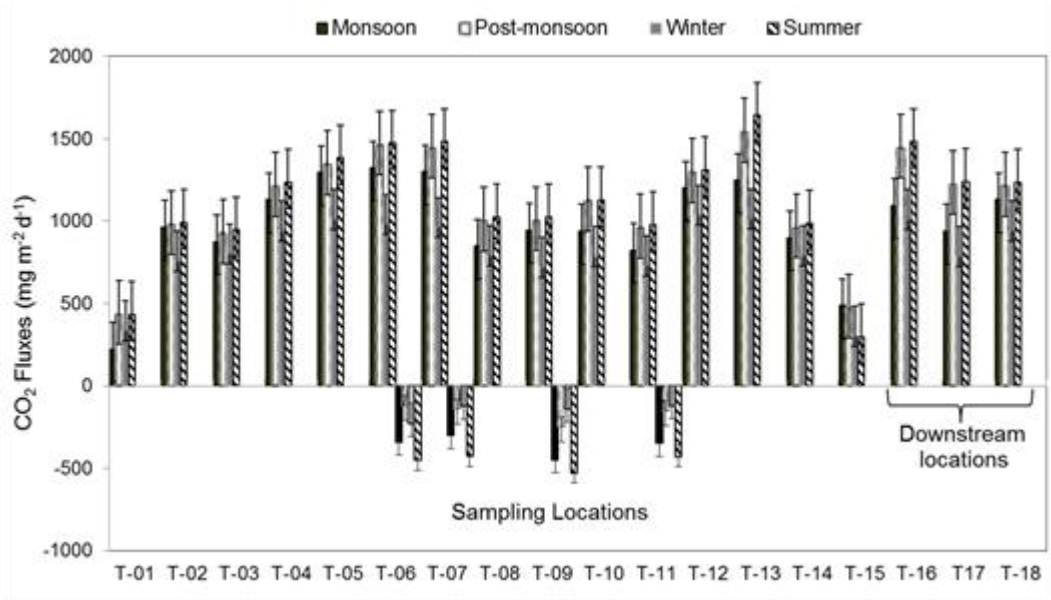

Fig III. CO_2 emission through surface fluxes at different sampling location

Considering seasonal variations, during summer and pre-monsoon season at every sampling location, CO_2 fluxes were not significantly different with their average diffusive fluxes ($p = 0.24$ one way ANOVA test). However, during winter and monsoon season, average fluxes values were significantly different ($p = 0.02$, one way ANOVA test). Maximum CO_2 emission were observed during summer (1012.7 ± 203 mg m^{-2} d^{-1}) while minimum were observed during winter (737.1 ± 127 mg m^{-2} d^{-1}). As suggested by Rosa et al., (2002) and Donahue et al., (1998), these variations could be due to the variations in temperature and anthropogenic organic carbon transported in the different seasons impacting the water quality, photo oxidation and decomposition rate.

CO_2 emission observed throughout year ranged from −430 to 1482 mg m^{-2} d^{-1}. Throughout the year, considering cluster 1 and 2, the area weighted average CO_2 fluxes for Tehri reservoir was calculated to be 950 ± 65 mg m^{-2} d^{-1}. These results

were in lower range than results observed for tropical reservoir in the world as shown in Table 1.

Table I. Comparison of average GHG emissions from Tehri reservoir with the other reservoirs located in various ecoregion

Reservoir	Location	Climate	Age ofreservoir (year)	Area (km^2)	CO_2 (mg m^{-2} d^{-1})	Emission Pathways	Reference
Laforge 1	Canada	Boreal	4	1288	2061.84	Diffusion and Bubbling	Tremblay et al. (2005)
Laforge 2	Canada	Boreal	20	260	832.92		
La Grande 3	Canada	Boreal	20	2420	1707.2		
La Grande 4	Canada	Boreal	20	765	1177.88		
Robert-Bourassa	Canada	Boreal	24	2835	1705.88		
Lokka	Finland	Boreal	14	417	1540	Diffusion and Bubbling	Huttunen et al. (2003)
FD Roosevelt	U.S.	Temperate	59	306	−435.16	Diffusion and Degassing	Soumis et al. (2004)
Dworshak	U.S.	Temperate	28	37	−1030		
Wallula	U.S.	Temperate	47	157	−417.12		
Shasta	U.S.	Temperate	57	77	1364.88		
Balbina	Brazil	Tropical	17	2360	3344	Diffusion and Degassing	Guerin et al. (2006)
Samuel	Brazil	Tropical	16	540	42944		
Itaipu	Brazil	Tropical	14	1350	1205.16		
Three Gorges Reservoir	China	Subtropical	7	1084	4231.04	Diffusion	Zhao et al., 2013
Tehri	India	Tropical	6	42	1467.9	Diffusion, Bubbling and Degassing	Present study

3.4.2 Bubbling emissions

Due to high solubility of CO_2 in water, CO_2 content in the sampled bubbles was not significant. CO_2 bubbles were observed only at locations T-03, T-06, T-07, T-09 and T-11 (at the reservoir rim) where depth is less than 30 m as shown in Figure IV. As the other location were deep (> 30 m), long traveling path favours dissolution of the bubbles emitted from the sediment before reaching to surface (McGinnis et al., 2006). Sixty measurements were taken at the selected locations during four seasons. The observed bubbling emissions varied from 8.2 to 21.2 mg m^{-2} d^{-1} (average 5.9 ± 8.8 mg m^{-2} d^{-1}) is very low compared to diffusive fluxes because of high solubility of CO_2. Considering seasonal variation, bubbling emission at various location, were significantly different than their average values ($p < 0.05$, one way ANOVA test). The

average bubbling emissions were slightly higher than the results obtained by dos Santos et al., (2006) at Tres Marias (4.01 mg m^{-2} d^{-1}) and Serra da Mesa reservoir (1.5 mg m^{-2} d^{-1}) in Brazil.

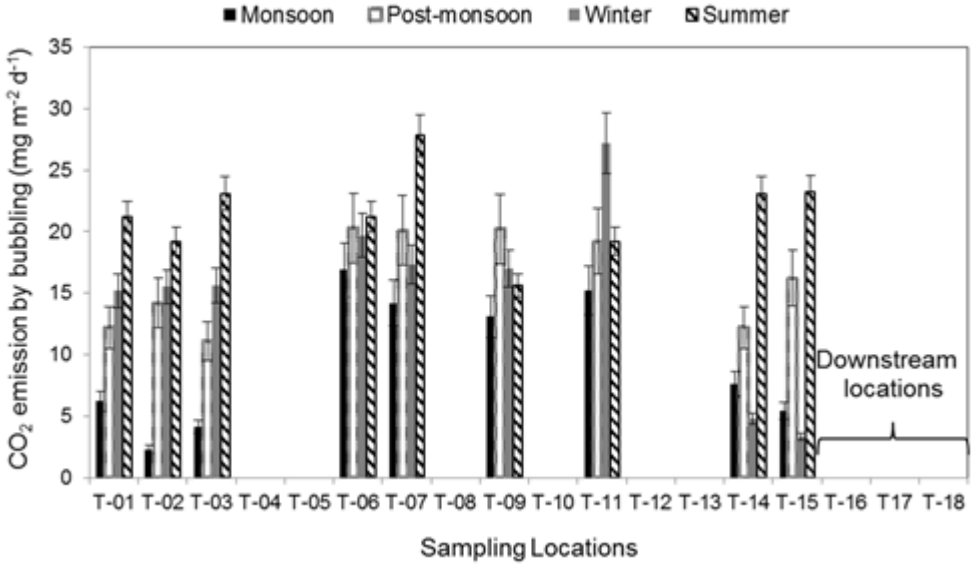

Fig IV. CO_2 emissions by bubbling at different sampling locations

3.4.3 Degassing and diffusive emission at the downstream locations

Downstream emissions consists of degassing and diffusive fluxes. Most of the dissolved CO_2 is released by degassing at the turbine outlet and remaining is transported downstream, and gradually released to the atmosphere by diffusion. Throughout the year 48 measurements were made in four different seasons at downstream locations located at the 0 m, 1000 m and 2000 m interval from turbine outlet. Degassing efficiency at T-16 was 65%. These values are higher than in the Petit Saut Reservoir (18%) (Abril et al., 2005), Balbina Reservoir (51%) (Kemenes et al., 2007) and Nakai dam (54%) (Deshmukh et al., 2013). The higher degassing efficiency in Tehri was probably due to a difference in structure design of the dams. Also, high head in Tehri dam creates high turbulence in released water. The average CO_2 degassing emissions at the downstream range from 22 to 87 Mg d^{-1} (average 81.06 ± 7.4 Mg d^{-1}) and diffusive fluxes range from 219 to 461 mg m^{-2} d^{-1} (average 343.4 ± 69.98 mg m^{-2} d^{-1}) as shown in Figure III. With the varying water discharge in different seasons, the CO_2 degassing varies throughout the year. It reflects the seasonal variation of CO_2 concentration at location T-13 (turbine water intake) and water discharge. Lowest values of diffusive fluxes were observed during monsoon (72 ± 34 mg m^{-2} d^{-1}) and winter (63 ± 25 mg m^{-2} d^{-1}) season when the CO_2 concentrations were at the lowest at T-13 location. The highest degassing fluxes were observed in summer (450 ± 123 mg m^{-2} d^{-1}) and pre-monsoon (392 ± 89 mg m^{-2} d^{-1})

when CO_2 concentrations were the highest. Throughout the year, maximum diffusive fluxes were observed at nearest location from the turbine i.e. T-16 and it decreased as distances increases downstream from the turbine. Diffusive fluxes during summer season at T-16 drops from 461 mg m^{-2} d^{-1} to 328 mg m^{-2} d^{-1} at T-18 location where as minimum value at T-18 location during winter season drops from 348 mg m^{-2} d^{-1} to 219 mg m^{-2} d^{-1}. Similar seasonal variation were observed at the downstream of Nakai dam, Petit Saut dam and Balbina dam (Chanudet et al., 2011; Abril et al., 2005; Kemenes et al., 2011). The results of degassing fluxes were in the range of results found by Deshmukh (2013) at Nakai dam in Lao, PDR (82 ± 63 Mg d^{-1}) and Kemenes et al., (2011) at Balbina reservoir (367 Mg d^{-1}). However it was higher at Petit Saut reservoir (27 Mg d^{-1}) after 6 years of impoundemnet (Abril et al., 2005).The results of diffusive fluxes were very low compared to the results found at Nakai dam in Lao PDR (26796 ± 19580 gm m^{-2} d^{-1}, Deshmukh, 2013) and Petit Saut Dam in French Guiana (41,800 gm m^{-2} d^{-1}, Abril et al., 2005) as shown in Table 1. The difference in the results is may be due to physiological and hydrodynamic condition of reservoir and rate of turbine discharge.

4 Annual gross and net CO_2 emission (Gg CO_2 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 CO_2 emission for each pathway in four different seasons and respective reservoir water surface area. Annual average CO_2 emission after 6 years of impoundment through different pathways was estimated to be 18.01 Gg yr^{-1} which was less than the average CO_2 emissions estimated for Petit Saut reservoir after 6 years of impoundment (957.8 Gg yr^{-1}) (Abril et al., 2005). However, even after 18 years of impoundment, Balbina reservoir shows 5.2 Gg km^{-2} yr^{-1} of CO_2 emission. At Tehri reservoir, diffusive fluxes contribute 75%, bubbling contribute 21% and downstream emission contribute 4% of the total CO_2 emission. At Petit Saut reservoir the contribution of diffusive and degassing emissions after 10 years of impoundment was 61% and 7% respectively (Abril et al., 2005). Net CO_2 emission for the year 2011-2012 was calculated to be 16.36 Gg yr^{-1}. Net emissions were higher than the gross emission (16.25 Gg yr^{-1}) due to negative pre-impoundment emissions (CO_2 sink).

5 Conclusions

From the present study, it was found that Tehri reservoir area before impoundment was sink of atmospheric CO_2 and after impoundment, all the sampling stations were the sources of CO_2 to the atmosphere. Sometimes, the reservoir surface act as a sink for atmospheric CO_2, and it mostly happened at the rim of the reservoir (d > 30 m) during pre-monsoon and summer season. This could likely be attributed to the withdrawal of CO_2 by photosynthesis in those locations. While at the reservoir surface, higher temperature and allochthonous carbon inputs led to a relatively higher

CO_2 fluxes in pre-monsoon and summer compared to monsoon and winter season. This study has also explored the spatial–temporal patterns of CO_2 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. Overall, higher CO_2 fluxes were observed at reservoir surface than downstream. Major portion of total emissions were contributed by diffusive fluxes (75%) and bubbling (21%) from the reservoir surface, while only 4% contributed in the form of degassing emisssions at the downstream. This difference is due to physical dynamics and structural design of the Tehri hydropower system which generates a physical mixing of the hypolimnetic and epilimnetic waters and thereby outgassing of CO_2 before the turbine intake.

Finally, gross CO_2 emission from Tehri reservoir for the year 2011-2012 was calculated to be 0.30 ± 0.15 Gg CO_2 km^{-2} yr^{-1}. The results revealed that the CO_2 emissions from Tehri hydropower system were lower than the other tropical hydropower systems in the world, partly due to the higher depth and lower allochthonous organic carbon input from the reservoir catchment. As Tehri reservoir area were sink of CO_2 emission before impoundement, net emissions were higher than the gross emissions and the final value calculated to be 26.89 Gg CO_2 yr^{-1}.

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