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Vincent Chanudet, Stéphane Descloux, Atle Harby, Håkon Sundt, Bjørn Henrik Hansen, et al..
Gross CO₂ and CH₄ emissions and carbon budget of the Nam Ngum and Nam Leuk subtrop-
ical Reservoirs in Lao PDR. *Science of the Total Environment*, 2011, 409 (24), pp.5382-5391.
10.1016/j.scitotenv.2011.09.018 . hal-00999782

HAL Id: hal-00999782

<https://hal.science/hal-00999782>

Submitted on 25 Oct 2021

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Gross CO₂ and CH₄ emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR

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Gross CO₂ and CH₄ emissions (degassing and diffusion from the reservoir) and the carbon balance were assessed in 2009–2010 in two Southeast Asian sub-tropical reservoirs: the Nam Ngum and Nam Leuk Reservoirs (Lao PDR). These two reservoirs are within the same climatic area but differ mainly in age, size, residence time and initial biomass stock. The Nam Leuk Reservoir was impounded in 1999 after partial vegetation clearance and burning. However, GHG emissions are still significant 10 years after impoundment. CH₄ diffusive flux ranged from 0.8 (January 2010) to 11.9 mmol m⁻² d⁻¹ (April 2009) and CO₂ diffusive flux ranged from – 10.6 (October 2009) to 38.2 mmol m⁻² d⁻¹ (April 2009). These values are comparable to other tropical reservoirs. Moreover, degassing fluxes at the outlet of the powerhouse downstream of the turbines were very low. The tentative annual carbon balance calculation indicates that this reservoir was a carbon source with an annual carbon export (atmosphere+downstream river) of about 2.2±1.0 GgC yr⁻¹. The Nam Ngum Reservoir was impounded in 1971 without any significant biomass removal. Diffusive and degassing CO₂ and CH₄ fluxes were lower than for other tropical reservoirs. Particularly, CO₂ diffusive fluxes were always negative with values ranging from – 21.2 (April 2009) to – 2.7 mmol m⁻² d⁻¹ (January 2010). CH₄ diffusive flux ranged from 0.1 (October 2009) to 0.6 mmol m⁻² d⁻¹ (April 2009) and no degassing downstream of the turbines was measured. As a consequence of these low values, the reservoir was a carbon sink with an estimated annual uptake of – 53±35 GgC yr⁻¹.

1. Introduction

The conversion of terrestrial land to an aquatic area for the creation of a reservoir is a major issue with regard to greenhouse gas (GHG) emission and carbon cycle change (St Louis et al., 2000). The flooding and subsequent degradation of organic carbon initially present in soils and vegetation together with the flux of carbon from upstream catchments and processes within the flooded land lead to changes in the production of carbon dioxide (CO₂) and methane (CH₄) (Abril et al., 2005; Galy-Lacaux et al., 1999; Guérin et al., 2008a; Kelly et al., 1997; St Louis et al., 2000). Once produced, GHGs are emitted to the atmosphere via several pathways either at the surface of the reservoir (diffusion and ebullition), from the downstream river (degassing and

diffusion) (Abril et al., 2005; Galy-Lacaux et al., 1997; Guérin et al., 2006; Kemenes et al., 2007) or, as occurs in natural lakes and some reservoirs, through the vegetation (Bastviken et al., 2004; Chen et al., 2009). 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; Guérin et al., 2008a; Roland et al., 2010) hydroelectric reservoirs. These datasets show that processes leading to GHG production and emission are probably enhanced in the tropics where fluxes are significantly higher than in the boreal region (Barros et al., 2011). The comparison of emissions from hydropower tropical reservoirs with emissions from thermal alternatives shows that some reservoirs are suspected to emit more GHG than thermal power plants of equivalent power output (Fearnside, 1995; Delmas et al., 2001; dos Santos et al., 2006).

The main biogeochemical processes leading to GHG production and emission in reservoirs are well identified and similar to those occurring in natural lakes (Bastviken et al., 2008) and most of the

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discussions on GHG studies focus on: (1) the representativeness of the studied reservoirs in the tropics since most of them flood mainly primary forest and not other cover types; (2) the lack of standardised methodology; (3) the spatial and temporal resolution in data; (4) the significance and the consideration of all emissions pathways; (5) the seasonal and long term changes and (6) the net emissions (as defined in Delmas et al., 2001 and Guérin et al., 2008b).

In this study, we aim at quantifying, for the first time, gross CO₂ and CH₄ emissions and assessing the carbon balance of two Southeast Asian sub-tropical reservoirs. We compared these emissions to data from other tropical hydroelectric reservoirs. The Nam Ngum and Nam Leuk Reservoirs are located in the Lao People's Democratic Republic (Lao PDR) and differ significantly from previously studied reservoirs in terms of type and the amount of flooded biomass together with climatic conditions. These two sites, five kilometres apart, are within the same climatic area but differ mainly in age, size, residence time and initial organic carbon stock. Accordingly they therefore constitute a relevant pair of reservoirs to assess the cumulative effect of the key parameters leading to GHG emissions.

2. Material and methods

2.1. Study sites

The Nam Ngum and Nam Leuk Reservoirs (Fig. 1) are located approximately 70 km north of the city of Vientiane, in Lao PDR. The cover type within the upstream catchment of the two reservoirs is dominated by dense forest similar to that found in the Nam Theun 2 Reservoir area in Lao PDR (Descloux et al., 2011). The Nam Ngum dam was completed in 1971. The Nam Ngum River is a tributary of the Mekong River and drains a region of low mountains in Central Laos. The water from the Nam Leuk River was diverted into the Nam Ngum Reservoir (via the Nam Xan River) when the Nam Leuk Reservoir was commissioned in 1999. The main characteristics of two reservoirs are given in Table 1: they differ mainly in size, water inflow, residence time and age.

The region is characterised by a warm and humid climate. The average air temperature is 25 °C and the annual precipitation is about

Table 1
Characteristics of the Nam Ngum and Nam Leuk Reservoirs.

	Nam Ngum	Nam Leuk
Location	18°32'N, 103°33'E	18°27'N, 102°57'E
Impoundment year	1971	1999
Capacity (MW)	155	60
Altitude at full supply level (m asl)	212	405
Maximum reservoir surface (km ²)	350	13
Catchment surface area (km ²)	8460	323
Maximum reservoir volume (km ³)	7.0	0.19
Mean depth (m)	19	14
Water level variation (m)	16	17
Water intake level (m above the bottom)	20	8
Mean annual discharge (m ³ s ⁻¹) ^a	294	17
Residence time (year)	0.75	0.35

^a Observation period: 1982–2006 for Nam Ngum and 2000–2006 for Nam Leuk.

2000 mm (Beeton, 1991). The warm dry season (mean air temperature: 27.6 °C) extends from mid-February to May. The warm rainy season (mean air temperature: 27.2 °C) usually starts in May and continues until September. It contributes to 83% of the annual precipitation. The cold dry season (mean air temperature: 22.6 °C) starts in November and continues up to mid-February.

2.2. Sampling

Three field campaigns were carried out during different seasons between April 2009 and January 2010. The sampling locations are shown in Fig. 1. Details about sampling are also given in Tables SI 1 to SI 3. Four sampling stations were chosen in the Nam Ngum Reservoir and three in the Nam Leuk Reservoir, based on the water depth. There were two further sampling stations immediately below the outflow from the powerhouses (about 50–100 m in the Nam Ngum and about 20 m in the Nam Leuk). Vertical profiles of temperature, oxygen concentration and saturation, conductivity and pH were measured at each station. A multi-parameter probe (Quanta, Hydrolab) with a 0.5-m resolution above the oxic-anoxic limit and 1-m below was used. Water samples for CO₂, CH₄ and organic and inorganic

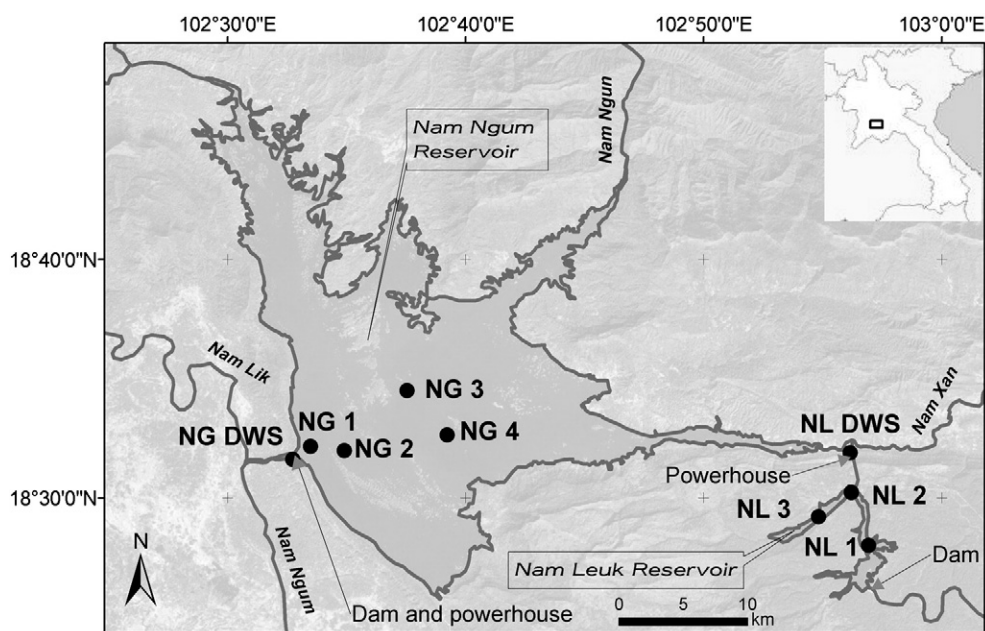


Fig. 1. Location map of the Nam Ngum and Nam Leuk Reservoirs in Lao People's Democratic Republic. Sampling stations (black circles) are also shown.

carbon were taken using a 2-L water sampling bottle at 3 to 5 depths including surface and bottom. Water for CH₄ and CO₂ concentrations was sampled into 60-mL serum bottles which were sealed and poisoned with HgCl₂ (Guérin and Abril, 2007). Samples for organic and inorganic carbon analysis were stored in 150-mL HDPE bottles at 0 °C in a cool box and analysed within 2 days. In the rivers downstream of the powerhouses, the multi-parameter probe was deployed from the shore and CH₄, CO₂ and carbon samples were collected at the sub-surface as described in Abril et al. (2007).

2.3. Dissolved CH₄ and CO₂

CH₄ and CO₂ concentrations were measured after creating a 20-mL N₂ headspace as described in Guérin and Abril (2007). After equilibration between the water and gas phases, the CH₄ and CO₂ concentrations in the headspace were measured (one duplicate for each depth) using a gas chromatograph (8610 C, SRI) equipped with a flame ionisation detector and a FID methanizer, respectively (Abril et al., 2005; Guérin et al., 2006). Commercial standards at 2 to 1000 ppmv were used for calibration. The calculations of CO₂ and CH₄ concentrations in water were made using the solubility coefficients of Weiss (1974) and Yamamoto et al. (1976). The differences between duplicates were within 5%.

2.4. Atmospheric CH₄ and CO₂ fluxes

2.4.1. Diffusive fluxes from the reservoirs

Diffusive CH₄ and CO₂ fluxes across the water-air interface were measured directly with a floating chamber, from a small boat that was left to drift during measurements. The floating chambers (0.20 m² and 26.3 L in April and October 2009 and 0.20 m² and 47.0 L in January 2010) were equipped with a rubber stopper that allowed sampling of the chamber headspace with a syringe and a needle (Guérin et al., 2007). Four to seven gas samples were taken within 45 min in the three chambers (triplicates). Calculated fluxes were rejected if the correlation coefficient of concentration vs. time was below 0.75. For the first two missions CO₂ analysis was carried out with a portable gas chromatograph (Agilent 3000A Micro GC). Gas transfer velocities were calculated from the CO₂ dataset (concentration and fluxes) and water temperature. This gave the instantaneous gas transfer velocity during the flux measurement which was corrected following Jähne et al. (1987) for the computation of the CH₄ flux. For the third mission CH₄ and CO₂ analyses were carried out with the same gas chromatograph (8610 C, SRI) as for dissolved gas analysis.

2.4.2. Degassing fluxes downstream the powerhouse

CH₄ and CO₂ degassing fluxes were calculated by subtracting the concentrations in the reservoir near the water intake and in the downstream outlet of the powerhouse. Analysis of upstream (reservoir) and downstream temperature, conductivity and oxygen data revealed that, on the sampling dates, the released water was not from the whole water column but from a layer of about 15 m for the Nam Ngum Reservoir and 10 m for the Nam Leuk reservoir, centred around the water intake depth at about 20 and 8 m above the bottom for the two reservoirs. Upstream concentrations were thus calculated by integrating values (NG1 and NL2) within this layer. No downstream measurement was done in April and degassing fluxes were then estimated using the degassing rate calculated in October.

2.5. Inorganic and organic carbon

Total organic carbon (TOC) and total inorganic carbon (TIC), excluding CO₂ and CH₄ (mainly HCO₃⁻), concentrations were determined using a high temperature combustion method with a TOC 5000-A Shimadzu analyzer. Milli-Q water was used as blank.

2.6. Annual carbon budget calculation

2.6.1. Atmospheric fluxes (diffusion + degassing)

Annual fluxes were estimated assuming that the three campaigns were representative of the three seasons. The measurements were carried when the seasonal conditions (weather, water temperature, discharges...) were clearly established and typical of the three seasons.

For diffusive fluxes, the average daily value for a given reservoir was assumed to be the average between the fluxes measured at each station. Average daily fluxes were then transformed into seasonal fluxes taking into account the variable duration of each season. Finally the seasonal fluxes were multiplied by the average seasonal reservoir surface areas: 291, 312 and 339 km² for the Nam Ngum Reservoir (observation period: 1982–2006) and 9.2, 10.6 and 12.0 km² for the Nam Leuk Reservoir (observation period: 2000–2006).

Daily degassing values were integrated over one year using the annual average discharge from the turbines. Although the discharge was variable and depended on the electricity demand, it was considered to be constant throughout the year for this survey. The values were: 294 m³ s⁻¹ and 17 m³ s⁻¹ for the Nam Ngum and Nam Leuk Reservoirs (Table 1).

To sum up the contributions of both CO₂ and CH₄ in total GHG emissions from the two reservoirs, the emission terms were also expressed in CO₂ equivalent. A global warming potential for CH₄ of 25 was taken (Forster et al., 2007).

2.6.2. Carbon input and output through the rivers

For practical reasons, no measurements were done in the tributaries upstream of the reservoirs. Annual average inorganic carbon data are taken from Jayawardena et al. (1997) for the Nam Ngum River, the main tributary of the reservoir ([HCO₃⁻] = 1.2 ± 0.2 mmol L⁻¹), and from the environmental impact assessment for the Nam Leuk Reservoir ([HCO₃⁻] = 0.3 ± 0.1 mmol L⁻¹). TOC data (average: 0.12 ± 0.04 mmol L⁻¹ for 2008–2010; unpublished) from the tributaries of the Nam Theun Reservoir were used for both reservoirs since they are located in watersheds with similar land use.

Only a few CH₄ concentration measurements on tropical rivers are available: between 0.1 ± 0.2 μmol L⁻¹ and 0.6 ± 2.5 μmol L⁻¹ (Richey et al., 1988; Guérin et al., 2006). More data is available for CO₂ concentration and the average worldwide value is 109 μmol L⁻¹ (Richey et al., 2002). This value is consistent with measurements upstream of the Petit Saut Reservoir (136 μmol L⁻¹) (Abril et al., 2005; Guérin et al., 2006) and in the tributaries of the Lao Nam Theun 2 Reservoir (100–141 μmol L⁻¹, unpublished results). Values of 0.3 ± 0.1 and 120 ± 20 μmol L⁻¹ for CH₄ and CO₂ concentrations in input rivers were assumed for the calculations.

Annual output fluxes were calculated from the measured daily fluxes in a way similar to that done for the degassing fluxes assuming (i) that the three campaigns were representative of the three seasons and (ii) there was a constant discharge throughout the year (Table 1).

2.6.3. Uncertainties on the annual carbon budget calculation

For each campaign, the standard deviation associated with the mean diffusive flux value gives indications on the spatial variability at the reservoir scale. Errors associated with literature data (section 2.6.2) are also representative of a spatial variability but at a larger scale (other Lao rivers). The calculated errors associated with the annual carbon budgets are therefore also related to local (reservoir) or regional (Laos) spatial variability. These error values do not take into account the relative low number of measurements and thus the temporal variability within each season. That is why, given the low frequency of measurements of biogeochemical parameters, the carbon budget of the two reservoirs can only be considered as a rough estimate. Only general trends can be outlined and discussed.

3. Results and discussion

3.1. Distribution of oxygen and carbon

3.1.1. Nam Leuk Reservoir

A thermal stratification was present in April, reduced in October and almost disappeared in January (Fig. 2 and SI 1). The epilimnion was well oxygenated (above 6 mg L^{-1}) and the hypolimnion was depleted in oxygen throughout the year, with a slightly higher concentration in January. The oxic/anoxic limit ranged from 5 m in April to 15 m in January.

The decomposition in anoxic conditions of the flooded and recently settled organic matter at the bottom of the reservoir led to an increase in CH_4 concentration with depth especially in April and October (mean: $100 \pm 34 \mu\text{mol L}^{-1}$) (Fig. 3 and SI 2). At the oxycline, CH_4 oxidation probably consumed a large part of the CH_4 diffusing upward (Dumestre et al., 1999; Guérin and Abril, 2007) leading to a decrease in surface CH_4 concentration: from 0.06 to $2.1 \mu\text{mol L}^{-1}$ (mean: $0.63 \pm 0.73 \mu\text{mol L}^{-1}$). Oxidation also explained the lower CH_4 bottom concentration ($4 \mu\text{mol L}^{-1}$) observed in January when almost the whole water column was oxygenated.

Primary production in the epilimnion presumably led to the low CO_2 surface concentration (from 13 to $20 \mu\text{mol L}^{-1}$) while higher values were found in the hypolimnion (from 384 to $480 \mu\text{mol L}^{-1}$). In January, after the reservoir mixing, CO_2 concentrations were homogeneously distributed in the water column (64 – $148 \mu\text{mol L}^{-1}$ in the surface and 177 – $264 \mu\text{mol L}^{-1}$ in the bottom water).

In April most of the water withdrawn was from the epilimnion with a high temperature and dissolved oxygen concentration (Table 2). In October, the downstream water was colder and depleted in oxygen (low saturation). In January, the higher dissolved oxygen content (Fig. 2) and low methane concentration in the water column of the reservoir (Fig. 3) was reflected in the downstream releases.

3.1.2. Nam Ngum Reservoir

The Nam Ngum Reservoir had thermal stratification with a thermocline depth ranging from 8 m in April to 25 m in January after the reservoir overturn (Figs. 2 and SI 3). For shallower stations (<25 m depth

such as NG2 and NG3, Figure SI 3), the stratification was not present in January. The same seasonal evolution was observed in 1972 (Beeton, 1991). In April and October, the surface oxygen concentration was above 7 mg L^{-1} and decreased down to 0 mg L^{-1} at 18 m and 30 m depth (Figs. 2 and SI 3). In January, the whole water column was oxygenated. CH_4 concentration for the deepest stations (NG1 and NG4) ranged from 16 to $88 \mu\text{mol L}^{-1}$ (mean: $59 \pm 32 \mu\text{mol L}^{-1}$) (Figs. 3 and SI 4). At the oxycline, methane oxidation was presumably responsible for a decrease in CH_4 concentration from $59 \pm 32 \mu\text{mol L}^{-1}$ to 0.01 – $0.25 \mu\text{mol L}^{-1}$ (mean: $0.09 \pm 0.09 \mu\text{mol L}^{-1}$) at the thermocline/oxycline. In January, CH_4 concentration was very low throughout the water column ($0.02 \pm 0.01 \mu\text{mol L}^{-1}$).

During the stratified conditions (April and October), the high photosynthetic activity, suggested by the high pH (CO_2 consumption during photosynthesis) and TOC (biomass production) values in the epilimnion (Fig. 3), was responsible for the low CO_2 surface concentration (below $16 \mu\text{mol L}^{-1}$). After the reservoir overturn (January), the mixing of the water and the absence of stratification led to an increase in CO_2 surface concentration (between 163 and $210 \mu\text{mol L}^{-1}$) (Fig. 3 and SI 4). Concentration at the bottom remained constant throughout the year but exhibited high spatial variation ($628 \pm 408 \mu\text{mol L}^{-1}$).

The downstream measurements (Table 2) mostly reflected the water composition in the reservoir close to the water intake. The downstream water remained oxygenated for all the seasons and the CH_4 and CO_2 concentration ranged from 0.01 to $6 \mu\text{mol L}^{-1}$ and from 91 to $231 \mu\text{mol L}^{-1}$, respectively. HCO_3^- and TOC were not measured in October and concentrations in April and January were of the same order of magnitude, around $1000 \mu\text{mol L}^{-1}$ for TIC and $100 \mu\text{mol L}^{-1}$ for TOC.

3.1.3. Comparison with other reservoirs

Although similar pattern of dissolved oxygen, CH_4 and CO_2 profiles are often observed in stratified tropical reservoirs (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007; 2011), the average CH_4 and CO_2 concentrations in the epilimnion and hypolimnion of the Nam Ngum and Nam Leuk Reservoirs were in the lower range of previously published data (Table 3).

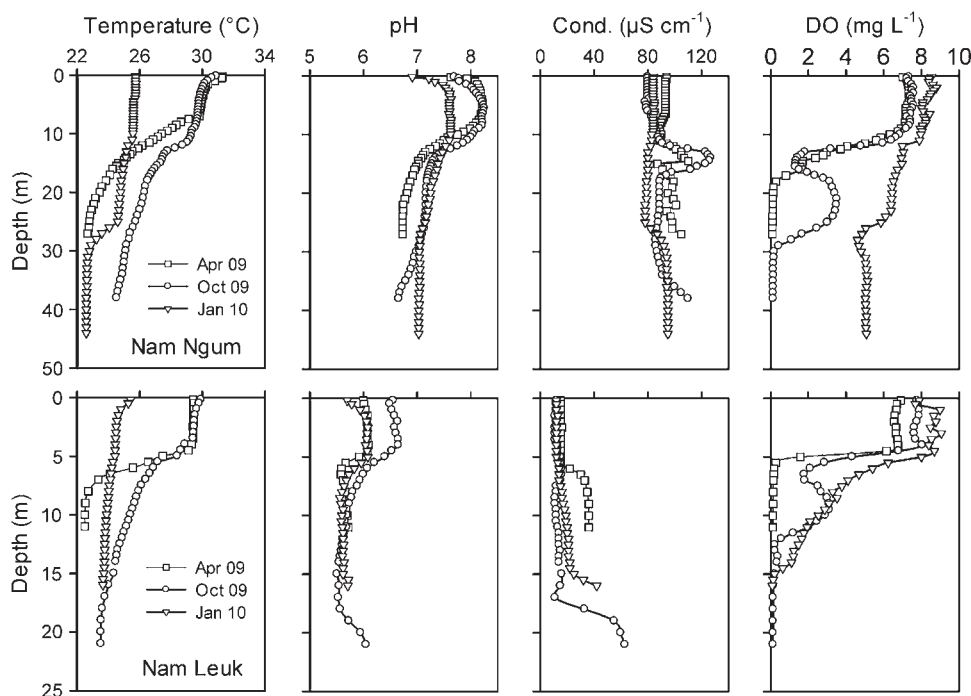


Fig. 2. Vertical profiles of temperature, pH, conductivity and dissolved oxygen in the Nam Ngum (NG1, top) and Nam Leuk (NL2, bottom) Reservoirs for the three measurement campaigns: April 09 (square), October 09 (circle) and January 10 (triangle). For the other stations (Table SI1), the seasonal variations in the vertical patterns were similar.

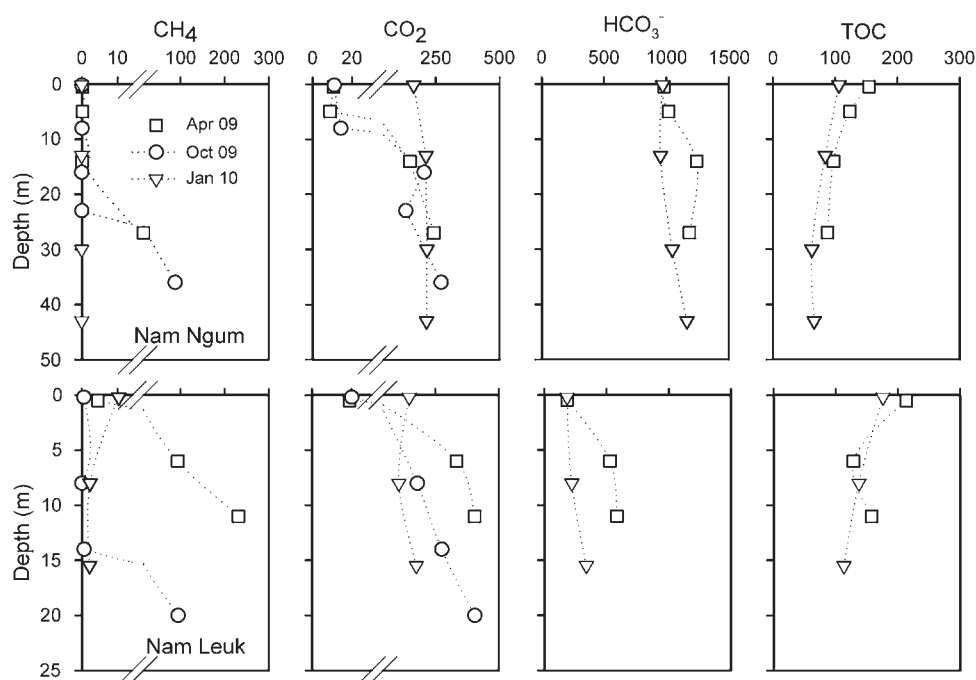


Fig. 3. CH₄, CO₂, HCO₃⁻ (total inorganic carbon, excluding CH₄ and CO₂) and total organic carbon (TOC) concentration profiles in the Nam Ngum Reservoir (NG1, top) in the Nam Leuk Reservoir (NL2, bottom) for the three missions (April 09, October 09 and January 10). All results are expressed in µmol L⁻¹.

Ten years after impoundment (in 2009 for the Nam Leuk Reservoir and 2005 for the Petit Saut Reservoir), the highest CH₄ concentration in the hypolimnion of the Nam Leuk Reservoir ($76 \pm 25 \mu\text{mol L}^{-1}$) was one tenth that in the hypolimnion of the Petit Saut Reservoir in December 2003 ($702 \pm 185 \mu\text{mol L}^{-1}$). Average CH₄ concentrations in the epilimnion and the hypolimnion of the Nam Leuk Reservoir was also significantly lower than in April 2004 in the Balbina and Samuel Reservoirs (respectively 15 and 16 years old in 2004) (Table 3).

The initial carbon stock in the Nam Leuk Reservoir area has been estimated at 200 tC ha⁻¹ (Richard et al., 2005). The vegetation was partly burnt before the impoundment, eliminating almost all the rapidly degradable above-ground biomass. However, the CH₄ concentration in this reservoir was still significant, the lowest values comparable with those measured in the Petit Saut Reservoir in 2005. The vegetation burning is thought to have a limited effect on GHG emission (Delmas et al., 2001) since most of the CO₂ and CH₄ production in tropical reservoirs is assumed to be attributable to the degradation of the organic carbon from the flooded soil as it was demonstrated for the Petit Saut Reservoir (Guérin et al., 2008a).

At Nam Ngum Reservoir, no accurate data on the initial carbon stock (above and below ground) is available but it should be close to that of the Nam Leuk Reservoir. In spite of a probably higher initial carbon stock (no vegetation clearance) and higher residence time, CH₄ and CO₂ average hypolimnion concentrations were lower in the Nam Ngum Reservoir than in the Nam Leuk Reservoir. This difference is likely to be a consequence of the age difference (Table 1) as was shown for other tropical reservoirs (Abril et al., 2005).

3.2. Gross emissions from the reservoirs

3.2.1. Diffusive fluxes from the reservoirs

3.2.1.1. Nam Leuk Reservoir. CH₄ and CO₂ fluxes are shown in Fig. 4 (all stations included) and in Table 4 (average of all sampling stations for a given campaign). CH₄ fluxes exhibited high spatial and temporal variability (Fig. 4) with values ranging from 0.3 (NL2N, January) up to 11.9 mmol m⁻² d⁻¹ (NL1, April) and a coefficient of variation between stations of about 85% in October and January (only one measurement in April). The mean fluxes (Table 4) were 11.9 ± 4.9 , $2.0 \pm$

Table 2
Characteristics of released water immediately after the turbines.

	Nam Ngum (NG DWS)			Nam Leuk (NL DWS)		
	Apr 09 ^a	Oct 09	Jan 10	Apr 09 ^a	Oct 09	Jan 10
Temperature (°C)	26	26.4	24.4	29	24.6	24.0
pH	7.1	6.5	6.1	6.1	5.7	5.5
Conductivity (µS cm ⁻¹)	105	96	84	15	19	19
Dissolved oxygen (mg L ⁻¹)	2.5	2.5	6.5	6.5	0.5	3.3
Dissolved CO ₂ (µmol L ⁻¹)	140	186	231	227	359	66
Dissolved CH ₄ (µmol L ⁻¹)	0.6	6	0.01	6	4	0.6
Total inorganic carbon (except CO ₂ and CH ₄) (µmol L ⁻¹)	1120	NM	950	350	NM	308
Total organic carbon (µmol L ⁻¹)	125	NM	75	167	NM	119

NM: not measured.

^a No downstream measurement were done during the first mission. The given values are only tentative estimates based on the water characteristics in the reservoir See text for details.

Table 3
Concentration and diffusive fluxes of CH₄ and CO₂ in some tropical reservoirs. (the number in parenthesis indicates the number of measurements).

Reservoir	Date	Concentration ($\mu\text{mol L}^{-1}$)						Diffusive flux ($\text{mmol m}^{-2} \text{d}^{-1}$)		Ref	
		CH ₄			CO ₂			CH ₄	CO ₂		
		Epilimnion	Hypolimnion	Downstream	Epilimnion	Hypolimnion	Downstream				
Nam Ngum	Laos	04/09–01/10	0.10 ± 0.09 (26)	13.6 ± 29.1 (17)	2.1 ± 3.4 (3)	75 ± 87 (26)	184 ± 108 (17)	169 ± 71 (3)	0.2 ± 0.2 (11)	–16 ± 12 (13)	1
Nam Leuk			0.8 ± 1.2 (13)	69 ± 107 (13)	3.5 ± 2.7 (3)	88 ± 96 (13)	275 ± 140 (13)	217 ± 146 (3)	2.5 ± 4.0 (8)	3.1 ± 21 (6)	1
Petit Saut	French Guyana	11/94–12/03	24 [0.1–275] (1521)	300 [0.3–1300] (483)	73 [8–371] (190)	140 [4–773] (105)	475 [157–1516] (175)	359 [127–674] (77)			2
		05/03	0.3 ± 0.1 (23)	223 ± 25 (33)	64 (1)	148 ± 58 (7)	669 ± 415 (15)	323 (1)	7.7 ± 8.8 (18)	133 ± 340 (35)	2,3
		12/03	10.3 ± 10.9 (22)	702 ± 185 (20)	92 (1)	229 ± 156 (22)	1369 ± 295 (20)	426 (1)	2.7 ± 1.6 (17)	131 ± 110 (117)	2,3
		03/05	2.4 ± 2.8 (3)	121 ± 31 (9)	48 (1)	120 ± 12 (3)	571 ± 59 (9)	311 (1)	0.1 ± 0.1 (3)	103 ± 68 (3)	2,3
		05/05	0.3 ± 0.1 (3)	34 ± 46 (11)	22 (1)	41 ± 39 (3)	347 ± 106 (11)	206 (1)	0.7 ± 0.5 (6)	102 ± 143 (6)	2,3
Balbina	Brazil	11/04	9.3 ± 10.3 (12)	424 ± 139 (15)	77 ± 7 (3)	119 ± 29 (12)	596 ± 146 (15)	203 ± 27 (3)	2.1 ± 3.0 (6)	76 ± 46 (6)	3
		01/05 to 11/05							3 [0.4–2.9] (80–140)		4 ^a
		09/04 to 02/06				[42–180] (72)	[128–608] (72)	215 ± 66 (72)	10 [0.3–1.48]	315 [29–708] (72)	5
Samuel		98–99				154 ± 59 (4)	778 ± 218 (4)	337 (1)	5.0 ± 5.9 (2)	184 [52–371]	6
Miranda		98–99	1.9 ± 0.2 (4)	257 ± 72 (4)	40 (1)				15 [1.2–2.86]	976 ± 1213 (2)	2,3
Três Manas		98–99							0.9 [0.2–1.8]	113 [0.4–1391]	6,7
Barra Bonita		98–99							3.5 [0.05–1.5]	–3.1 [–229–0.8]	6,7
Segredo		98–99							0.5 [0.001–4]	146 [37–760]	6,7
Xingo		98–99							1.8 [0.2–8.9]	108 [0–1064]	6,7
Tucuruí		98–99							12 [0.02–180]	223 [0.7–2027]	6,7
Itaipu		98–99							0.8 [0.09–2.9]	237 [30–3243]	6,7
Serra da Mesa		98–99							0.6 [0.2–5.9]	27 [–60–181]	6,7
										30 [–11–57]	6,7

References : 1 : this study; 2 : Abril et al., 2005; 3 : Guérin et al., 2006; 4 : Kemeses et al., 2007; 5 : Kemeses et al., 2011; 6 : dos Santos et al., 2005; 6 : dos Santos et al., 2006.

^a Chamber emissions in the reservoir were assumed to include both diffusive and ebullitive fluxes. The number of measurement was not precisely given in the paper.

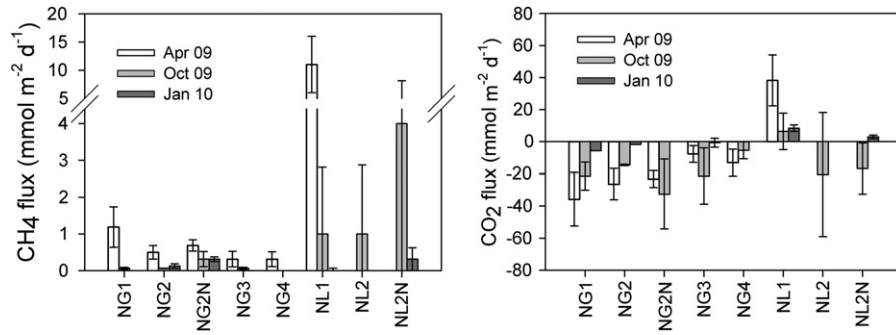


Fig. 4. CH₄ and CO₂ fluxes from the surface of the Nam Ngum (NG1, NG2, NG2N, NG3 and NG4) and Nam Leuk (NL1, NL2 and NL2N) Reservoirs. CH₄ fluxes in April and October were estimated from dissolved CH₄ concentrations in surface water and velocity transfer calculated for CO₂ (see text for details). Error bars represent ± 1 standard deviation. (given the very low fluxes (absolute value) in January, measurements were more delicate and several values were discarded (correlation coefficient too low)).

1.7 and $0.8 \pm 0.6 \text{ mmol m}^{-2} \text{ d}^{-1}$ in April, October and January, respectively. These values were comparable to other tropical reservoirs (Table 3). CO₂ diffusive flux ranged from -20 to $38 \text{ mmol m}^{-2} \text{ d}^{-1}$ with mean values between the stations of 38.2 ± 15.9 , -10.6 ± 14.5 and $5.7 \pm 3.8 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the three campaigns (Fig. 4, Table 4). These fluxes were lower than in other tropical reservoirs (Table 3) except the Três Marias Reservoir. Since no significant (*t*-test, $p < 0.05$) difference was found between the taxonomic richness of the phytoplankton and biomasses in the Nam Ngum and Nam Leuk Reservoirs ($0.57 \pm 0.37 \text{ mgC L}^{-1}$ and $0.55 \pm 0.26 \text{ mgC L}^{-1}$ respectively; Tables SI 5 to 22) and assuming that the gross primary production in the epilimnion is similar (same CO₂ uptake), the higher flux at Nam Leuk could be due to a higher bacterial heterotrophic activity or lower pH values (Fig. 2). On yearly average, the annual diffusive fluxes were $0.38 \pm 0.35 \text{ GgC-CO}_2 \text{ yr}^{-1}$ and $0.21 \pm 0.07 \text{ GgC-CH}_4 \text{ yr}^{-1}$ (see Section 2.6.1 for calculation methodology). It corresponds to emission per surface area of $0.04 \text{ GgC-CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$ and $0.02 \text{ GgC-CH}_4 \text{ km}^{-2} \text{ yr}^{-1}$. For the Petit Saut Reservoir ten years after impoundment, these values were $0.25 \text{ GgC-CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$ and $0.005 \text{ GgC-CH}_4 \text{ km}^{-2} \text{ yr}^{-1}$ (Abril et al., 2005). Proportionally, the Nam Leuk Reservoir emitted much less CO₂ than the Petit Saut Reservoir for a similar age whereas CH₄ diffusive fluxes from the Nam Leuk Reservoir were higher. This might be a consequence of a higher primary production in the Nam Leuk Reservoir leading to an enhanced labile carbon amount that reaches the bottom and fuels the methanogenesis (Fearnside, 2004).

3.2.1.2. Nam Ngum Reservoir. In the Nam Ngum Reservoir, CH₄ fluxes had high spatial and temporal variability (Fig. 4) with values ranging from 0.04 (NG3, October) up to $1.2 \text{ mmol m}^{-2} \text{ d}^{-1}$ (NG1, April) and a coefficient of variation between stations ranging from 60% to 103% in April and October. For each campaign, the mean fluxes between the stations (Table 4) were 0.6 ± 0.4 , 0.1 ± 0.1 and $0.2 \pm 0.1 \text{ mmol m}^{-2} \text{ d}^{-1}$. These fluxes were lower than fluxes from other tropical reservoirs

(Table 3), except the Petit Saut Reservoir in March 2005. The annual CH₄ diffusive flux is $0.40 \pm 0.18 \text{ GgC yr}^{-1}$. CO₂ diffusive fluxes ranged from -36 to $-0.7 \text{ mmol m}^{-2} \text{ d}^{-1}$ with mean fluxes between the stations of -21.2 ± 9.4 , -19.0 ± 7.4 and $-2.7 \pm 2.6 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the three campaigns. This large seasonal variation in CO₂ diffusive flux can be explained by the seasonal variability of CO₂ surface concentration. CO₂ fluxes were always negative meaning that there was a CO₂ uptake by the reservoir which is mainly significant at the end of the dry-warm and wet seasons (April and October) and close to zero at the end of the dry-cold season (January). The annual CO₂ diffusive flux was $-21.8 \pm 6.1 \text{ GgC yr}^{-1}$. Negative average CO₂ fluxes were rarely measured in other tropical reservoirs. However some negative values are reported at Três Marias (Table 3) or at Petit Saut (Abril et al., 2005). These latter values, possibly related to high phytoplankton activity, are usually associated with very high CH₄ diffusive fluxes which was not the case in the Nam Ngum Reservoir.

3.2.2. Degassing at the outlet of the powerhouse

3.2.2.1. Nam Leuk Reservoir. In October and January, CH₄ concentrations in the reservoir were 18 and $0.9 \mu\text{mol L}^{-1}$ and downstream concentrations were 4 and $0.6 \mu\text{mol L}^{-1}$. This leads to a degassing efficiency of 77% and 33% in October and January, respectively. These values are lower than in the Petit Saut Reservoir (92%) (Abril et al., 2005) but in the same range as in the Balbina Reservoir (53%). In the first case, the high efficiency was due to the presence of an aerating weir just downstream of the turbines while in the second case turbulences were limited (Kemenes et al., 2007) as it is the case for the Nam Leuk Reservoir. Assuming a similar degassing rate in April as in October, the annual average carbon loss was $11 \pm 9 \mu\text{mol L}^{-1}$. With an annual discharge of $17 \text{ m}^3 \text{ s}^{-1}$, the annual average degassing flux is $0.07 \pm 0.06 \text{ GgC-CH}_4 \text{ yr}^{-1}$. Degassing through possible spillage at the dam was not considered.

Table 4
Atmospheric (diffusion and degassing) CH₄ and CO₂ fluxes from the Nam Ngum and Nam Leuk Reservoirs for the sampling campaigns (diffusive flux values (± 1 SD) are the average values of all the stations for a given campaign).

		Nam Ngum			Nam Leuk		
		April	October	January	April	October	January
Season		Warm-dry	Warm-wet	Cold-dry	Warm-dry	Warm-wet	Cold-dry
Season duration (month)		4	5	3	4	5	3
Reservoir area (km ²)		291	312	339	9.2	10.6	12.0
Diffusion	$\text{mmol m}^{-2} \text{ d}^{-1}$	CH ₄ 0.6 ± 0.4	0.1 ± 0.1	0.2 ± 0.1	11.9 ± 4.9	2.0 ± 1.7	0.8 ± 0.6
	Mg C d^{-1}	CO ₂ -21.2 ± 9.4	-19.0 ± 7.4	-2.7 ± 2.6	38.2 ± 15.9	-10.6 ± 14.5	5.7 ± 3.8
Degassing	Mg C d^{-1}	CH ₄ 2.2 ± 1.4	0.4 ± 0.4	0.8 ± 0.4	1.3 ± 0.5	0.3 ± 0.2	0.1 ± 0.1
		CO ₂ -79.3 ± 34.8	-75.2 ± 29.3	-11.3 ± 10.9	4.2 ± 1.8	-1.3 ± 1.8	0.8 ± 0.5
		CH ₄ NM	0	0	NM	0.2	0.01
		CO ₂ NM	0	0	NM	0	0

In October and January, CO₂ concentrations in the reservoir were 330 and 125 μmol L⁻¹ and downstream concentrations were 359 and 66 μmol L⁻¹. In January, the downstream CO₂ loss is compensated by an increase of TIC concentration (+ 42 μmol L⁻¹). No clear CO₂ flux was thus observed downstream of the powerhouse and the CO₂ degassing flux was neglected.

3.2.2.2. Nam Ngum Reservoir. The CH₄ concentrations in the reservoir nearby the water intake (4 and 0.01 μmol L⁻¹) in October and January were similar to or slightly lower than concentrations in the river downstream of the dam (6 and 0.01 μmol L⁻¹). The same observation can be made for CO₂: 164 and 197 μmol L⁻¹ in the reservoir and 186 and 231 μmol L⁻¹ in downstream water. The increase in CO₂ concentration after the turbine is compensated by a decrease in TIC concentration between upstream and downstream concentrations. Therefore, the degassing, if any, was probably not significant.

3.3. Tentative carbon budget

3.3.1. Nam Leuk Reservoir

The annual carbon input in the Nam Leuk Reservoir is estimated at 3.2 ± 0.5 GgC yr⁻¹, with a balanced contribution of CO₂, TOC and inorganic carbon and a minor contribution of CH₄. (Fig. 5). The carbon output consisted of atmospheric diffusive fluxes from the reservoir surface (0.59 ± 0.17 GgC yr⁻¹ or 8400 tCO_{2eq} yr⁻¹, see Section 3.2.1.1) and downstream of the turbines (0.07 ± 0.06 GgC yr⁻¹ or 2300 tCO_{2eq} yr⁻¹, see Section 3.2.2.1) and an export of carbon to the Nam Ngum Reservoir of 4.6 ± 0.9 GgC yr⁻¹. In one year about, 2.1 ± 1.0 GgC escaped the Nam Leuk Reservoir (Fig. 5). This reservoir is thus a source of carbon (CO₂ and CH₄) to the atmosphere, probably mainly due to the decomposition of the initial organic carbon stock in sediments. Expressed in CO₂ equivalent, the total atmospheric GHG flux (diffusion + degassing) was $10,700 \pm 3300$ tCO_{2eq} yr⁻¹.

No bubbles were observed in the reservoir and the bubbling flux was not measured. The complexity of the bubbling process in

reservoirs (function of depth, age, sediment porosity and composition, oxygenation, water temperature, etc) makes estimation from literature data difficult. However, these data were used to have an order of magnitude of this emission pathway (microbubbles). CO₂ bubbling flux was probably negligible because of its high solubility (Abril et al., 2005; dos Santos et al., 2005). CH₄ bubbling flux has been measured in some Amazonian tropical reservoirs older than 10 years: Petit Saut (Abril et al., 2005; Galy-Lacaux et al., 1997; 1999); Trés Maria, Barra Bonita, Segredo, Samuel, Tucuruí and Itaipu (Abril et al., 2005; dos Santos et al., 2006; Rosa et al., 2003); Curuá-Una (Fearnside, 2005)) and Gatun Lake (Keller and Stallard, 1994). Bubbling flux is mainly significant in shallow water (<10 m) areas (Abril et al., 2005; Galy-Lacaux et al., 1997; 1999) and the average bubbling flux in these areas is 2.8 ± 4.0 mmol CH₄ m⁻² d⁻¹ with values ranging from 0.03 (Itaipu and Tucuruí Reservoirs) up to 150 mmol CH₄ m⁻² d⁻¹ (Gatun Lake below 1 m depth in April 1988). The surface area shallower than 10 m is about 9 km² for the Nam Leuk Reservoir leading to a CH₄ flux of 0.1 ± 0.2 GgC yr⁻¹. If this flux is considered, the total emissions amounted to $14,400 \pm 6400$ tCO_{2eq} yr⁻¹.

The annual average energy production for the Nam Leuk and Petit Saut hydropower plants is 184 and 560 GWh, respectively. About ten years after the impoundment, the gross GHG emission (diffusive + degassing) per electricity production unit was 58 ± 18 tCO_{2eq} GWh⁻¹ for Nam Leuk and 940 tCO_{2eq} GWh⁻¹ for Petit Saut. If bubbling is included, emissions increased to 78 ± 35 tCO_{2eq} GWh⁻¹ for Nam Leuk and 970 tCO_{2eq} GWh⁻¹ for Petit Saut. In both cases, the Nam Leuk Reservoir emits between 12 and 16 times less than the Petit Saut Reservoir ten years after impoundment.

3.3.2. Nam Ngum Reservoir

The output water discharge of the Nam Leuk Reservoir constitutes about 6% of the total water discharge in the Nam Ngum Reservoir. In term of CO₂ and CH₄, this contribution increased to 11% and 17%, respectively but was only 1% and 6% for TIC and TOC. The high concentration of bicarbonates in the Nam Ngum River strongly influenced

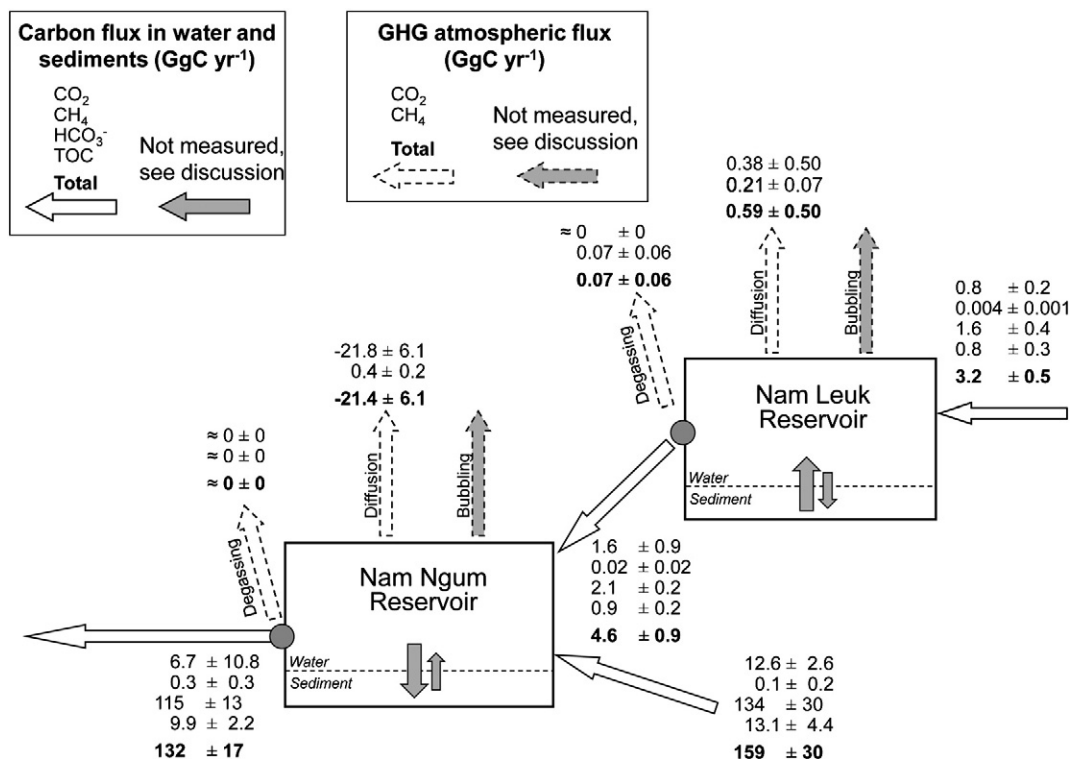


Fig. 5. Tentative carbon budget of the Nam Ngum and Nam Leuk Reservoirs. Continuous arrows indicate the carbon species fluxes in the rivers and dotted arrows show the atmospheric flux (diffusion and degassing). All results are expressed in GgC yr⁻¹.

the carbon input in the reservoir which was estimated at 159 GgC yr^{-1} (Fig. 5). With the contribution of the Nam Leuk Reservoir, the total carbon input in the Nam Ngum reservoir was $164 \pm 30 \text{ GgC yr}^{-1}$. The atmospheric CO_2 and CH_4 efflux from the reservoir was $-21.4 \pm 6.1 \text{ GgC yr}^{-1}$ or $-67,000 \text{ tCO}_{2\text{eq}} \text{ yr}^{-1}$ (Section 3.2.1.2). As for the Nam Leuk Reservoir, no bubbling has been observed and the same literature data were used to have an order of magnitude of potential emissions through microbubbles. The surface area shallower than 10 m is about 90 km^2 in the Nam Ngum Reservoir and the CH_4 bubbling flux is estimated at $1.1 \pm 1.6 \text{ GgC yr}^{-1}$. If this pathway is considered, the total efflux from the reservoir surface was -20.3 tC yr^{-1} or $-30,300 \text{ tCO}_{2\text{eq}} \text{ yr}^{-1}$.

An important amount of carbon was also transferred to the downstream river ($132 \pm 17 \text{ GgC yr}^{-1}$) however, the Nam Ngum Reservoir is a carbon sink ($-53 \pm 35 \text{ GgC yr}^{-1}$) (Fig. 5). This carbon loss might be due to its burial in the sediments. Assuming that the totality of the absorbed carbon is transferred to the sediment, it corresponds to a burial rate of $165 \text{ gC m}^{-2} \text{ yr}^{-1}$. This rate is in the range of values measured for organic carbon in natural lakes (between 5 and $94 \text{ gC m}^{-2} \text{ yr}^{-1}$) and in reservoirs (between 260 and $980 \text{ gC m}^{-2} \text{ d}^{-1}$) (Cole et al., 2007; Dean and Gorham, 1998; Mulholland, and Elwood, 1982). Assuming an average bulk density of 1 g cm^{-3} for organic carbon, the burial of $165 \text{ gC m}^{-2} \text{ yr}^{-1}$ represents an annual sedimentation rate of 0.2 mm yr^{-1} . This value is compatible with the organic carbon sedimentation rate in the Nam Ngum reservoir estimated at between 0.1 and 2.6 mm yr^{-1} (Axelsson, 1992) assuming an average organic carbon content of 2% (Dean and Gorham, 1998). Organic carbon sedimentation probably also occurs in the Nam Leuk Reservoir but in this case sediments are still a net source of carbon because of the decomposition of the initial carbon stock.

4. Conclusion

This study was the first to assess the carbon balance, including the GHGs, in two sub-tropical reservoirs in Southeast Asia (Lao PDR). Nevertheless, it appears clearly that in spite of the burning of the vegetation prior to the impoundment (in 1999), the Nam Leuk Reservoir is still a GHG emitter 10 years after impoundment. CH_4 and CO_2 diffusive fluxes were comparable to other tropical reservoirs with values ranging from 0.8 (January 2010) to $11.9 \text{ mmol m}^{-2} \text{ d}^{-1}$ (April 2009) and from -10.6 (October 2009) to $38.2 \text{ mmol m}^{-2} \text{ d}^{-1}$ (April 2009), respectively. In spite of some negative CO_2 fluxes, the tentative annual carbon balance calculation indicates that this reservoir is a carbon source (2.2 GgC yr^{-1}). This carbon export is mainly due to the decomposition of the initial organic carbon stock, with gross GHG emissions, particularly CH_4 , in the same range as those of the Petit Saut Reservoir for a similar age. The Nam Ngum Reservoir, due to its low CH_4 production and its high CO_2 uptake by the phytoplankton, had much lower diffusive and degassing fluxes. CH_4 diffusive flux ranged from 0.1 (January 2010) to $0.6 \text{ mmol m}^{-2} \text{ d}^{-1}$ (April 2009) and no degassing was measured. CO_2 diffusive fluxes were always negative with values ranging from -21.2 (April 2009) to $-2.7 \text{ mmol m}^{-2} \text{ d}^{-1}$ (January 2010). At an annual scale, this reservoir is a carbon sink ($-53 \pm 35 \text{ GgC yr}^{-1}$) with negative gross GHG emissions. The age is probably the main factor influencing GHG emissions from these reservoirs.

Acknowledgement

The authors thank Dr Bounthan from the Water Resources and Environment Administration (WREA) for the different authorizations and the staff he provided for field trips (Messrs Yingyong, Vongsouli, Sithavong, Phanphomgsa and Khamsana), and Mr Xay from Electricité du Laos. We are also grateful to the Nam Theun 2 Power Company for logistical support and to the members of the Aquatic Environmental Laboratory (AEL) of the Nam Theun 2 project for the help during

field trips and for the analysis, especially Pierre Guédant, Fabien Becerra, Maud Cottet, Arnaud Godon, Joanna Martinet and Sylvie Pighini.

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