Biogeosciences Discuss., 12, 11313–11347, 2015
www.biogeosciences-discuss.net/12/11313/2015/
doi:10.5194/bgd-12-11313-2015

Biogeosciences Discussions
Open Access

Low methane (CH_4) emissions downstream of a monomictic subtropical hydroelectric reservoir (Nam Theun 2, Lao PDR)

C. Deshmukh[1,2,3,a], F. Guérin[1,4,5], S. Pighini[6,b], A. Vongkhamsao[6], P. Guédant[6], W. Rode[6], A. Godon[6,c], V. Chanudet[7], S. Descloux[7], and D. Serça[2]

[1]Université de Toulouse, UPS GET, 14 Avenue E. Belin, 31400, Toulouse, France
[2]Laboratoire d'Aérologie – Université de Toulouse – CNRS UMR5560, 14 Av. Edouard Belin, 31400, Toulouse, France
[3]TERI University, New Delhi, India
[4]IRD, UR234, GET, 14 Avenue E. Belin, 31400, Toulouse, France
[5]Departamento de Geoquimica, Universidade Federal Fluminense, Niteroi-RJ, Brasil
[6]Nam Theun 2 Power Company Limited (NTPC), Environment & Social Division – Water Quality and Biodiversity Dept. – Gnommalath Office, P.O. Box 5862, Vientiane, Lao PDR
[7]Electriciteì de France, Hydro Engineering Centre, Sustainable Development Dpt, Savoie Technolac, 73373 Le Bourget du Lac, France
[a]now at: Nam Theun 2 Power Company Limited (NTPC), Environment & Social Division – Water Quality and Biodiversity Dept.– Gnommalath Office, P.O. Box 5862, Vientiane, Lao PDR

[b]now at: Innsbruck University, Institute of Ecology, 15 Sternwartestrasse, 6020 Innsbruck, Austria and Foundation Edmund Mach, FOXLAB-FEM, Via E. Mach 1, IT-38010 San Michele all'Adige, Italy
[c]now at: Arnaud Godon Company, 44 Route de Genas, Nomade Lyon, 69003 Lyon, France

Received: 5 June 2015 – Accepted: 3 July 2015 – Published: 20 July 2015

Correspondence to: F. Guérin (frederic.guerin@ird.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

BGD
12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

Abstract

Methane (CH_4) emissions from hydroelectric reservoirs could represent a significant fraction of global CH_4 emissions from inland waters and wetlands. Although CH_4 emissions downstream of hydroelectric reservoirs are known to be potentially significant, these emissions are poorly documented in recent studies. We report the first quantification of emissions downstream of a subtropical monomictic reservoir. The Nam Theun 2 Reservoir (NT2R), located in Lao People's Democratic Republic, was flooded in 2008 and commissioned in April 2010. This reservoir is a trans-basin diversion reservoir which releases water to two downstream streams: the Nam Theun River below the dam and an artificial channel downstream of the powerhouse and a regulating pond that diverts the water from the Nam Theun watershed to the Xe Bangfai watershed. We quantified downstream emissions during the first four years after impoundment (2009–2012) on the basis of a high temporal (weekly to fortnightly) and spatial (23 stations) resolution of the monitoring of CH_4 concentration.

Before the commissioning of NT2R, downstream emissions were dominated by a very significant degassing at the dam site resulting from the occasional spillway discharge for controlling the water level in the reservoir. After the commissioning, downstream emissions were dominated by degassing which occurred mostly below the powerhouse. Overall, downstream emissions decreased from 10 Gg CH_4 y^{-1} after the commissioning to 2 Gg CH_4 y^{-1} four years after impoundment. The downstream emissions contributed only 10 to 30 % of total CH_4 emissions from the reservoir during the study.

Most of the downstream emissions (80 %) occurred within 2–4 months during the transition between the warm dry season (WD) and the warm wet season (WW) when the CH_4 concentration in hypolimnic water is maximum (up to 1000 µmol L^{-1}) and downstream emissions are negligible for the rest of the year. Emissions downstream of NT2R are also lower than expected because of the design of the water intake. A significant fraction of the CH_4 that should have been transferred and emitted downstream of the powerhouse is emitted at the reservoir surface because of the artificial

turbulence generated around the water intake. The positive counterpart of this artificial mixing is that it allows O_2 diffusion down to the bottom of the water column enhancing aerobic methane oxidation and it subsequently lowering downstream emissions by at least 40 %.

1 Introduction

Methane (CH_4) emission from hydroelectric reservoirs at the global scale was recently revised downward and it would represent only 1 % of anthropogenic emissions (Barros et al., 2011). This latter estimate is mostly based on CH_4 diffusion at the reservoir surface and in a lesser extent on CH_4 ebullition which are the two best documented pathways to the atmosphere. However, emissions from the drawdown area (Chen et al., 2009, 2011) and emissions downstream of dams (Galy-Lacaux et al., 1997; Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007; Chanudet et al., 2011; Teodoru et al., 2012; Maeck et al., 2013) were poorly studied and are not taken into account in the last global estimate (Barros et al., 2011). Some authors attempted to include these two pathways to the global estimation of greenhouse gas emissions from reservoirs (Lima et al., 2008; Li and Zhang, 2014) and it increased drastically the emission factors of reservoirs.

The downstream emissions include the so-called degassing which occurs just below the turbines. It is attributed to the high turbulence generated by the discharge of the reservoir water into the river below the dam and the large pressure drop that the water undergoes while being transported from the bottom of the reservoir to the surface of the river below the dam. It also includes emissions by diffusion from the river below the dam. Downstream emissions were found for the first time at the Petit Saut Reservoir (Galy-Lacaux et al., 1997) and this pathway was later confirmed in some Brazilian reservoirs (Guérin et al., 2006; Kemenes et al., 2007). Abril et al. (2005); Kemenes et al. (2007); Maeck et al. (2013) have shown that downstream emissions would contribute 50 to 90 % of total CH_4 emissions from temperate and tropical hydroelectric reservoirs when all emission pathways from reservoirs (disregarding the drawdown emissions) are taken into account. At two other sites located in Canada and in Lao People's Democratic Republic (Lao PDR) where this pathway was studied, downstream emissions were found to contribute less than 25 % when it exists (Chanudet et al., 2011; Teodoru et al., 2012). According to the differences from one reservoir to the other, it appears that the factors controlling downstream emissions from reservoirs must be identified in order to propose realistic estimations of the global emissions from reservoirs including downstream emissions.

In the present study, we quantified emissions downstream of the Nam Theun 2 Reservoir (NT2R) located in Lao PDR on the basis of a high temporal (weekly to fortnightly) and spatial (23 stations) resolution monitoring of CH_4 concentration. The significance of the aerobic CH_4 oxidation in the dynamics of CH_4 in the reservoir and the downstream rivers was also evaluated. We characterized the seasonal patterns of downstream emissions and evaluated the contribution of this pathway to CH_4 emissions by ebullition (Deshmukh et al., 2014) and diffusive fluxes at the surface of the reservoir (Guérin et al., 2015). We finally discuss the contribution of downstream emissions according to the reservoir hydrodynamics and the design of the water intake by comparing our results to previously published studies.

2 Material and methods

2.1 Study area

The NT2 hydroelectric Reservoir was built on the Nam Theun River located in the subtropical region of Lao PDR. The NT2 hydroelectric scheme is based on a trans-basin diversion that receives water from the Nam Theun River and releases it into the Xe Bangfai River through a 27 km long artificial downstream channel (Fig. 1) (see Descloux et al. (2014) for a detailed description of the study site). Below the powerhouse, the turbinated water reaches first the tailrace channel (TRC1 in Fig. 1) and the wa-

BGD
12, 11313–11347, 2015

ter is then stored in an 8 Mm^3 regulating pond (RD in Fig. 1) located around 3.5 km below the powerhouse. The regulating pond also receives water inputs from the Nam Kathang River (3 % of its volume annually). Daily, the water discharge of Nam Kathang River that reaches the regulating pond is returned to the downstream reach of the Nam Kathang River, below the regulating pond. The remaining water from the regulating pond is released to the artificial downstream channel. To prevent potential problem of deoxygenation in the water that passed through the turbines, an aeration weir was built at midway between the turbines and the confluence to the Xe Bangfai River (AW in Fig. 1). A continuous flow of 2 $m^3 s^{-1}$ (and occasionally spillway release) is discharged from the Nakai Dam (ND in Fig. 1) to the Nam Theun River. Annually, the NT2 Reservoir receives around 7527 Mm^3 of water from the Nam Theun watershed, which is more than twice the volume of the reservoir (3908 Mm^3), leading to a residence time of nearly six months.

Typical meteorological years are characterized by three seasons: warm wet (WW) (mid June–mid October), cool dry (CD) (mid October–mid February) and warm dry (WD) (mid February–mid June). During the CD season, the reservoir water column overturns and during the WW season, sporadic destratification occurs allowing oxygen to diffuse down to the bottom of the water column (Chanudet et al., 2012; Guérin et al., 2015). Daily average air temperature varies between 12 °C (CD season) to 30 °C (WD season). The mean annual rainfall is about 2400 mm and occurs mainly (80 %) in the WW season (NTPC, 2005).

The filling of the reservoir began in April 2008, the full water level was first reached in October 2009 and stayed nearly constant until the power plant was commissioned in March 2010. After the commissioning, during the studied period the reservoir surface varied seasonally and reached its maxima (489 km^2) and minima (between 168 and 221 km^2 depending on the year) during the WW and WD seasons, respectively.

BGD
12, 11313–11347, 2015

2.2 Sampling strategy

A total of 23 stations were monitored weekly to fortnightly in order to determine physico-chemical parameters and the CH_4 concentrations and emissions in pristine rivers, the reservoir, and all rivers and channels located downstream of the reservoir. In the reservoir, two stations were monitored (RES1 and RES9, Fig. 1). The station RES1 is located 100 m upstream of the Nakai Dam and RES9 is located ∼ 1 km upstream of the water intake which transports water to the turbines.

Below the powerhouse, the water was monitored at nine stations: in the tailrace channel (TRC1), regulating pond (REG1), artificial downstream channel (DCH1, DCH2, DCH3 and DCH4), and the Xe Bangfai River (XBF2, XBF3 and XBF4). Owing to existence of the above-listed civil structures downstream of the powerhouse, three sections were defined in order to calculate emissions and degassing downstream of the powerhouse, the regulating pond and the aeration weir (Fig. 1). The influence of the water released from the regulating pond on the Nam Kathang River was evaluated by the monitoring of two pristine stations (NKT1 and NKT2) upstream of the regulating pond and three stations (NKT3–NKT5) below the regulating pond (Fig. 1).

Below the Nakai Dam, 4 sampling stations (NTH3–NTH5 and NTH7) were used for the monitoring of the Nam Theun River. The Sect. 4 refers to the Nam Theun River section located between the stations NTH3 and NTH4 (Fig. 1).

Additionally, we monitored the pristine Xe Bangfai River (XBF1) upstream of the confluence with the artificial channel and one of its pristine tributaries (Nam Gnom River: NGM1) and a pristine tributary of the Nam Theun River (Nam Phao River: NPH1) downstream of the Nakai Dam.

During various field campaigns (March 2010, June 2010, March 2011, June 2011 and June 2013), aerobic methane oxidation rates (AMO) were determined at three stations in the reservoir (RES1, RES3 and RES7, Fig. 1). Additionally, AMO was also determined in the reservoir at the water intake (RES9) in June 2013.

BGD
12, 11313–11347, 2015

2.3 Experimental methods

2.3.1 In situ water quality parameter

Oxygen and temperature were measured in situ at all sampling stations with a multi-parameter probe Quanta® (Hydrolab, Austin, Texas) since January 2009. In the reservoir, the vertical resolution of the vertical profiles was 0.5 m above the oxic–anoxic limit and 1–5 m in the hypolimnion, whereas it was only measured in surface waters (0.2 m) in the tailrace channel, downstream channel and rivers.

2.3.2 Methane concentration in water

The CH_4 concentrations at all stations have been monitored between May 2009 and December 2012 on a fortnightly basis. Surface and deep-water samples for CH_4 concentration were taken with a surface water sampler (Abril et al., 2007) and a Uwitec water sampler, respectively. Water samples were stored in serum glass vials, capped with butyl stoppers, sealed with aluminium crimps and poisoned (Guérin and Abril, 2007). A N_2 headspace was created and the vials were vigorously shaken to ensure an equilibration between the liquid and gas phases prior to CH_4 concentration gas chromatography (GC) analysis. The concentration in the water was calculated using the solubility coefficient of Yamamoto et al. (1976).

2.3.3 Aerobic methane oxidation

In the reservoir, water samples for AMO rate measurements were collected in the epilimnion and in the metalimnion (at the oxicline). At RES9, the samples were taken in the middle of the water column since the water column was well mixed. The water was collected in 1 L HDPE bottles, homogenized, oxygenated and redistributed to twelve serum vials (160 mL). Each vial contained 60 mL of water and 100 mL of air. Vials were covered with aluminium foil to avoid effect of light on any bacterial activity and incu-

BGD
12, 11313–11347, 2015

bated in the dark (Dumestre et al., 1999; Murase and Sugimoto, 2005) at 20 to 30 °C, depending on in situ temperatures. According to in situ concentration of CH_4 in the water, different amounts of CH_4 were added by syringe while withdrawing an equal volume of air from the headspace with a second syringe in order to obtain concentrations of dissolved CH_4 in the incubated water ranging from in situ to four times in situ. Incubations were performed with agitation to ensure continuous equilibrium between gas and water phases. Total CH_4 concentrations in the vials were measured 5-times in a row at a 12 h interval, and oxidation rates were calculated as the total loss of CH_4 in the vial (Guérin and Abril, 2007). The oxidation rate for each concentration was the average value of the triplicates with standard deviation (± SD).

2.3.4 Gas chromatography

Analysis of CH_4 concentrations were performed by gas chromatography (SRI 8610C gas chromatograph, Torrance, CA, USA) equipped with a flame ionization detector. A subsample of 0.5 mL from the headspace of water sample vials was injected. Commercial gas standards (10, 100 and 1010 ppmv, Air Liquid "crystal" standards and mixture of N_2 with 100 % CH_4) were injected after analysis of every 10 samples for calibration. Duplicate injection of samples showed reproducibility better than 5 %.

2.4 Calculations

2.4.1 Estimation of diffusive fluxes from surface concentrations

The diffusive CH_4 fluxes downstream of the powerhouse (Sects. 1–3 in Fig. 1), and downstream of the Nakai Dam (NTH3–NTH7, Fig. 1) were calculated with the thin boundary layer (TBL) equation (Liss and Slater, 1974) from the difference between the water surface CH_4 concentrations and the concentration at the equilibrium with the overlying atmosphere (1.8 ppmv) combined with a gas transfer velocity (k_{600}).

BGD
12, 11313–11347, 2015

Downstream of the powerhouse in the Sects. 2 and 3 and downstream of the dam, floating chamber measurement was not possible for safety reason because of strong water currents. In a handful occasions, k_{600} was calculated from floating chamber measurements (Guérin et al., 2007; Deshmukh et al., 2014) and concomitant CH_4 water surface concentrations in the turbulent waters downstream of the powerhouse (Sect. 1 at stations TRC1 and REG1), in the Xe Bangfai River downstream of its confluence with the artificial channel (XBF2) and in pristine rivers (XBF1, Nam On River and Nam Noy River). The gas transfer velocity reached up to 45 $cm\,h^{-1}$ and averaged $10.5 \pm 12.1\,cm\,h^{-1}$ (data not showed) which is similar to the k_{600} found by Guérin et al. (2007) below the Petit Saut Reservoir. We therefore used a k_{600} of 10 $cm\,h^{-1}$ for the artificial channel, the Xe Bangfai River and downstream of the Nakai Dam (NTH3–NTH7).

2.4.2 Degassing

Although the so-called "degassing" usually occurs only below dams (Galy-Lacaux et al., 1997; Abril et al., 2005; Kemenes et al., 2007; Maeck et al., 2013), degassing occur at 4 sites at NT2R: (1) the Nakai Dam, (2) the turbine release in the tailrace channel, (3) the regulating dam and (4) the aeration weir. On each of these structures, the degassing was calculated using the water discharges and the difference of CH_4 concentration between the stations: (1) NTH3 located below the Nakai Dam and RES1, (2) TRC1 located below the turbines and RES9, (3) NKT3 below the Regulating Dam and REG1, and (4) DCH3 below the Aeration Weir and DCH2 (Fig. 1). In addition, degassing was calculated for the occasional spillway releases from the Nakai Dam.

The estimation of the concentration upstream of the degassing sites was different for the four sites. For the degassing below the turbines and below the regulating dam, the average of the vertical profile of CH_4 concentrations at RES9 and REG1 were considered as concentrations before degassing, respectively. Surface concentration at DCH2 was considered for the degassing at the aeration weir. For the degassing below the Nakai Dam, since the continuous flow of $2\,m^3\,s^{-1}$ was released from the surface

BGD
12, 11313–11347, 2015

water layer, we considered the average CH_4 concentration in the upper 3 m water layer at RES1 located ~ 100 m upstream of dam. For the spillway release of the Nakai Dam, as the spillway gate is located at 12 m below the maximum reservoir water level, the degassing due to spillway release was calculated using the average CH_4 concentration in the upper 15 m water layer at RES1.

3 Results

3.1 Temperature, O_2 and CH_4 concentrations in the reservoir (RES1 and RES9)

Before the commissioning of the power plant, the vertical profiles of temperature and oxygen and CH_4 concentrations at the stations RES1 located at the Nakai Dam and RES9 located at the water intake were similar. As already shown in Chanudet et al. (2015) and Guérin et al. (2015), the reservoir was thermally stratified with higher temperature at the surface than at the bottom during the WD (surface: 26.8 ± 2.7 °C and bottom: 18.9 ± 1.6 °C) and WW (surface: 28.0 ± 1.6 °C and bottom: 21.5 ± 1.7 °C) seasons and it overturns during the CD season (Average = 23.2 ± 3.9 °C). During the WD and WW season, the epilimnion was always oxygenated with surface O_2 concentrations ranging from 14 to 354 µmol L^{-1} (5 to 137 % saturation) and the hypolimnion was anoxic. In the CD season, the reservoir water column was poorly but entirely oxygenated during a few weeks/month (127 ± 93 µmol L^{-1}). In the WD and WW seasons, the CH_4 concentrations ranged between 0.02 and 201.7 µmol L^{-1} in the epilimnion and 0.02 to 1000 µmol L^{-1} in the hypolimnion. In the CD season, the CH_4 concentrations are only slightly higher in the hypolimnion than in the epilimnion. After the starting of turbines, the hydrodynamics of the water column at RES1 followed the same seasonal pattern as described before whereas the CH_4 vertical profiles of concentration at RES9 located upstream of the water intake were homogeneous from the surface to the bottom. At RES9 during the years 2010 to 2012, the temperature was constant from the bottom to the surface whatever the season and the water column was always

BGD
12, 11313–11347, 2015

oxygenated (O_2 = 166 µmol L^{-1}). During this period, CH_4 concentration peaked up to 215 µmol L^{-1} with averages of 39.8 ± 48.8, 29.9 ± 55.4 and 1.9 ± 4.3 µmol L^{-1} during the WD, WW and CD seasons, respectively. For the two stations, the average CH_4 concentrations over the water column were always the highest in the WD season, intermediate in the WW season and the lowest in the CD season. At the two stations, the average concentrations were significantly higher in 2009 and 2010 than they were in 2011 and 2012.

The average CH_4 concentrations at NT2R were in the range reported for tropical reservoir flooded 10–20 years ago (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007).

3.2 Emissions downstream of the Nakai Dam

3.2.1 CH_4 and O_2 concentrations below the Nakai Dam

Downstream of the Nakai Dam (NTH3) after the commissioning, the average O_2 concentration was 224 µmol L^{-1} that is 87 % saturation and the concentration increased below. When excluding the periods of spillway releases, the CH_4 concentration at NTH3 ranged from 0.03 to 6 µmol L^{-1} (average: 0.94 ± 1.2 µmol L^{-1}) with the highest CH_4 concentrations in the WW season and the lowest in the CD season (Fig. 3a). High CH_4 concentrations (up to 69 µmol L^{-1}) were occasionally observed when CH_4-rich water was released from the spillway, especially in 2009. Ten kilometers downstream of the Nakai Dam, CH_4 concentration decreased down to 0.41 ± 0.32 µmol L^{-1} at NTH4 and NTH5 without any clear seasonal pattern.

The concentrations observed below the Nakai Dam at the stations NTH4 and NTH5 were similar to the CH_4 concentrations found in the pristine Nam Phao River (NPH1) in the watershed and 40 % lower than the CH_4 concentrations at the station NTH7 located 50 km downstream of the dam. They were 2 orders of magnitude lower than the concentrations observed downstream of 10–20 years old-reservoirs in Brazil and in French Guiana (Guérin et al., 2006; Kemenes et al., 2007).

3.2.2 Diffusive fluxes below the Nakai Dam

The average diffusive flux downstream of the Nakai Dam was $3.3 \pm 3.9\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ for the year 2010 and fluxes decreased down to 1.9 ± 2.5 and $1.4 \pm 0.9\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ for the years 2011 and 2012, respectively (Fig. 3b). Ten kilometres downstream from the Nakai Dam at NTH4 and at NTH5 downstream of the confluence of the Nam Phao River, the CH_4 fluxes decreased down to $1.14 \pm 0.92\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ on average. As for the concentrations, no seasonal or interannual trends were found. Globally, 10 km downstream of the dam, the CH_4 emission was similar to what found in pristine river of the watershed and it was 2 orders of magnitude lower than the emissions observed downstream of 10–20 years-old reservoirs (Guérin et al., 2006; Kemenes et al., 2007).

Considering that the CH_4 emissions from the Nam Theun River below the dam can be attributed to the reservoir over a length of 10 km and a constant width of 30 m, annual emissions below the Nakai Dam decreased from 20 to 1 Mg-CH_4 $\mathrm{month^{-1}}$ between 2009 and 2012, respectively (Fig. 3c). The very high emissions in 2009 were due to spillway releases (see below).

3.2.3 Degassing below the Nakai Dam

Due to the low water discharge at the Nakai Dam ($2\,\mathrm{m^3\,s^{-1}}$), CH_4 emissions by degassing reached a maximum of 0.1 MgC-CH_4 $\mathrm{d^{-1}}$ at NTH3 (Fig. 3e). The occasional spillway releases occurred mostly in 2009 before the commissioning of the power plant and in the CD after the commissioning. They led to very intense degassing (up to 72 Mg-CH_4 $\mathrm{d^{-1}}$, August 2009, Fig. 3d). In total, 99 % of the degassing below the Nakai Dam is due to the spillway releases in 2009 which represent 32 % of total emissions downstream of the Nakai Dam during the study (2009–2012). Total degassing below

BGD
12, 11313–11347, 2015

the Nakai Dam was very significant in 2009 due to the spillway releases and it dropped below 3 Mg-CH_4 $month^{-1}$ when only 2 $m^3\,s^{-1}$ were released for the years 2010 to 2012.

3.3 Emissions downstream of the powerhouse

3.3.1 CH_4 and O_2 concentrations below the powerhouse

Downstream of the turbines at the station TRC1 after the commissioning, the average O_2 concentration was 174 ± 58 µmol L^{-1} that is 67 ± 20 % saturation. After the commissioning of the power plant, the O_2 saturation downstream of the station DCH4 located 30 km below the turbines was always around 100 % saturation in the artificial downstream channel. Just below the regulating dam, in the Nam Kathang River (NKT3), the average O_2 concentration was 237 µmol L^{-1} that is 93 % saturation. There was no marked inter-annual change in the O_2 concentration.

Surface CH_4 concentration at the station TRC1, which is located below the turbines and receives water from the homogenized water column in the reservoir (RES9), varied by four orders of magnitude; from 0.01 µmol L^{-1} (August–February, WW and CD seasons) to 221 µmol L^{-1} (June, end of the WD and beginning of the WW season) (Fig. 4a). The seasonal pattern of the CH_4 concentrations at TRC1 mimicked the concentrations at RES9. In 2010, the surface CH_4 concentration decreased from 117 ± 71 µmol L^{-1} at TRC1 to 1.55 ± 1.15 µmol L^{-1} at DCH4 in the WD season and from 88 ± 84 to 1.26 ± 1.59 µmol L^{-1} in the WW season. In 2011 and 2012, the average CH_4 concentrations just below the turbines at TRC1 were fourfold (33.4 ± 32.0 µmol L^{-1}) and ninefold (9.8 ± 29.6 µmol L^{-1}) lower than in 2010 for the WD and WW seasons, respectively. At DCH4, the surface CH_4 concentration drops to 1.1 ± 2.4 µmol L^{-1} (WD) and 0.3 ± 0.5 µmol L^{-1} (WW) in the years 2011 and 2012 that is similar to what was observed in 2010. Whatever the years, in the CD season, surface CH_4 concentrations varied in a narrow range along the 30 km long watercourse (0.02–14.5 µmol L^{-1}).

BGD
12, 11313–11347, 2015

On average, at the station DCH4 (30 km below the turbines) and at the station XBF4 located 90 km below the confluence of the downstream channel and the Xe Bangfai River, the CH_4 concentrations were 0.54 ± 0.95 and $0.3 \pm 0.4\,\mu mol\,L^{-1}$, respectively. These concentrations are the same as those found in the pristine Xe Bangfai River ($0.78 \pm 0.86\,\mu mol\,L^{-1}$ at XBF1 station).

At the station NKT3 located in the Nam Kathang River just below the regulating dam, the average surface CH_4 concentration was $0.87 \pm 0.77\,\mu mol\,L^{-1}$. At the station NKT5 located 15 km downstream of the regulating dam, the average CH_4 concentration was $1.34 \pm 2.09\,\mu mol\,L^{-1}$. These concentrations are not statistically different from the concentrations found in the pristine Nam Kathang Noy River ($0.42 \pm 0.49\,\mu mol\,L^{-1}$ at NKT1 station), the pristine Nam Kathang Gnai River ($1.01 \pm 1.73\,\mu mol\,L^{-1}$ at NKT2 station) and the pristine Nam Gnom River ($1.08 \pm 1.45\,\mu mol\,L^{-1}$ at NGM1) all located in the same watershed.

3.3.2 Diffusive fluxes below the Powerhouse

In 2010, in the Sect. 1, the flux was $198 \pm 230\,mmol\,m^{-2}\,d^{-1}$, which was two times higher than in Sect. 2 ($94 \pm 102\,mmol\,m^{-2}\,d^{-1}$) (Fig. 4c). In the Sect. 3 (below the aeration weir), fluxes were fifteen times lower than the fluxes in Sect. 1 ($12.7 \pm 18.6\,mmol\,m^{-2}\,d^{-1}$). After the confluence with the Xe Bangfai River, CH_4 fluxes dropped down to $0.95 \pm 0.76\,mmol\,m^{-2}\,d^{-1}$ for the next 30 km. For the years 2011 and 2012, the average diffusive fluxes below the powerhouse decreased by a factor of four as compare to 2010. In 2010, most of the diffusive fluxes occurred from the middle of the WD season until the late WW season ($155 \pm 127\,mmol\,m^{-2}\,d^{-1}$) whereas diffusive fluxes in the CD season were 100 times lower ($1.4 \pm 1.1\,mmol\,m^{-2}\,d^{-1}$). In 2011 and 2012, most of the emissions occurred during the WD season ($61.9 \pm 50\,mmol\,m^{-2}\,d^{-1}$) whereas emissions were twentyfold lower during both the WW and the CD seasons ($3.7 \pm 3.9\,mmol\,m^{-2}\,d^{-1}$).

As observed for the concentrations, emissions downstream of DCH4 in the downstream channel ($1.5 \pm 2.7\,mmol\,m^{-2}\,d^{-1}$) and at NKT3 downstream of the regulat-

BGD
12, 11313–11347, 2015

ing dam in the Nam Kathang River ($2.03 \pm 2.23\,mmol\,m^{-2}\,d^{-1}$) (Fig. 4b) were not significantly different from those calculated for the pristine Xe Bangfai River ($2.2 \pm 2.6\,mmol\,m^{-2}\,d^{-1}$ at XBF1 station), Nam Kathang Noy River (NKT1 station) and Nam Kathang Gnai River (NKT2 station) ($1.98 \pm 4.01\,mmol\,m^{-2}\,d^{-1}$).

The average diffusive flux for the Sects. 1 to 3 during the monitoring was $12 \pm 22\,mmol\,m^{-2}\,d^{-1}$, which is 7 times lower than the diffusive flux along the 40 km reach below the Petit Saut Dam ($90\,mmol\,m^{-2}\,d^{-1}$) (Guérin and Abril, 2007) 10 years after impoundment and twelve times lower than the diffusive flux along the 30 km reach downstream of the Balbina Dam ($140\,mmol\,m^{-2}\,d^{-1}$) (Kemenes et al., 2007) 18 years after impoundment.

The sum of the CH_4 emissions by diffusion from the Sects. 1–3 (Fig. 1) peaked at 333, 156 and 104 Mg-CH_4 month^{-1} at the end of the WD-beginning of the WW season in 2010, 2011 and 2012, respectively (Fig. 4c). Diffusion was negligible for more than half of the year. The results clearly show that emissions decrease with time within the first four years after flooding.

3.3.3 Degassing below the Powerhouse

The degassing mainly occurred within 3 to 5 months around the transition between the WD and the WW seasons (Fig. 4d). Below the powerhouse (TRC1), the degassing reached up to 385 Mg-CH_4 month^{-1} at the end of the WD season and beginning of the WW season in 2010, just after the turbines were operated (Fig. 4d). Below the regulating dam, the degassing was almost three times higher (1240 Mg-CH_4 month^{-1}) than below the turbines, and the degassing from the release to the Nam Kathang River was 55 Mg-CH_4 month^{-1} in the WD season. Even if CH_4 concentrations at DCH2 were 50 % lower than at TRC1, still up to 756 Mg-CH_4 month^{-1} were emitted at the aerating weir. This shows the very high degassing efficiency of the aeration weir (up to 99 %), especially in the WD season (Descloux et al., 2015). Therefore, most of the degassing emissions occurred below the regulating dam and at the aerating weir.

In 2010, most of the degassing occurred from April to August whereas it occurred only from March to June in 2011 and 2012. The annual degassing emissions almost deceased by a factor of four in 2011 and 2012 compare to 2010 (Fig. 4e).

3.4 Aerobic CH_4 oxidation in the reservoir and downstream of the powerhouse and the Nakai Dam

In the reservoir, the potential AMO rates increased linearly with the CH_4 concentration (Fig. 5a–c) in both epilimnetic and metalimnic waters at the stations RES1, RES3 and RES7. The AMO rates in the middle of the well-mixed water column at the station RES9 were not statistically different from the AMO rates in the metalimnion at the other stations of the reservoirs. Therefore, the AMO rates from RES9 were plotted vs. the initial CH_4 concentration together with AMO rates from the metalimnion. The slope of the linear correlation, or the so-called specific oxidation rate (SOR, d^{-1}) in the metalimnion was similar for the CD and WD seasons (SOR = $0.88 \pm 0.03\,d^{-1}$) (Fig. 5a). In the epilimnion the SOR was twice higher in the WD season ($5.28 \pm 0.43\,d^{-1}$) than in the CD season ($2.24 \pm 0.41\,d^{-1}$) (Fig. 5b and c). Overall, the SOR in the epilimnion was two to fourfold higher than the SOR in the metalimnion. The values of SOR observed at the NT2R are in same range as those reported at the Petit Saut Reservoir (2.64–4.13 d^{-1}) (Dumestre et al., 1999; Guérin and Abril, 2007) and boreal experimental reservoirs during the summer period (0.36–2.4 d^{-1}) (Venkiteswaran and Schiff, 2005).

The depth-integrated CH_4 oxidation rate was calculated at the stations RES1 and RES9 based on the CH_4 oxidation rates described above and the CH_4 and O_2 concentrations in the water column as done for the Petit Saut Reservoir (Guérin and Abril, 2007). The depth-integrated oxidation rates ranged from 0.16 to 931 $mmol\,m^{-2}\,d^{-1}$ at RES9 and from 0.13 to 310 $mmol\,m^{-2}\,d^{-1}$ at RES1 upstream of the Nakai Dam. Overall, for the years 2010, 2011 and 2012, the average integrated oxidation rate at RES9 is 122 $mmol\,m^{-2}\,d^{-1}$ that is more than three times higher than the average integrated oxidation rate at RES1 (35 $mmol\,m^{-2}\,d^{-1}$). Since oxidation occurs from the surface to the bottom of the water column at RES9 and mostly around the oxicline at RES1, the depth-integrated oxidation rates were 5–20 times higher at RES9 than at RES1 during the WD season and no clear tendency can be drawn for the WW and CD seasons (Table 1). At RES9, the total amount of oxidized CH_4 decreased from 5 to 1 Gg (CH_4) y^{-1} between 2010 and 2012 whereas it ranged between 0.4 and 0.7 Gg (CH_4) y^{-1} without clear trend at RES1 (Table 1).

4 Discussion

4.1 Spatial and temporal variations of downstream emissions

Before the power plant was commissioned in March 2010, only a few m^3 of water was discharged at the powerhouse for testing the turbines and most of the water was discharged at the Nakai Dam. The continuous water discharge at the Nakai Dam was about 2 $m^3 s^{-1}$ and occasionally, water was spilled in order to prevent dam overflow. The continuous discharge at the Nakai Dam mimics the lowest annual water flow in the Nam Theun River before it was dammed. Since it expels CH_4-poor water (0.95 µmol L^{-1}) from the surface associated with a very low discharge, subsequent degassing and diffusive emissions below the Nakai Dam were lower than 4 Mg-CH_4 $month^{-1}$ in 2010 just after the commissioning and lower than 1 Mg-CH_4 $month^{-1}$ in 2012 (Fig. 3e). Degassing was four fold higher in 2010 than in 2012 because of the very high CH_4 concentrations in the water column resulting from the long residence time of water in the reservoir before the first water releases. In 2011, the concentrations were lower than in 2012 due to the high water discharges from the inflows that decreased the CH_4 concentrations by dilution (Guérin et al., 2015). The spillway releases reached up to 5309 $m^3 s^{-1}$ and water from the top 15 m of the water column having an average concentration around 100 µmol L^{-1} at RES1 were released at these occasions. During these short releases, up to 3000 Mg-CH_4 $month^{-1}$ were released in 2009 (Fig. 3d). After the commissioning, the spillways were used only twice in October 2010 and September 2011. The diffusive fluxes in the Nam Theun River below the

Nakai Dam were only highly significant during the spillway releases when it reached up to 20 Mg month^{-1} in 2009. After the commissioning, the diffusion ranged between and and 1.5 Mg-CH_4 month^{-1} (Fig. 3c) and contributed to only a few percent of total downstream emissions below the Nakai Dam (Fig. 3f). Emissions below the Nakai Dam are low compare to emissions below the powerhouse because, except during spillway releases, only a small amount of water is discharged downstream and this water has a low CH_4 concentration since surface water is released. However, we show here that short spillway releases with high water discharge and moderate CH_4 concentrations could contribute up to 30 % of downstream emissions in 4 years.

Downstream of the powerhouse, maximum yearly emissions were dominated by degassing (Fig. 4e). They ranged between 1 and 3 Gg month^{-1} and had a clear seasonal pattern. Emissions below the powerhouse peaked during the WD season until the beginning of the WW season when the CH_4 concentration in the hypolimnion of the reservoir is up to 1000 µmol L^{-1} (Guérin et al., 2015) and concentration at RES9 higher than 100 µmol L^{-1}. Emissions were negligible in the late WW and during the CD seasons when hypolimnic concentration in the reservoir and concentration at RES9 decreased down to 5 µmol L^{-1} (Guérin et al., 2015). Due to the accumulation of CH_4 in the reservoir in absence of turbining until commissioning, emissions downstream of the powerhouse in 2010 were higher than in 2011 and 2012 and lasted from the commissioning to the beginning of the next CD season in 2010. After the commissioning, the high emissions downstream of the powerhouse occurred within 3–5 month in the WD season and the very beginning of the WW season. During the wet 2011-year, emissions became negligible after the first rainfalls. For all years, downstream emissions were negligible in the CD season. These results show the very high seasonal variations over 3–4 orders of magnitude for downstream emissions as already observed in tropical reservoirs flooding primary forest (Abril et al., 2005; Kemenes et al., 2007). However, we show in this monomictic reservoir that downstream emissions are negligible most of the year and this is mostly due to the seasonal overturn in the CD and some sporadic destratification events and dilution of the hypolimnoion in the WW season. Overall,

BGD
12, 11313–11347, 2015

these results highlight the fact that the precise determination of downstream emissions cannot be done on the basis of discrete sampling one to four times in a year. It requires weekly to monthly monitoring in order to (1) capture the hot moment(s) of emissions and (2) determine their duration. For instance, downstream emissions reported for the Nam Ngum and Nam Leuk Reservoirs located in the same region were obtained at the beginning of the WD season when downstream emissions are moderate and during the CD and WW season when no emission occur (Chanudet et al., 2011). Therefore, emissions were probably underestimated since the peak of downstream emissions at the end of the WD season-beginning of the WW season was missed.

4.2 Contribution of downstream emissions to CH_4 gross emissions

Table 2 reports CH_4 emissions by ebullition and diffusion at the surface of the reservoir from the Deshmukh et al. (2014) and Guérin et al. (2015), respectively. These estimates take into account the seasonal variations of the reservoir water surface and the variations of depth. Between June and December 2009, the spillway releases contributed to 30 % of total gross emissions from the NT2R. In 2010, downstream emissions (degassing + diffusive fluxes) contributed to more than 30 % of total gross emissions (disregarding drawdown emissions). In 2011 and 2012, downstream emissions contributed to about 10 % of total gross emissions. This contribution of downstream emissions to total emissions is low compare to tropical reservoirs located in South America (Abril et al., 2005; Kemenes et al., 2007). Disregarding the first two years of monitoring (2009 and 2010) during which the quantification highly depends on the management of the reservoir, the contribution of downstream emissions to total emissions is even lower than in boreal reservoirs (Teodoru et al., 2012). The low downstream emissions arise from the fact that the reservoir is monomictic. Each time the reservoir overturns in the CD season, 1–3 Gg of CH_4 are emitted to the atmosphere within a few days and up to a month which purge the reservoir water column (Guérin et al., 2015). As a consequence, bottom concentrations decrease from 500 to less than 5 μmol L^{-1} during these events and the amount of CH_4 transferred from the reservoir to the downstream

BGD
12, 11313–11347, 2015

reaches decrease by two orders of magnitude and stays low during 8 to 9 months, before the CH_4 concentration in the reservoir increases again. Monomictic reservoirs like Nam Theun 2, Nam Leuk, Nam Ngum in Lao PDR (Chanudet et al., 2011), the Three Gorges Dam in China (Li et al., 2014) and the Cointzio Reservoir in Mexico (N. Gratiot, personal communication, 2015) are common in the subtropics and especially in Asia where 60 % of the worldwide hydroelectric reservoirs are. Although CH_4 emissions below amictic reservoirs like Petit Saut and Balbina are high and very significant in the total emissions (Abril et al., 2005; Kemenes et al., 2007), low emission downstream of monomictic/dimictic/polymictic reservoirs is likely to be a general feature. The thermal stratification of hydroelectric reservoirs has to be taken into account for the estimation of global downstream emissions from hydroelectric reservoirs. Therefore, global estimates of CH_4 emissions from hydroelectric reservoirs that include downstream emissions (Lima et al., 2008; Li and Zhang, 2014) calculated on the basis of the results from Amazonian reservoirs (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2007) must be considered with caution.

4.3 Consequence of outgassing and aerobic CH_4 oxidation at the water intake for the emissions below the powerhouse

In addition to the dynamic of the thermal stratification of the NT2R, the design of the water intake contributes to lower the emissions downstream of the powerhouse. After the power plant was commissioned, the water column at the station RES9 was always completely mixed from the top to the bottom as revealed by the vertical profiles of temperature. Consequently, O_2 penetrated down to the bottom of the water column and CH_4 concentration were higher than 100 µmol L^{-1} from the top to the bottom of the water column in the WD season and at the beginning of the WW season. The overturn of the water column at RES9 results from the artificial mixing due to the advection of water caused by the water current generated by the water intake localized around 11–20 m under the water surface depending on the water level. The water intake is responsible for the mixing of the whole water column over an area of 3 km^2 according

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

BGD

12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

to the hydrodynamic model of Chanudet et al. (2012). This mixing has a strong effect on both the outgassing (Guérin et al., 2015) and the aerobic oxidation of CH_4 around the water intake and on the oxidation of CH_4 below the powerhouse.

In the area of influence of the water intake where RES9 is, large amount of CH_4 (up to 600 $mmol\,m^{-2}\,d^{-1}$) are emitted by diffusive fluxes at the end of the WD season-beginning of the WW (Guérin et al., 2015). The artificial mixing at RES9 generated a hotspot of CH_4 emissions where diffusive fluxes are 15 to 150 times higher than at other stations in the reservoir for the years 2010 to 2012 (Guérin et al., 2015). The emissions at RES9 correspond to 20 to 40 % of the total downstream emissions (Table 2). Therefore, a very significant amount of CH_4 that could be emitted downstream is emitted at the reservoir surface and this contributes to lower downstream emissions.

However, the mixing at the water intake has a strong impact on aerobic CH_4 oxidation. The vertical mixing allows O_2 to penetrate down to the bottom in the vicinity the water intake and enhances both oxidation at the water intake and downstream of the powerhouse. On average, depth-integrated CH_4 oxidation at RES9 upstream of the water intake is one order of magnitude higher than at the station RES1 upstream of the Nakai Dam where the water column is thermally stratified. Over the 3 km^2-area representative for RES9 between 2010 and 2012, aerobic CH_4 oxidation consumed an amount of CH_4 that is equivalent to 50 % of total CH_4 downstream emissions (Tables 1 and 2). In absence of artificial mixing, aerobic CH_4 oxidation would only remove an amount of CH_4 that is equivalent to the amount of CH_4 removed by oxidation at RES1 that is on average, that is 11 % of total downstream emissions over the three years of monitoring (Tables 1 and 2). Total downstream emissions were therefore lowered by 20 % due to the enhancement of aerobic CH_4 oxidation at RES9 if we compare total downstream emissions to total downstream emissions plus the amount of CH_4 that would not be oxidized in absence of mixing (oxidation at RES9 minus oxidation at RES1). In addition, aerobic methane oxidation in the downstream channel might be enhanced too since water from RES9 being transferred to the artificial downstream channel is better oxygenated that it would be in absence of artificial mixing.

Overall, the design of the water intake that mixes the whole water column decreases virtually downstream emissions since part of the CH_4 is outgassed at the reservoir surface instead of being transported and emitted downstream. The very positive counterpart of this artificial mixing at the water intake is that the mixing allows O_2 to penetrate down to the bottom of the water column enhancing aerobic methane oxidation both at the water intake and in the river/channel downstream of the powerhouse. Roughly, CH_4 emissions from NT2 Reservoir are lowered by 40 % or more due to the artificial mixing of the water column at the water intake.

5 Conclusion

This first quantification of CH_4 emissions downstream of a subtropical monomictic hydroelectric reservoir shows that emissions are negligible most of the year due to low CH_4 concentration in the hypolimnion. They occurred only during 2–4 month per the year at the end of the warm season-beginning of the wet season and globally contribute to 10 % of total emissions as observed during normal reservoir operation years (2011 and 2012). The hydrodynamics but also the water residence time significantly impact downstream emissions and must be taken into account for future estimation of total emissions from hydroelectric reservoirs at the global scale.

The monitoring of downstream emissions before and just after the commissioning (2009 and 2010) after a period with long water residence time in the reservoir (up to 5 years) with occasional use of spillways stresses that reservoir management can have very significant impact on emissions by enhancing diffusive emissions and downstream emissions resulting from the use of spillways.

Emissions downstream of the Nam Theun 2 Reservoir have a low contribution to total emissions also because a very significant amount of CH_4 that could be emitted downstream of the reservoir is (1) emitted upstream of the water intake and (2) is oxidized in the vicinity of the water intake because of the artificial mixing it generates. This artificial mixing contributes to improve the water quality downstream of the turbines

BGD
12, 11313–11347, 2015

since the water that passes through is well oxygenated (70 % saturation). The other positive counterpart is that it generates a hotspot of aerobic methane oxidation that contributes to the oxidation of 20 % of the CH_4 that would potentially be emitted at the water intake or downstream of the turbines. This study shows that downstream emissions from future or existing reservoirs could be significantly mitigated by the adoption of water intake-design or the installation of devices enhancing artificial water column destratification and oxygenation upstream of the turbines.

Acknowledgements. The authors thank everyone who contributed to the NT2 monitoring programme, especially the Nam Theun 2 Power Company (NTPC) and Electricité de France (EDF) for providing financial, technical and logistic support. We are also grateful to the Aquatic Environment Laboratory of the Nam Theun 2 Power Company whose Shareholders are EDF, Lao Holding State Enterprise and Electricity Generating Public Company Limited of Thailand. CD benefited from a PhD grant by EDF.

References

Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., and Matvienko, B.: Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), Global Biogeochem. Cy., 19, Gb4007 doi:10.1029/2005gb002457, 2005.

Abril, G., Commarieu, M. V., and Guérin, F.: Enhanced methane oxidation in an estuarine turbidity maximum, Limnol. Oceanogr., 52, 470–475, 2007.

Barros, N., Cole, J. J., Tranvik, L. J., Prairie, Y. T., Bastviken, D., Huszar, V. L. M., del Giorgio, P., and Roland, F.: Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude, Nat. Geosci., 4, 593–596, 2011.

Chanudet, V., Descloux, S., Harby, A., Sundt, H., Hansen, B. H., Brakstad, O., Serça, D., and Guérin, F.: Gross CO_2 and CH_4 emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR, Sci. Total Environ., 409, 5382–5391, 2011.

Chanudet, V., Fabre, V., and van der Kaaij, T.: Application of a three-dimensional hydrodynamic model to the Nam Theun 2 Reservoir (Lao PDR), J. Great Lakes Res., 38, 260–269, doi:10.1016/j.jglr.2012.01.008, 2012.

BGD

12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

Chanudet, V., Guédant, P., Rode, W., Godon, A., Guérin, F., Serça, D., Deshmukh, C., and Descloux, S.: Evolution of the physico-chemical water quality in the Nam Theun 2 Reservoir and downstream rivers for the first 5 years after impoundment, Hydroécol. Appl., doi:10.1051/hydro/2015001, in press, 2015.

Chen, H., Wu, Y., Yuan, X., Gao, Y., Wu, N., and Zhu, D.: Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir, J. Geophys. Res., 114, D18301, doi:10.1029/2009JD012410, 2009.

Chen, H., Yuan, X., Chen, Z., Wu, Y., Liu, X., Zhu, D., Wu, N., Zhu, Q. a., Peng, C., and Li, W.: Methane emissions from the surface of the Three Gorges Reservoir, J. Geophys. Res., 116, D21306, doi:10.1029/2011jd016244, 2011.

Descloux, S., Guedant, P., Phommachanh, D., and Luthi, R.: Main features of the Nam Theun 2 hydroelectric project (Lao PDR) and the associated environmental monitoring programmes, Hydroécol. Appl., doi:10.1051/hydro/2014005, in press, 2014.

Descloux, S., Chanudet, V., Taquet, B., Rode, W., Guédant, P., Serça, D., Deshmukh, C., and Guerin, F.: Efficiency of the Nam Theun 2 hydraulic structures on water aeration and methane degassing, Hydroécol. Appl., doi:10.1051/hydro/2015002, in press, 2015.

Deshmukh, C., Serça, D., Delon, C., Tardif, R., Demarty, M., Jarnot, C., Meyerfeld, Y., Chanudet, V., Guédant, P., Rode, W., Descloux, S., and Guérin, F.: Physical controls on CH_4 emissions from a newly flooded subtropical freshwater hydroelectric reservoir: Nam Theun 2, Biogeosciences, 11, 4251–4269, doi:10.5194/bg-11-4251-2014, 2014.

Dumestre, J. F., Guezennec, J., Galy-Lacaux, C., Delmas, R., Richard, S., and Labroue, L.: Influence of light intensity on methanotrophic bacterial activity in petit saut reservoir, French Guiana, Appl. Environ. Microb., 65, 534–539, 1999.

Galy-Lacaux, C., Delmas, R., Jambert, C., Dumestre, J. F., Labroue, L., Richard, S., and Gosse, P.: Gaseous emissions and oxygen consumption in hydroelectric dams: a case study in French Guyana, Global Biogeochem. Cy., 11, 471–483, 1997.

Guérin, F. and Abril, G.: Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir, J. Geophys. Res.-Biogeo., 112, G03006 doi:10.1029/2006jg000393, 2007.

Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P., and Delmas, R.: Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers, Geophys. Res. Lett., 33, L21407 doi:10.1029/2006gl027929, 2006.

Guérin, F., Abril, G., Serça, D., Delon, C., Richard, S., Delmas, R., Tremblay, A., and Varfalvy, L.: Gas transfer velocities of CO_2 and CH_4 in a tropical reservoir and its river downstream, J. Marine Syst., 66, 161–172, 2007.

Guérin, F., Deshmukh, C., Labat, D., Pighini, S., Vongkhamsao, A., Guédant, P., Rode, W., Godon, A., Chanudet, V., Descloux, S., and Serça, D.: Effect of sporadic destratification, seasonal overturn and artificial mixing on CH_4 emissions at the surface of a subtropical hydroelectric reservoir (Nam Theun 2 Reservoir, Lao PDR), Biogeosciences Discuss., 12, 11349–11385, doi:10.5194/bgd-12-11349-2015, 2015.

Kemenes, A., Forsberg, B. R., and Melack, J. M.: Methane release below a tropical hydroelectric dam, Geophys. Res. Lett., 34, L12809 doi:10.1029/2007gl029479, 2007.

Li, S. and Zhang, Q.: Carbon emission from global hydroelectric reservoirs revisited, Environ. Sci. Pollut. R., 21, 13636–13641, doi:10.1007/s11356-014-3165-4, 2014.

Li, Z., Zhang, Z., Xiao, Y., Guo, J., Wu, S., and Liu, J.: Spatio-temporal variations of carbon dioxide and its gross emission regulated by artificial operation in a typical hydropower reservoir in China, Environ. Monit. Assess., 186, 3023–3039, doi:10.1007/s10661-013-3598-0, 2014.

Lima, I., Ramos, F., Bambace, L., and Rosa, R.: Methane emissions from large dams as renewable energy resources: a developing nation perspective, Mitigation and Adaptation Strategies for Global Change, 13, 193–206, 2008.

Liss, P. S. and Slater, P. G.: Flux of gases across the air–sea interface, Nature, 247, 181–184, doi:10.1038/247181a0, 1974.

Maeck, A., DelSontro, T., McGinnis, D. F., Fischer, H., Flury, S., Schmidt, M., Fietzek, P., and Lorke, A.: Sediment trapping by dams creates methane emission hot spots, Environ. Sci. Technol., 47, 8130–8137, doi:10.1021/es4003907, 2013.

Murase, J. and Sugimoto, A.: Inhibitory effect of light on methane oxidation in the pelagic water column of a mesotrophic lake (Lake Biwa, Japan), Limnol. Oceanogr., 50, 1339–1343, 2005.

NTPC: Environmental Assessment and Management Plan – Nam Theun 2 Hydroelectric Project. Nam Theun 2 Power Company, NTPC, Nam Theun 2 Power Company, Vientiane, 212, 2005.

Teodoru, C. R., Bastien, J., Bonneville, M.-C., del Giorgio, P. A., Demarty, M., Garneau, M., Hélie, J.-F., Pelletier, L., Prairie, Y. T., Roulet, N. T., Strachan, I. B., and Tremblay, A.: The net carbon footprint of a newly created boreal hydroelectric reservoir, Global Biogeochem. Cy., 26, GB2016, doi:10.1029/2011gb004187, 2012.

Venkiteswaran, J. J. and Schiff, S. L.: Methane oxidation: isotopic enrichment factors in freshwater boreal reservoirs, Appl. Geochem., 20, 683–690, 2005.
Yamamoto, S., Alcauskas, J. B., and Crozier, T. E.: Solubility of methane in distilled water and seawater, J. Chem. Eng. Data, 21, 78–80, doi:10.1021/je60068a029, 1976.

BGD
12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

Table 1. Depth-integrated methane oxidation rates (mmol m^{-2} d^{-1}) and annual amount of oxidized CH_4 (Gg (CH_4) y^{-1}) at the stations RES9 and RES1 of the Nam Theun 2 Reservoir. The depth-integrated CH_4 oxidation rates are given for each season: cold dry (CD), warm dry (WD) and warm wet (WW) for each year.

		RES9		RES1	
Year	Season	mmol m^{-2} d^{-1}	Gg (CH_4) y^{-1}	mmol m^{-2} d^{-1}	Gg (CH_4) y^{-1}
2010	CD	11.6 ± 5.5		2.8 ± 1.0	
	WD	444.1 ± 106.1	5.2 ± 1.2	18.2 ± 6.5	0.7 ± 0.2
	WW	442.3 ± 93.6		96.3 ± 29.8	
2011	CD	1.0 ± 0.2		7.5 ± 2.7	
	WD	128.2 ± 46.2	1.0 ± 0.5	5.3 ± 2.4	0.4 ± 0.2
	WW	46.9 ± 31.8		50.2 ± 26.3	
2012	CD	33.9 ± 9.6		34.7 ± 11.3	
	WD	94.1 ± 19.4	1.2 ± 0.3	41.9 ± 21.8	0.6 ± 0.2
	WW	80.7 ± 24.2		26.13 ± 5.3	

BGD
12, 11313–11347, 2015

Table 2. Methane emissions from the Nam Theun 2 Reservoir between 2009 and 2012.

Gg (CH_4) y^{-1}	2009	2010	2011	2012
Emission from reservoir				
Ebullition[1]	11.21 ± 0.16	14.39 ± 0.11	14.68 ± 0.10	12.29 ± 0.09
Diffusion at RES9 only[2]	0.02 ± 0.01	2.33 ± 0.21	0.86 ± 0.12	0.66 ± 0.11
Diffusion at RES1 only[2]	0.06 ± 0.03	0.09 ± 0.07	0.01 ± 0.00	0.01 ± 0.00
Total diffusion[2]	4.45 ± 1.01	9.34 ± 2.32	3.71 ± 0.81	4.95 ± 1.09
Total emissions from reservoir	15.66 ± 1.02	23.73 ± 2.32	18.39 ± 0.82	17.25 ± 1.09
Emissions from downstream				
Degassing (continuous release)	0.49 ± 0.03	8.48 ± 0.74	1.83 ± 0.41	1.67 ± 0.31
Degassing (Spillway release)	7.20 ± 0.90	0.92 ± 0.39	0.14 ± 0.00	0.00 ± 0.00
Diffusion	0.10 ± 0.02	1.33 ± 0.03	0.32 ± 0.02	0.33 ± 0.03
Total downstream emissions	7.79 ± 0.90	10.73 ± 0.83	2.29 ± 0.41	2.00 ± 0.32
(reservoir + downstream)	23.45 ± 1.36	34.46 ± 2.46	20.67 ± 0.92	19.24 ± 1.14
Downstream emissions (%)	33	31	11	10

[1] Deshmukh et al. (2014).
[2] Guérin et al. (2015).

BGD

12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

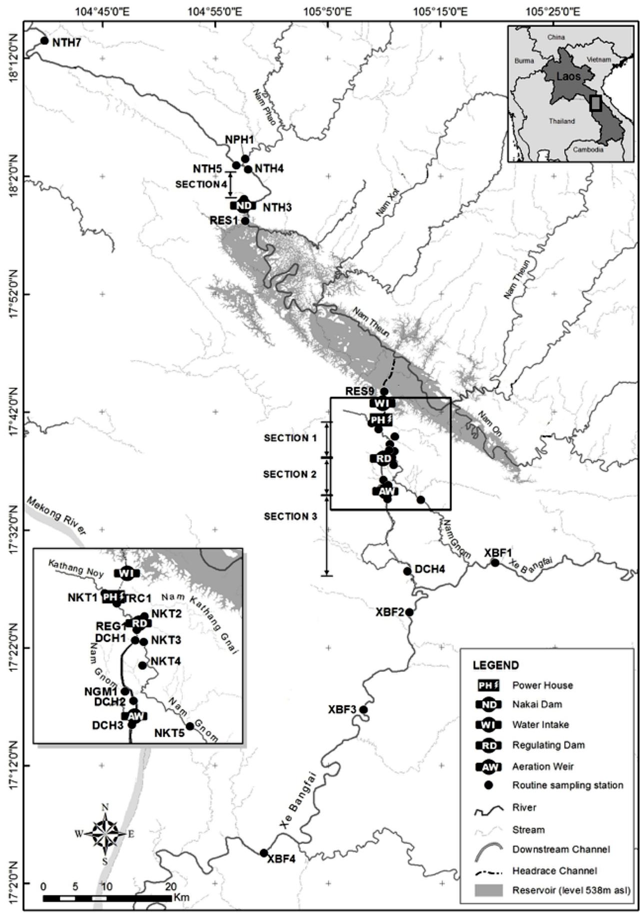


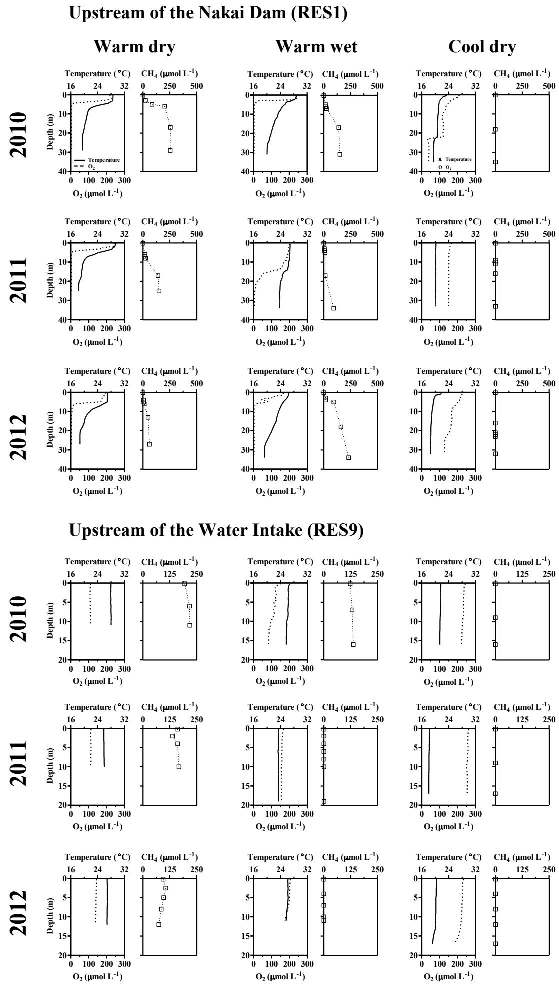
Figure 1. Map of the Nam Theun 2 Hydroelectric Reservoir (Lao People's Democratic Republic).

BGD
12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◄ ►
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



BGD
12, 11313–11347, 2015

Low CH_4 emissions downstream of a dam

C. Deshmukh et al.

Figure 2. Vertical profiles of temperature, oxygen and methane concentrations at the stations RES1 and RES9 in the Nam Theun 2 Reservoir during the three seasons in 2010, 2011 and 2012.

BGD
12, 11313–11347, 2015

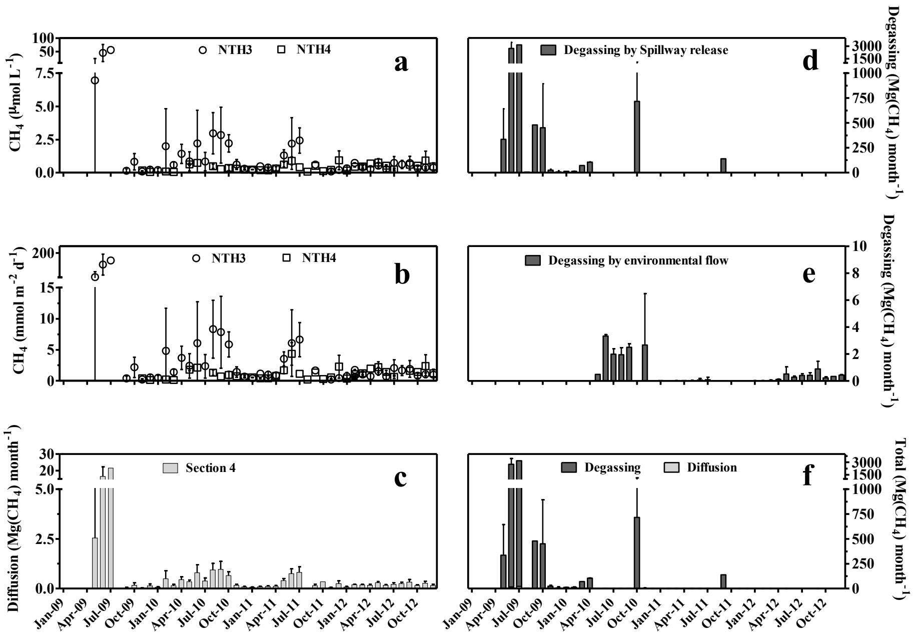


Figure 3. Methane concentrations and emissions downstream of the Nakai Dam at the Nam Theun 2 Reservoir between 2009 and 2012. **(a)** Time series of CH_4 concentrations at the stations NTH3 and NTH4, **(b)** diffusive fluxes at the stations NTH3 and NTH4, **(c)** emissions by diffusive fluxes in the Sect. 4 (between NTH3 and NTH4), **(d)** degassing due to spillway release below the Nakai Dam, **(e)** degassing below the Nakai Dam due to the continuous water discharge of $2\,m^3\,s^{-1}$ and **(f)** total emissions by degassing and diffusion downstream of the Nakai Dam.

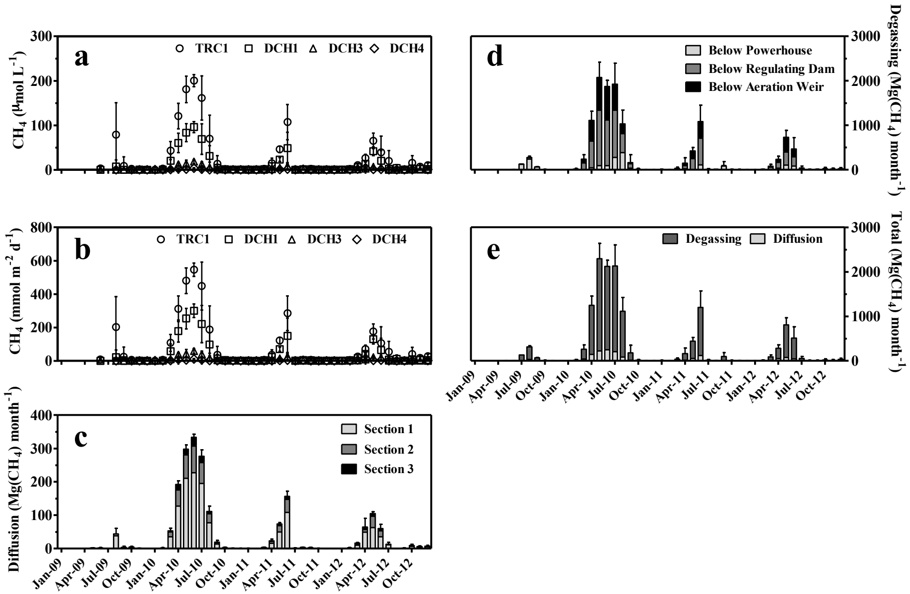


Figure 4. Methane concentrations and emissions downstream of the powerhouse of the Nam Theun 2 Reservoir between 2009 and 2012. **(a)** Time series of CH_4 concentrations at the stations TRC1, DCH1, DCH3 and DCH4, **(b)** diffusive fluxes at the stations TRC1, DCH1, DCH3 and DCH4, **(c)** emissions by diffusive fluxes in the Sects. 1–3 (see Fig. 1), **(d)** degassing downstream of the powerhouse, the regulating dam and the aeration weir, **(e)** total emissions by degassing and diffusion downstream of the Nakai Dam.

BGD
12, 11313–11347, 2015

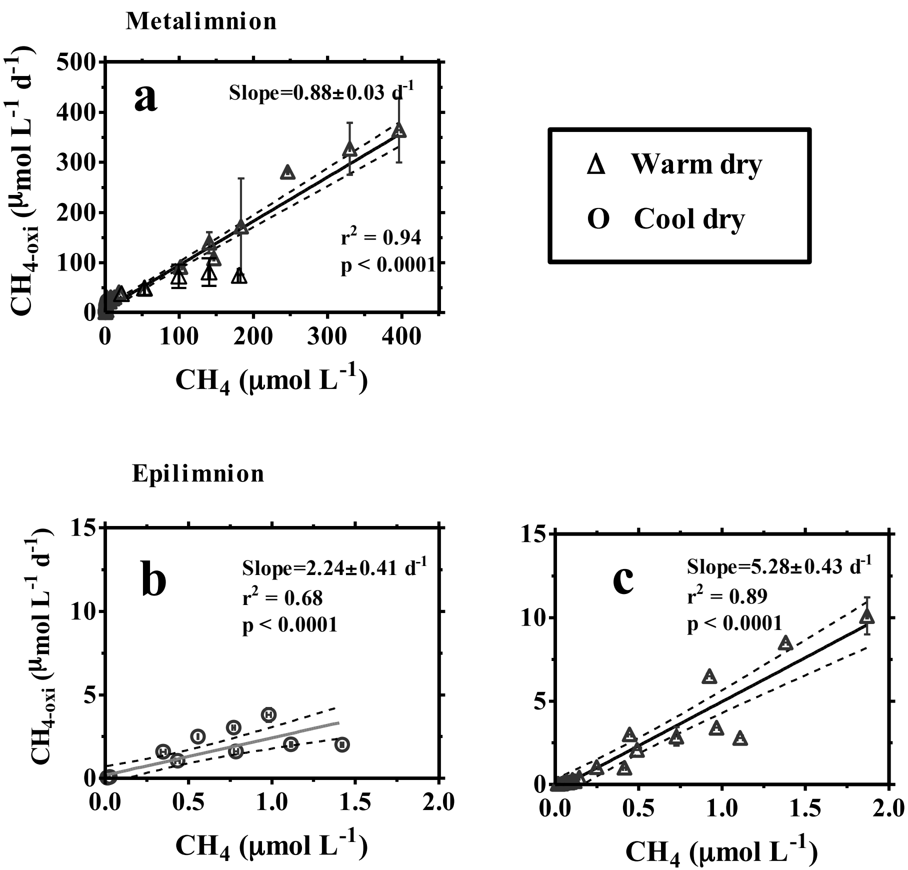


Figure 5. Linear relationships between methane (CH_4) concentrations and aerobic methane oxidation in the **(a)** metalimnion, **(b)** the epilimnion in the cool dry season and **(c)** the epilimnion in the warm dry season at the Nam Theun 2 Reservoir.

BGD
12, 11313–11347, 2015

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion