CLEAN DEVELOPMENT MECHANISM
PROPOSED NEW BASELINE AND MONITORING METHODOLOGIES
(CDM-NM) Version 01

CONTENTS

Section I. Summary and applicability of the baseline and monitoring methodology

1. Methodology title (for baseline and monitoring)

Hydropower Projects that Create New Reservoirs or Expand Existing Ones.
Version 3
February 14, 2007

If this methodology is based on a previous submission or an approved methodology, please state the reference numbers (NMXXXX/AMXXXX/ACMXXXX) here. Explain briefly the main differences and their rationale.

This is a new methodology, but what originally submitted as NM0121. This is a revision of that original submission based on comments from the Methodologies Panel.

2. Selected baseline approach from paragraph 48 of the CDM modalities and procedures

X Existing actual or historical emissions, as applicable;
☐ Emissions from a technology that represents an economically attractive course of action, taking into account barriers to investment;
☐ The average emissions of similar project activities undertaken in the previous five years, in similar social, economic, environmental and technological circumstances, and whose performance is among the top 20 per cent of their category.

Explanation/justification of choice:

This project will compare the project scenario with what the emissions would have been from the continuing of fossil fuels used to generate electricity. Thus, comparing to historical emissions, which would have occurred with under the baseline scenario, is appropriate.

3. Applicability conditions

Methodology procedure:

This method applies to situations in which:

- The project will provide electricity to the electric grid, displacing power that would otherwise be provided by other generating sources through the operation and expansion of the electric sector. The geographic and system boundaries for the relevant electricity grid can be clearly identified and information on the characteristics of the grid is available;

- The project is in an electric sector that is not dominated by generating sources with zero- or low-operating costs such as hydro, geothermal, wind, solar, nuclear, and low-cost biomass, and this fuel mix is expected to persist for the duration of the crediting period;

Also, this methodology will apply in cases where reservoirs are created or expanded as a result of a hydroelectric project.

Explanation/justification:

This methodology relies on the basic approach described in ACM002 but tries to address the impact on greenhouse gas emission reductions from the creation of a reservoir. The availability of data will be critical to complete these additional steps of analysis. As with ACM002, the electricity must be displacing at least some portion of fossil fuel generation and address the potential of cross border issues with imports of electricity.

4. Summary description of major baseline and monitoring methodological steps

a. Baseline methodology:

This methodology will use the elements of ACM002 to quantify the emission reductions from a renewable energy project and make allowances for the impact of creating a reservoir using the most advanced metering and monitoring techniques. The elements from this methodology will include use of the Executive Board-approved additionality tool, as well as the combined margin approach to determine the baseline emissions factor.

In addition, this methodology will propose a conservative approach to make an allowance for cases when grid in question is extremely small and/or a significant proportion of the additional generation will be used to meet demand previously unmet by the grid. This is the situation in many of the poorest parts of the world, particularly countries with a very small percentage of the population served by the grid. In some cases, much of the electricity from a renewable energy project will displace both off-grid diesel and grid-connected electricity. In cases when the hydroelectric facility is displacing a significant portion of off-grid diesel generation, the project developer, upon providing clear evidence that this is the case, can assume an emission coefficient for a modern high efficiency diesel generating unit (as is allowed for in the small-scale methodology for renewable energy), as long as it is lower – and thus more conservative – than the average TCO2/MWH ratio from any grid-connected plants.

While it is clear that this methodology covers projects that do not fall into the small-scale category the diesel-generation default supplied by the small-scale methodology is quite conservative and appropriate in certain cases. It is conservative since it assumes that all the diesel generation is modern and highly efficient, which in many cases is not the case. It is appropriate because it allows the project developer to more accurately and conservatively extract the real emission-reduction picture from project boundary and opens up the poorest countries and most underdeveloped electricity supply systems to CDM projects which might otherwise be passed over for lack of an appropriate emission measurement tool.

b. Monitoring methodology:

Reservoirs: This methodology allows the approach presented in ACM002 to be applied in cases where reservoirs are created or expanded. Studies indicate that hydroelectric power reservoirs can emit substantial amounts of methane, as well as CO2. Methane is emitted from reservoirs that are stratified and where the bottom layers are anoxic (lacking oxygen), leading to degradation of biomass through anaerobic processes. Where the water is well oxygenated, degradation of biomass generates carbon dioxide, not methane. Based on extensive research and field measurements, it is currently impossible to tell beforehand how much reservoir emissions there will be without actual measurements that take place after the reservoir is created. Emissions will vary depending on a number of factors, and thus the most practical way to determine emissions is to simply monitor them after the dam impoundment takes place.

There are three types of emissions that will be considered here:

- Bubbling: Methane forms in sediments when the decomposition of organic matter exhausts all other available oxidants (dissolved oxygen, nitrate, and sulfate). When methane concentrations become sufficiently high, a separate gas phase forms that eventually coalesces into bubbles below the sediment–water boundary. The methane that is emitted in this case is called bubbling.[1]

- Diffusion: Diffusion are emissions of GHGs that take place above the sediment-water boundary and generally take place in deeper, colder, less productive settings.

- Degassing: Degassing represents GHG emissions associated with turbulent conditions found at the turbines and spillway outflows. Once water goes through a hydroelectric facilities, they may release gases at the downsteam end. This must also be accounted for.

This methodology will require the project participants to measure the greenhouse gas emissions coming from the reservoir using techniques described in the monitoring methodology. The project developer will measure these emissions from the reservoir and subtract them from any CO2 savings identified from the renewable energy source displacing fossil fuels. Finally, the project participants will be required to estimate the baseline case changes in carbon stock that would have occurred if the land was not inundated. This last point is important because it measures the change in carbon stocks if the project did not occur. While the sampling of reservoir emissions measures the greenhouse gas release of the entire carbon stock that will be inundated, this process does not account for the changes in carbon stock if the project were never built. For example, if the dam were not constructed, previously forested land might otherwise be sequestering carbon. Thus, during the crediting period, it is important to measure using adjacent sample plots, the amount of carbon that could be sequestered in the absence of the project in order to better reflect the project emissions. This process is described in the project emissions section.

[1] "Physical Controls on Methane Ebullition from Reservoirs and Lakes" by JENNIFER JOYCE PAUL W. JEWELL. *Environmental & Engineering Geoscience*, Vol. IX, No. 2, May 2003, pp. 167–178.

Section II. Baseline methodology description

1. Project boundary

Methodology procedure:

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Emissions sources included in or excluded from the project boundary [add/delete gases and sources as needed]

	Source	Gas	Included?	Justification / Explanation
Baseline		CO_2	Yes	Displaced electricity will be from fossil fuels, the combustion of which emits CO2.
		CH_4	No	Pre-dam emissions from lands that will be inundated may be included
		N_2O	No	Pre-dam emissions from lands that will be inundated may be included
Project Activity		CO_2	Yes	Project emissions from reservoirs include CO2
		CH_4	Yes	Project emissions from reservoirs include CH4
		N_2O	No	Project emissions from reservoirs include N2O, but they are very small and can be excluded

Explanation/justification:

The **spatial extent** of the project boundary includes the project site and all power plants connected physically to the electricity system that the CDM hydro facility is connected to. For the purpose of determining the build margin (BM) and operating margin (OM) emission factor, as described below, a (regional) **project electricity system** is defined by the spatial extent of the power plants that can be dispatched without significant transmission constraints. Similarly, a **connected electricity system,** e.g. national or international, is defined as a (regional) electricity system that is connected by transmission lines to the project electricity system and in which power plants can be dispatched without significant transmission constraints. In determining the project electricity system, project participants should justify their assumptions. Electricity transfers from connected electricity systems to the project electricity system are defined as **electricity imports** and electricity transfers to connected electricity systems are defined as **electricity exports**.

2. Procedure for selection of the most plausible baseline scenario

Methodology procedure:

The project developer will use the same methodology in ACM002 to analyze the potential scenarios and undertake the analysis required to ensure that of all the alternatives, none is likely to happen except the baseline scenario. The project developer can also use Step 1 of the Additionality Test tool to look at the potential scenarios. In the case of a hydro project, possible alternatives could include, (1) other zero emitting energy resources (wind or biomass); (2) developing the hydro-project without the involvement of CDM; (3) importing more electricity; (4) using other fossil fuels to generate that electricity or continuing with the current situation; or (5) doing nothing and facing possible supply constraints or more off-grid resources like diesel generation. The project developer should review these and other possible scenarios, ensure that one or more alternative is legal under local laws, and develop an analysis for why options that provide the same or similar levels of GHG emissions as the proposed hydro project are not able to be implemented.

Explanation/justification:

ACM002 adequately addresses the issues raised in developing a baseline for this methodological approach. The key difference of the impact of the reservoir has on emission reductions is really the only difference between this methodology and ACM002.

3. Additionality

Methodology procedure:

The methodology would propose that the project participants use the "Tool for the demonstration and assessment of additionality.

Explanation/justification:

The Additionality test tool is standard use in ACM002, which this methodology is based on. The five steps can adequately determine if the project would have happened without CDM.

4. Baseline emissions

Methodology procedure:

1. Baseline Emissions from Fossil Fuel-Generated Electricity: Baseline emissions (*BEy* in tCO_2) are the product of the baseline emissions factor (*EFy* in tCO2/MWh) multiplied by the electricity supplied by the project activity to the grid (*EGy* in MWh), as follows:

$BEy = (EGy * EFy) - \Delta C_{ACTUAL,y}$

Because this is a hydropower project, the baseline scenario utilizes the method as approved in the Approved Consolidated Methodology for zero-grid connected renewables. A baseline emission factor

(*EFy*) is calculated as a combined margin (*CM*), consisting of the combination of operating margin (*OM*) and build margin (*BM*) factors. Calculations for this combined margin must be based on data from an official source (where available) and made publicly available. The combined margin approach is outlined in ACM002. The baseline scenario also includes an adjustment for any carbon sequestration that would likely have occurred in the baseline case in the area inundated by the reservoir $\Delta CO2_{FF}$ in year y.

As with ACM002, in most cases EFy will be adequately dealt with through the combined margin approach outlined by ACM002. In some cases, however, as clearly recognized by the Methodology Panel[2], the combined margin approach does not necessarily give the most appropriate or conservative outcome. To deal specifically with cases in which the grid is very small (under 5 generating units of greater than 15MW capacity[3]) or underdeveloped providing electricity to less than 50% of consumers it would be more appropriate to take the more conservative of the following: a) the combined margin as outlined in ACM002 using the best available data or b) the small scale default for high efficiency diesel generation .8 Tonnes of CO_2 per MWh. By definition, this approach would provide a more appropriate and conservative result than employing the combined margin approach alone since it takes the more conservative of the two numbers. It also seems appropriate given that in many of the CDM countries/electricity grids that fit this definition are likely to rely on less than highly efficient diesel generators to meet the electricity needs of many of its people and may be the most likely source of new generation capacity given the relatively low investment costs and investment barriers when compared to large scale grid connected electricity. For example, in a case where fewer than five generation plants of greater than 15MW exist on the grid and analysis showed using the combined margin approach that the emissions factor was 0.95 tonnes of CO_2/MWH, the combined margin could be over-counting the emissions impact of a renewable energy project, if that project replaced less carbon-intensive diesel units. Taking the small scale default of .8 TCO_2/MWh would produce a more conservative and likely more accurate result.

A hydro-generated MWH may be displacing the off-grid diesel or may be displacing a grid-connected plant(s). But by using the more conservative number, the project participants would know that they are, if anything, undercounting emission reductions. Temporal factors would therefore not have to be explicitly taken into account, and the project participants would not have to worry about whether that MWH is generated in the wet season or dry season or if the plant is used as a peaking plant or baseload plant, etc. (which could significantly complicate the methodology and possibly raise the level of uncertainties).

2. Emissions from Reduction in Carbon Stocks: If the dam project would not have occurred, the land covered by the reservoir would otherwise not have been flooded and thus might have been a net carbon sink. This part of the methodology accounts for carbon that would not be sequestered because of this project. This deals with the original MP reviewer's comments about pre-dam emissions, when it was asked, "As a baseline scenario is possible when a new reservoir is being built, the quantification of pre dam

[2] See for example the presentation given by Michael Lazarus at the World Bank sponsored Workshop on CDM Methodologies and Technical Issues Associated with Power Generation and Power Saving Project Activities in Montreal, December 3, 2005.

[3] The numbers for this definition were chosen based on the current rules of the combined margin approach in ACM002 which suggests one approach to calculating the build margin would be based the most recent 5 plants installed. It would seem reasonable that if there are less than five plants meeting the Marrakech Accord's Definition for a large scale generating unit, then another approach might provide a more conservative result since the most recent five plants or the most recent 20% may include very old units which give little insight into future investments.

emissions should be elaborated on (e.g. describe the consequences if the pre-dam situation would be a carbon sink or carbon emitter)."

To deal with this issue, the project participants suggest following approach based on the Good Practice Guide on LULUCF projects to calculate changes in carbon stock in each type of land that will be flooded. The project participants will prepare sample control plots near the project site that correspond to the characteristics of each land type inundated in reasonable proximity to the reservoir site. The project participants would measure changes in carbon stock using sampling methods stated in the GPG to determine net GHG emissions (or sequestration). Each category of sample plot would develop a change in carbon stock in tones of CO_2/hectare/year and multiply that number by the number of hectares flooded (at maximum reservoir size) that correspond to each land category. The summation of these categories will equal the amount of carbon not being sequestered as a result of this project and provide a more accurate reflection of the baseline scenario.

The project participants will follow the Chapter 3 of the Good Practice Guidance on Land Use, land Use Change and Forestry (GPG/LULUCF) (IPCC 2004) for the formulas for measuring changes in carbon stock. Section 3.2.1, for example states that the greenhouse gas inventory for the land-use category 'Forest land Remaining Forest land (FF)' involves estimation of changes in carbon stock from five carbon pools (i.e. aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter), as well as emissions of non-CO_2 gases from such pools. The summary equation, which estimates the annual emissions or removals from FF with respect to changes in carbon pools is as follows:

$$\Delta C_{FF} = (\Delta C_{FFLB} + \Delta C_{FFDOM} + \Delta_{CFFSoils})$$

where:

ΔC_{FF} = annual change in carbon stocks from forest land remaining forest land, tonnes C yr^{-1}

ΔC_{FFLB} = annual change in carbon stocks in living biomass (includes above- and belowground biomass) in forest land remaining forest land; tonnes C yr^{-1}

ΔC_{FFDOM} = annual change in carbon stocks in dead organic matter (includes dead wood and litter) in forest land remaining forest land; tonnes C yr^{-1}

$\Delta C_{FFSoils}$ = annual change in carbon stocks in soils in forest land remaining forest land; tonnes C yr^{-1}

ΔCO_{2FF} (To convert tonnes C to tonnes CO_2, multiply the value by 44/12).

The section 3.2.3, Chapter 3 of GPG/LULUCF outlines the methodology for determining changes in carbon stock for the five carbon pools. In subsequent chapters of the GPG, the procedures for determining the changes in carbon stocks for wetlands, croplands, grasslands, settlements and other lands are outlined in detail. Using sample plot measurements, the project developers will follow the GPG procedures and formulae to determine the changes in carbon stock in the baseline and during the project period to determine the CO_2 sequestered.

With regards to the number of sample plots and stratification procedures, the project participants should follow the approved afforestation and reforestation baseline methodology AR-AM0001, "Reforestation of Degraded Land". The emissions from each plot shall be multiplied by the number of hectares of flooded reservoir area that correspond to the type of land use.

Baseline emissions from change in carbon stocks will thus equal:

$$\Delta C_{ACTUAL,t} = \sum_i \sum_j \sum_k \Delta C_{ijk,t}$$

where:

$\Delta C_{ACTUAL,y}$ actual net greenhouse gas removals by sinks, tonnes CO_2-e yr^{-1} for year y

$\Delta C_{ijk,y}$ verifiable changes in carbon stock change in carbon pools for stratum i sub-stratum j species k, tonnes CO_2 yr^{-1} for year y.

List of Data Sources: Electricity emissions factor (calculated from best available official statistics, scientific studies, etc. including data such as:

- Fuel emissions factor (from IPCC sources) for each fuel used in other power plants service the grid, including the power plant that will see the combined-cycle turbine installed.
- Fuel use of plants that make up the build and operating margins
- Total electricity generated by CDM project (measured)

This type of data for similar projects has been approved as appropriate by the CDM Executive Board.

Vintage and spatial level of data: National (grid) level data will be required to determine the carbon emissions factor. The measured production of electricity by the CDM project will be measured on site. The reservoir emissions will be measured at the reservoir site, and will thus be local. With regards to the vintage of baseline data when the grid is too small – and the bulk of the displaced electricity comes from off-grid, captive power sources – the emissions factor of the diesel generators can be measured for one year before the project begins. One year of baseline data should be sufficient because it can be assumed that on-going use of diesel generators will continue to degrade efficiency over time. Assuming a constant baseline emissions factor is therefore conservative since in the absence of the project, that emissions factor would have likely gotten worse.

Explanation/justification:

This methodology expands the scope of ACM002 to projects that involve the creation or expansion of a reservoir. By calculating potential impact of the land area that will be inundated by the reservoir as a carbon sink or emitter in the baseline, the project developer can accurately and conservatively calculate the emission reduction impacts of the project activities. The approach used for this calculation does not try to reflect all the intricacies of the approved and proposed AR methodologies. It requests the project developer to implement the sampling methods to assess the changes in the carbon stock changes and GHG emissions in the land types inundated with water and use the IPCC guidelines to calculate the net impact of land use change on greenhouse gas emissions. For equivalent comparison, similar procedures are implemented in the baseline and project scenarios to estimate the impact of the land area to be inundated by water under the project.

In addition, the project developer is suggesting a more conservative approach to the ACM002 combined margin in small or under-serving grids. In these cases, the combined margin should still be used, but should be capped at 0.8 Tonnes of CO_2 per MWh. This is appropriate as many of these projects in small or underserved grids will be replacing diesel generators.

5. Project emissions

Methodology procedure:

Part I

The literature recognizes three pathways of GHG emissions from reservoir: gas emitted within the reservoir (diffusion and bubbling) and gas exported to downstream aquatic systems (including degassing). The two most important GHG are CO_2 and CH_4.

Overall, the N_2O fluxes are negligible. N_2O is an intermediate by-product of two microbiological processes: denitrification (anaerobic process) and nitrification (aerobic process). Although N_2O has a global warming potential (GWP) 310 times greater than CO_2, the fluxes are negligible in the overall GHG budget (including all three gases) as measured in boreal reservoirs and in one Brazilian reservoir (Table 1). Moreover from the studies in Petit Saut reservoir, the N_2O fluxes are reported to not vary much throughout the system (upstream of the impoundment, within the reservoir and downstream of the reservoir (Delmas et al 2004). This absence of variation indicates some kind of an equilibrium condition. Althoughit is not possible to assume that all reservoirs will behave accordingly, the level of evidence (or the absence of data) so far indicates that N_2O is not a major concern. Therefore, the sampling protocol will not consider N_2O fluxes[4].

The CO_2 and CH_4 gas concentrations in water can be influenced by several factors (Table 2), including the reservoir metabolism (photosynthesis rate and organic matter decomposition rate into the water column and sediment), the water residence time, determined in part by the hydrological regime of the inflowing river, and the water oxygen content, which affects the rate of methane consumption by methanotrophic bacteria. The sampling approach, having to encompass all three components, will have to be adapted to the local reservoir characteristics.

[4] The FTIR (Fourier Transform Infrared) detection technique to measure diffusive GHG enables N_2O measurements.

TABLE 1: N_2O fluxes (mg m^{-2} d^{-1}) in boreal and tropical reservoirs and relative importance in the global GHG budget

Reservoirs	Sampling year	N_2O (mg N_2O m^{-2} d^{-1})		% of total GHG emissions in CO_{2eq}	Source
		mean	SD		
Eastmain-1 (summer), Canada	2006	0.26	0.33	0.9%	Environnement Illimité Inc., 2006a
Eastmain-1 (fall), Canada	2006	-0.05	0.45	-0.2%	Environnement Illimité Inc., 2006a
La Grande Complex, Canada	2006	0.12	0.28	3.1%	Environnement Illimité Inc., 2006b
Experimental Lakes Area (ELA), Canada	2000	0.0012	0.0002	< 1 %	Hendzel et al., 2005
Experimental Lakes Area (ELA), Canada	2001	-0.0030	0.0006	< 1 %	Hendzel et al., 2005
Serra da Mesa, Brazil	2004	0.08	0.52	3.1%	Sikar et al., 2005

TABLE 2: Temporal and spatial factors determining GHG emissions in tropical reservoirs

Scale↓	Emission type →	Diffusion		Bubbling
	Gas →	CO_2	CH_4	CH_4
Temporal	Daily	Photosynthesis (Fee and al., 1990) and photooxidation (Graneli et al., 1998)	Oxidation by methanotrophic bacteria (Matthews et al., 2005)	Diurnal cycle (daytime > night time) (Keller and Stallard, 1994)
	Meteorological variables	Wind (Cole and Caraco, 1998), waves (Wanninkhof, 1992), rainfall events (Ho et al. 1997; Guérin et al. 2006, JMS), atmospheric pressure (Stumm and Morgan, 1981)		Temperature (Galy-Lacaux et al., 1999), wind (Keller and Stallard, 1994), waves (hydrostatic pressure), atmospheric pressure (Mattson and Likens, 1990)
	Seasonal (hydrological cycle)	Water residence time associated with the alternation of wet and dry season (Abril et al., 2006). Flooding can destratify the water column and bring water richer in GHG near the water surface (Abril et al., 2006).		
	Multiaxe	Decreasing stock of flooded carbon, mean annual rainfall (more GHG diffusion during dry years) (Abril et al., 2005, 2006)		Decreasing stock of flooded carbon
Spatial	Depth		Oxidation probability increases at greater depth (longer water column) (Galy-Lacaux et al., 1999)	Hydrostatic pressure (bubbling limited to the 0-10 m range) (Galy-Lacaux et al., 1999; Bastviken et al., 2004), correlated with the presence of anoxia in the sediment (Bastviken et al., 2004)
	Flooded vegetation biomass and soil organic matter pool	Organic matter and nutrient availability (photosynthesis)	Organic matter availability	Organic matter availability
	Stratification	Sediment deposition affects light availability (influence on photosynthesis) (Cole and Hannan, 1990)	Oxygen content affects methanotrophic rate, Sediment deposition affects light availability (inhibition of methanotrophic bacteria) (Dumestre et al., 1999)	
	Water residence time (embayment vs main stream)	Accumulation of gases with high water residence time (Abril et al. 2006)		

Diffusion

Gas fluxes at the air-water interface are dependant on two main factors: the gas concentration gradient between air and water, and the gas exchange coefficient (k) for a given type of gas at a given temperature (Cole and Caraco, 1998). The flux equation is:

$$Flux = \propto k(P_{gas} K_h - [gas]_{sat})$$

where:

$[gas]_{sat}$ gas concentration the water would have at equilibrium with the overlaying atmosphere

K_h Henry's constant for the gas at a given temperature

P_{gas} I partial pressure of the gas in the surface water

P_{gas} x K_h product of partial gas pressure and Henry's constant represents the concentration of the gas in the water,

$\propto$ chemical enhancement factor

The diffusive fluxes show variation according to the local weather conditions. For example, the gas exchange coefficient (k) is dependant on wind (Wanninkhof, 1992; Cole and Caraco, 1998), rainfall (Ho et al., 1997; Guérin et al., 2006, JMS) and convection.

Bubbling

Bubbling is directly related to the rate of sediment/flooded soil methanogenesis (Keller and Stallard, 1994). This anaerobic decomposition process is determined by the organic matter availability and temperature (Kelly and Chynoweth, 1981). Although the oxygen availability will condition the CH_4 diffusion rate with transformation into CO_2 in oxic conditions, bubbling of CH_4 can escape oxidation since bubbles are rising up rapidly toward the water surface. The majority of bubbles are composed at 50 to 80% of CH_4 (Abril et al., 2005), bubbles being richer in CH_4 at shallow depths.

CH_4 bubbling is typically limited to shallow areas (0 to 4 m and up to 10 m) (Keller and Stallard, 1994; Galy-Lacaux et al., 1999; Bastviken et al., 2004) because of the relatively low hydrostatic pressure. Bubbles can escape from deeper sediments (> 10 m) but will disaggregate and dissolve into the water column during their ascent (Keller and Stallard, 1994). Changes in hydrostatic pressure, initiating bubbling episodes, can result from meteorological factors such as wind (Keller and Stallard, 1994) and atmospheric pressure (Mattson and Likens, 1990) and changes in water level (hydrological cycle with high and low water phases, water level of the reservoir). Naturally, bubbling is typically higher during the day than during the night as windy conditions will generally prevail (Keller and Stallard, 1994).

Gas exportation to downstream aquatic systems

Degassing represents GHG emissions associated with turbulent conditions found at the turbines and spillway outflows. Since CH_4 solubility is around 25 times lower than that of CO_2, turbulent conditions will usually result in CH_4 being emitted in higher proportion than CO_2 (Abril et al., 2005). The calculation of the degassing component by measuring the GHG concentrations both upstream and

downstream of the dam[5], would exclude the GHG emissions in downstream ecosystems that would not have otherwise occurred in the absence of the hydroelectric project. Therefore, the total export of GHG from the reservoir to downstream aquatic systems should be estimated, without any distinction of the way the gases are emitted.

Sampling approach

Part II. Determination of the sampling effort

If a reservoir being investigated has already been the subject of GHG measurements, available data should be used to determine the variability and mean fluxes. This estimation should be followed with a statistical method to calculate the number of samples needed to achieve the acceptable confidence levels and to meet the objectives of the GHG sampling program.

When there is no information available, the number of required sampling stations can usually only be estimated after statistical analysis of a preliminary sampling program in the best of cases. Because the CDM program requires monitoring of GHG emissions, it is unlikely that a preliminary survey can be carried out. The number of samples theoretically required is often unrealistic and technical and economical constraints have to be considered in the selection of the number of sampling stations in the study area. Therefore, an alternate approach is required to establish the number of stations (spatial coverage) and the number of field campaigns (temporal coverage).

A bootstrap method was applied to determine the uncertainty of the estimate for different scenarios of sampling effort. By choosing an uncertainty of less than 10%, the level of effort required can be determined sing different combinations of sampling stations and field campaigns. This approach is based on real field data from a boreal reservoir that have been adjusted to known estimates of tropical reservoir. This approach assumes that the reservoir being investigated will behave following the same distribution as the data used for the simulation. To verify this, the uncertainty of the yearly estimate that will be obtained for the reservoir being investigated will have to be calculated after the first year of monitoring so that the premises established here are verified.

General approach

The bootstrap method is a straightforward approach that serves to calculate the 95% confidence interval of an estimate (Efron and Tibshirani 1986, Manly 2006). This technique involves successive random sampling with replacement within a data set (n=2000). It was applied on a hybrid dataset (simulated and real data) to obtain different combinations of number of sampling campaigns and stations in order to verify how the uncertainty around the estimate (95% confidence interval) changed for different scenarios. This will serve to determine the required level of effort for the overall sampling approach. In addition, this statistical method will serve to demonstrate how it can be applied to a data set for the calculation of the uncertainty around the mean yearly flux.

The main advantage of the bootstrap method is that no particular assumption about the data distribution, such as normality, is required (Legendre and Legendre, 1998). With this approach, there is no need to follow classical algorithms of uncertainty propagation (Taylor, 1997), which assume normality of the

[5] The calculation is done by subtracting the GHG concentration in the natural river measured downstream of the dam from the GHG concentration just upstream of the dam at the water intake, multiplied by the discharge through the turbines.

random error. One only has to assume independence of the errors. The approach presented herein will have to be applied to the data set from the desired reservoir after the first year of the monitoring program. This will verify if the proposed sampling effort (30 stations over the whole reservoir) is sufficient to reach the expected level of precision for the mean yearly flux.

A typical data set comprising all three components of GHG emissions, diffusion, bubbling and degassing, was used. Because a real data set for a tropical reservoir was not available, it was chosen to simulate a data distribution by using actual data from a Canadian boreal reservoir for the diffusion emissions. The fluxes were then adjusted to comparable values that could be expected from a tropical reservoir based on a succinct literature review. This approach is interesting as it integrates real factors that would influence the field measurements.

The data distribution for the diffusion component was constructed using the median values of a distribution of the mean values and corresponding coefficients of variation of CO_2 and CH_4 emissions obtained from published data in tropical reservoirs (Table 3). The distribution of mean values was used because the raw data were not available. In order to integrate a more realistic variance in the simulated distribution, real data from a 2006 survey were used on a boreal reservoir (Eastmain-1 reservoir, Québec). The objective was to obtain a data set with a realistic variance that would take into account the instrumentation bias during sampling as well as the climatological bias. A correction factor was applied to the data in order to obtain a mean value comparable to that from a tropical reservoir (boreal reservoirs usually emit less GHG than tropical ones). The median and mean values obtained were then compared to observed values from tropical reservoirs (Table 4). This is acceptable since the coefficients of variation are comparable for the two types of environment.

TABLE 4: Median and mean values (mg m^{-2} d^{-1}) of CO_2 and CH_4 emission through diffusion and bubbling in tropical reservoirs (see Table 4) compared to values used for the bootstrap simulations.

		CO_2 diffusion (mg CO_2 m^{-2} d^{-1})	CH_4 diffusion (mg CH_4 m^{-2} d^{-1})	N_2O diffusion (mg N_2O m^{-2} d^{-1})	CH_4 bubbling (mg CH_4 m^{-2} d^{-1})
Tropical reservoirs	Median	4660*	30	NA	20
	Median C.V. (%)	80%	110%	NA	30%
	Mean	6175*	90	NA	160
	Mean C.V. (%)	90%	115%	NA	30%
Simulated data set	Mean	8,114	23	0.16	24
	SD	6,299	17	0.17	20
	C.V. (%)	78%	73%	111%	83%
	n	30	30	30	20

C.V.: SD/mean
* negative flux estimates excluded.

Determination of the level of effort

Confidence intervals of GHG emissions estimated by the bootstrap method are presented in Table 5 and Table 6, for 30 and 20 stations respectively per sampling campaign. These tables show the relative importance of each GHG process within the annual budget. The contribution of CH_4 degassing to the annual GHG emission budget of a tropical reservoir is comparable to diffusion and bubbling combined.

For a better visual representation, the total average fluxes from Table 5 and Table 6 are presented in Figure 1. The different sampling strategies simulated target an error of ± 10 %. Furthermore, the error between 30 and 20 stations is in the same range. But in order to have a more representative sampling strategy, 30 stations should be selected in the case of tropical reservoir as greater variation is expected.

The simulations also reveal that 4 sampling campaigns are sufficient to attain an acceptable error of ± 6.2%. Increasing the number of campaigns will only result in a small gain in term of the small range of confidence interval. More than 4 sampling campaigns should be considered if seasonal variations are significant.

Therefore, this methodology recommends 30 stations and 4 campaigns for first year measurements in a tropical reservoir. The suitability of the proposed level of effort with regard to the desired level of precision (assumed here to be ± 10% of total yearly GHG emission) will have to be tested when data from the reservoir will become available, by following the bootstrap method applied here. Depending on the bootstrap results, the number of stations or the number of campaigns may be downscaled if the simulated uncertainty is better than 10%, or increased in the opposite case.

The main purpose of any sampling protocol is to produce a representative sample of the statistical population of interest, i.e., a sample that adequately reflects the properties of interest of the parent population. From that sample, unbiased estimates of the means of the variables of interest can be obtained. The uncertainty of the estimate will be directly dependent upon the sampling design (e.g. random, stratified, systematic, adaptive; see Krebs, 1999) and the sampling effort (number of observations).

Uncertainty of the estimate and relative importance of the main GHG pathways

The uncertainty of the estimate as reflected through 95% confidence interval not only depends on the sampling effort (Figure 1) but also on the relative importance of the three main pathways of GHG emissions (Figure 2).

Using a fixed number of stations (n=30) and number of field campaigns (n=4) it is possible that the relative importance of the bubbling flux is less than 20% and the downstream export is between 10 and 60%, permitting the uncertainty to be kept below 10%. Furthermore, in reservoirs where the downstream exportation of GHG is an important component of the overall annual GHG budget, a more precise estimate can be obtained for a given effort since this component is relatively straightforward to measure and calculate precisely (compared to bubbling, for example).

The following general observations can be made with regard to the type of reservoirs and the effect of the relative importance of the GHG pathways:

- The relative importance of the three pathways of GHG emissions will change according to the morphology and limnological characteristics of the reservoir being investigated, hereby requiring the adaptation of the sampling plan and approach to the characteristics of the reservoir being investigated.

- In reservoirs with short residence time, the downstream exportation of GHG should be an important component of the overall annual GHG budget and a better resolution of the emissions will likely be obtained for a given effort since degassing is relatively straightforward to estimate precisely, compared to bubbling, for example.

- In shallow reservoirs where bubbling (bubbling is limited to depths shallower than 10 m) is a significant component of the overall budget , the stratification of the sampling plan according to depth and the soil organic carbon pool (that is partly related to the vegetation type) will be necessary in order to obtain a representative estimate for this process. Although some authors report a lower coefficient of variation for CH4 bubbling than for diffusive fluxes (Abril et al., 2005), this component is likely more heterogeneous spatially than diffusive fluxes.

- Accordingly, in deep reservoirs characterized with relatively small shallow depths (0-10 m) where bubbling is negligible compared to diffusive fluxes, a systematic sampling plan may be more appropriate and manageable, especially in the case of elongated valley-type reservoir where change in vegetation and soil type with depth is important.

- Finally, reservoirs characterized by several large and shallow embayments, comprising different vegetation and soil types as well as different water residence times, will require stratification of the sampling plan as bubbling is likely more important in those remote locations than in the core of the reservoir.

TABLE 5: Bootstrap analysis results: annual CO_{2eq} budget (Gg of CO_{2eq}) and its 95 % confidence interval (CI) for 30 stations at each sampling campaign

		Number of sampling campaigns				
		2	**3**	**4**	**5**	**6**
CO_2 diffusion	Upper CI	53.6	51.7	50.7	50.0	49.7
	Average	44.2	44.3	44.5	44.4	44.4
	Lower CI	36.4	37.9	38.8	39.4	39.7
CH_4 diffusion	Upper CI	3.40	3.31	3.24	3.20	3.16
	Average	2.86	2.84	2.85	2.85	2.85
	Lower CI	2.37	2.44	2.48	2.53	2.56
N_2O diffusion	Upper CI	0.33	0.31	0.30	0.30	0.30
	Average	0.25	0.25	0.25	0.25	0.25
	Lower CI	0.19	0.20	0.21	0.21	0.22
CH_4 bubbling	Upper CI	0.61	0.58	0.56	0.57	0.56
	Average	0.48	0.48	0.48	0.48	0.48
	Lower CI	0.36	0.38	0.40	0.40	0.40
CH_4 degassing	Value	48	48	48	48	48
TOTAL	**Upper CI**	**105**	**103**	**102**	**102**	**101**
	Average	**96**	**96**	**96**	**96**	**96**
	Lower CI	**88**	**89**	**90**	**91**	**91**

TABLE 6 — Bootstrap analysis results: annual CO_{2eq} budget and its 95 % confidence interval (CI) for 20 stations at each sampling campaign

		Number of sampling campaigns				
		2	**3**	**4**	**5**	**6**
CO_2 diffusion	Upper CI	53.1	51.6	50.4	49.6	49.2
	Average	43.9	43.9	44.0	43.9	43.8
	Lower CI	35.9	37.3	38.2	38.8	39.4
CH_4 diffusion	Upper CI	2.81	2.73	2.69	2.66	2.61
	Average	2.40	2.40	2.40	2.39	2.39
	Lower CI	1.99	2.07	2.13	2.15	2.17
N_2O diffusion	Upper CI	0.33	0.31	0.30	0.30	0.29
	Average	0.24	0.24	0.24	0.24	0.24
	Lower CI	0.16	0.18	0.18	0.19	0.19
CH_4 bubbling	Upper CI	0.59	0.57	0.58	0.56	0.55
	Average	0.47	0.47	0.48	0.47	0.47
	Lower CI	0.37	0.39	0.38	0.39	0.40
CH_4 degassing	Value	48	48	48	48	48
TOTAL	**Upper CI**	**104**	**103**	**102**	**101**	**100**
	Average	**95**	**95**	**95**	**95**	**95**
	Lower CI	**87**	**88**	**89**	**90**	**90**

FIGURE 1: Summary of the bootstrap analysis for 2 to 6 campaigns and 20 and 30 stations

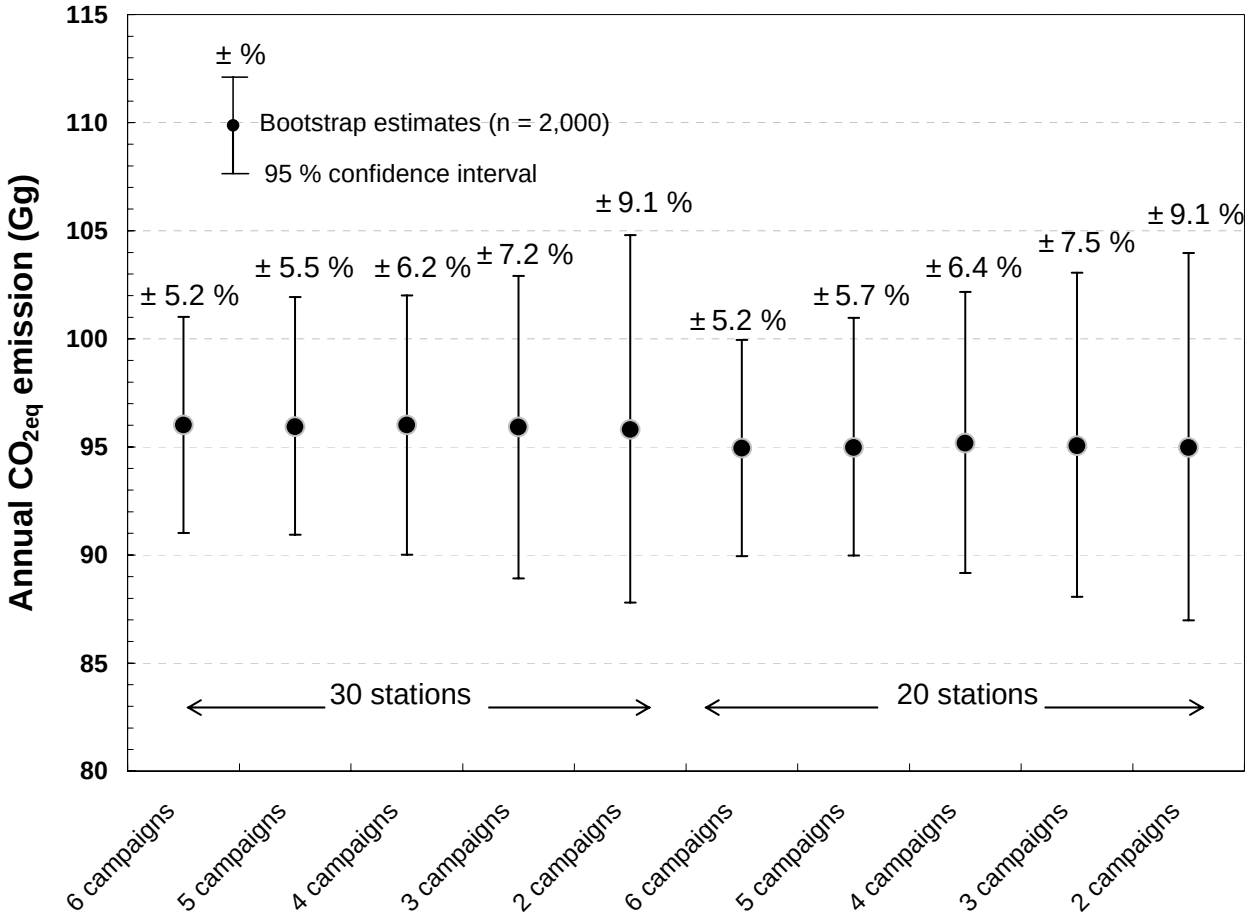
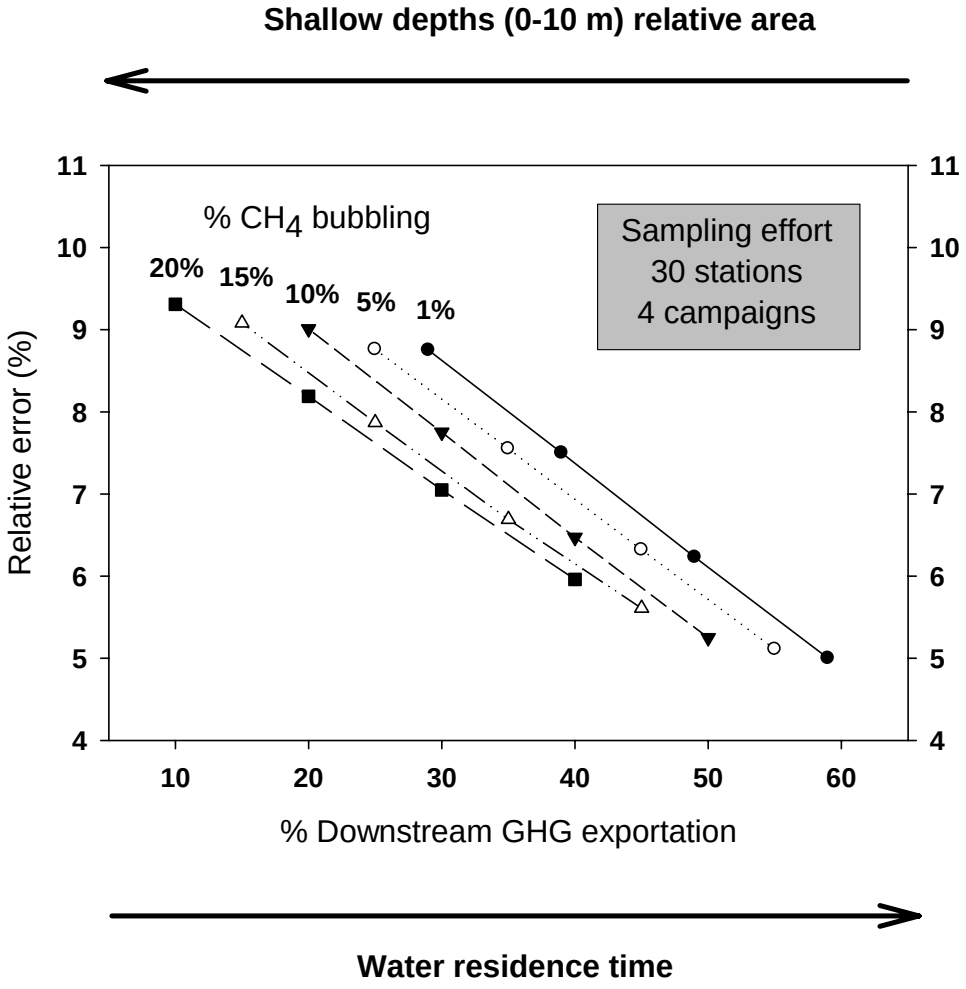


FIGURE 2: Influence of the relative importance of the three emission pathways within a reservoir (% (d a reservoir on the relative error (95% confidence limits) of the estimate of total GHG emission



Spatial distribution of sampling stations for the evaluation of gross GHG emissions

General considerations

It is recommended to evaluate the characteristics of the reservoir and to adapt the sampling plan accordingly. For the purpose of sampling design, the reservoirs are grouped into three main categories.

- Valley-type reservoir: characterized with a relatively short residence time, a large variation of vegetation and spoil type with depth. These reservoirs may be vertically stratified or not (thermocline).

- Lake-type reservoir: with a large surface area and vertically stratified (thermocline). The stratification of the reservoir will result in a two-layer system; the hypolimnion, influenced by benthic processes and the epilimnion, influenced by phytoplankton and macrophyte photosynthesis. These water masses will be affected by some horizontal mixing and display homogenous characteristics but limited vertical exchange of gases or nutrients (Wetzel, 2001). Therefore, measurements done at a given station may not be representative of the flooded carbon stock directly beneath it.

- Lake-type reservoir: with a large surface area and shallow depths. Bubbling fluxes should be relatively more important according to the surface area of the 0-10m depth range. Due to the absence of thermocline stratification, the measurements done at a given station should be more representative of the flooded carbon stock directly beneath it.

In suggesting the sampling plans, it is assumed that purely random distribution of sampling stations has a good chance of producing patterns that are segregated. However randomization may not always result in capturing all variables (Hurlbert, 1984). Therefore, the bases for distributing the sampling stations must be systematic along transect lines, a grid or a cluster of stratified study area.

Diffusive and bubbling fluxes

Valley-type reservoir

Diffusive fluxes

In **valley-type** reservoirs, the depth gradient is pronounced and changes in vegetation types will occur rapidly with changing depth. Furthermore, short residence time and possible large variations of the water level are conditions that should not favoured a direct relationship between the bottom carbon pool and the measurements directly above it.

The sampling stations (n=30) should be distributed along 10 transect lines (n=3 per transect). Each transect should be placed perpendicular to the shore and alternate between either sides. In this particular case, the shallowest station should be deeper than 10 m, unless the 0-10 m range accounts for a large surface area of the reservoir.

Bubbling fluxes

Because bubbling is limited to the 0-10 m depth range, all 30 stations will be distributed along transect lines running perpendicular to shore. Three stations per transect will be place at the 1 m, 3 m and 7 m

isobaths and the transect lines should be placed in continuity with those used for sampling of the diffusive fluxes.

Large, vertically stratified reservoir

Diffusive fluxes

Because there is not indication in the literature of the existence of a direct relationship between GHG diffusive fluxes at a given station and the pool of flooded terrestrial (vegetation and soil) organic matter immediately beneath it, a systematic sampling plan following a regular grid is suggested. All 30 stations should be placed at the nodes of a grid where each square is of equal surface area.

Bubbling fluxes

Because bubbling is limited to the 0-10 m depth range, all 30 stations will be distributed along transect lines running perpendicular to shore. Three stations per transect will be place at the 1 m, 3 m and 7 m isobaths. If shallow reefs occur within the reservoir, the transect line should originate from the shallowest point. It is possible that the number of non-contiguous shallow areas is greater than the number of transect (n=10). It is suggested to distribute the transect lines according to the relative importance of the surface area of the shallows.

Large, un-stratified reservoir

Diffusive fluxes

In this case, there is a better likelihood that measurements done at the surface are more representative of the organic carbon pool directly beneath it. If the organic carbon content in the soil is known, then it can be used to stratify the sampling plan. Otherwise, the type of vegetation can be used as a proxy.

Although a stratified sampling plan can be very advantageous statistically, as a mean of maximizing the precision around the mean for a given level of effort, it will create constraints in the framework of a monitoring program. There are several factors that can potentially affect the spatial distribution of GHG fluxes (Table 2), such as the type of flooded vegetation, soil organic matter pool and water depth. Taking all these factors into account within a stratified sampling plan can result in a quite high number of strata (CDM PDD version 03). Moreover, a high number of strata could make the sampling and data analysis more complicated. Most statisticians consider that, over six strata, there is no significant gain in precision to be had for a given level of effort.

Within those strata, the number of sampling stations (n=30) should be distributed evenly so that each sampling station covers the same surface area between all clusters.

Bubbling fluxes

The distribution of the sampling stations should follow the same general rules described above. Because that type of reservoir is likely shallower, there is a possibility that the depth will be generally shallower than 10 m. In such a case, stations used to monitor diffusive fluxes and bubbling fluxes will be the same.

Gas exportation to downstream aquatic ecosystems

In cases where the reservoir under investigation has not yet been flooded, it is recommended to measure the baseline concentrations of CO_2 and CH_4 in the river water along the future reservoir surface area. These measurements will serve as the comparative basis to the concentrations of CO_2 and CH_4 measured at the water intake or just upstream of the dam. The baseline data should be obtained at the same periods determined for the monitoring of diffusive and bubbling fluxes. The difference between those two concentrations will be multiplied by the discharge at the dam at the time of sampling to obtain the corresponding flux.

If the reservoir being investigated is already flooded, the baseline concentrations should be replaced by a reference concentration of CO2 and CH4. These reference concentrations would then be measured at each and every field campaign (n=4) from surrounding lakes or at the upstream reach of the reservoir where the main inputs are coming in. The latter location is possibly better as the limnological characteristics of the surrounding lakes may differ from those of the reservoir.

Temporal distribution of sampling campaigns

General approach

The sampling form should consider the hydrologic regime of the reservoir (for example, Tropical: two main seasons). During low flow conditions, the residence time of the reservoir will increase whereas it will be shorter during the flood period (Figure 3). For example, if the peak of the rain season is in September and the corresponding peak of the dry season is in March-April, the different water residence times will be well represented if sampling occurs in December, March, June and September, or in February, May, August and November (Figure 3). The date of the first campaign will be determined randomly between the months of December or February, with the following campaigns occurring 90 (365 days/4), 180 and 270 days later. The proposed approach prevents a situation where randomly-picked periods within each main seasons may be close together, resulting in long unsampled periods. Each year, the sampling campaigns will occur at the same dates.

The choice of the sampling period will be dictated by the local hydrological regime. It should be characterized following the same approach described here which refers to a reservoir located north of the equator (Figure 3).

This approach will enable to pair the observations after two or several years of sampling[6] and produce a two-way (space, time) factorial design that will allow a test of the interaction between space and time to be computed and enabling cross-testing of seasonal and yearly relationships.

Short term variations

In addition to the seasonal variation, there are also daily and hourly variations (climatic and light-controlled photosynthesis) to consider (Table 2). To obtain a fully representative sampling design, those sources of variations would need to be considered, but this may result in a high level of effort unnecessary in the context of a monitoring plan. Thus, it is assumed that the variations will get integrated over time as each sampling campaign is systematically carried out. The conditions that are not be covered are storm events and very windy conditions that would make navigation hazardous. Although wave mixing will favour GHG emissions, high winds conditions are observed only a small fraction of the time.

[6] Lowering the number of degrees of freedom in the denominator of the anova *F*-statistic

Therefore, it is suggested to consider only the diurnal cycle as a sampling constraint with no samples taken during the mid-day period (11:00 a.m. to 14:00 p.m.) when fluxes may be lower due to high levels of phytoplanktonic photosynthesis (CO_2 absorption). Night time diffusive fluxes may be higher due to respiration, but mixing by wind is usually higher during the day. Thus, daily sampling should provide conservatively high fluxes and will also offer safer working conditions.

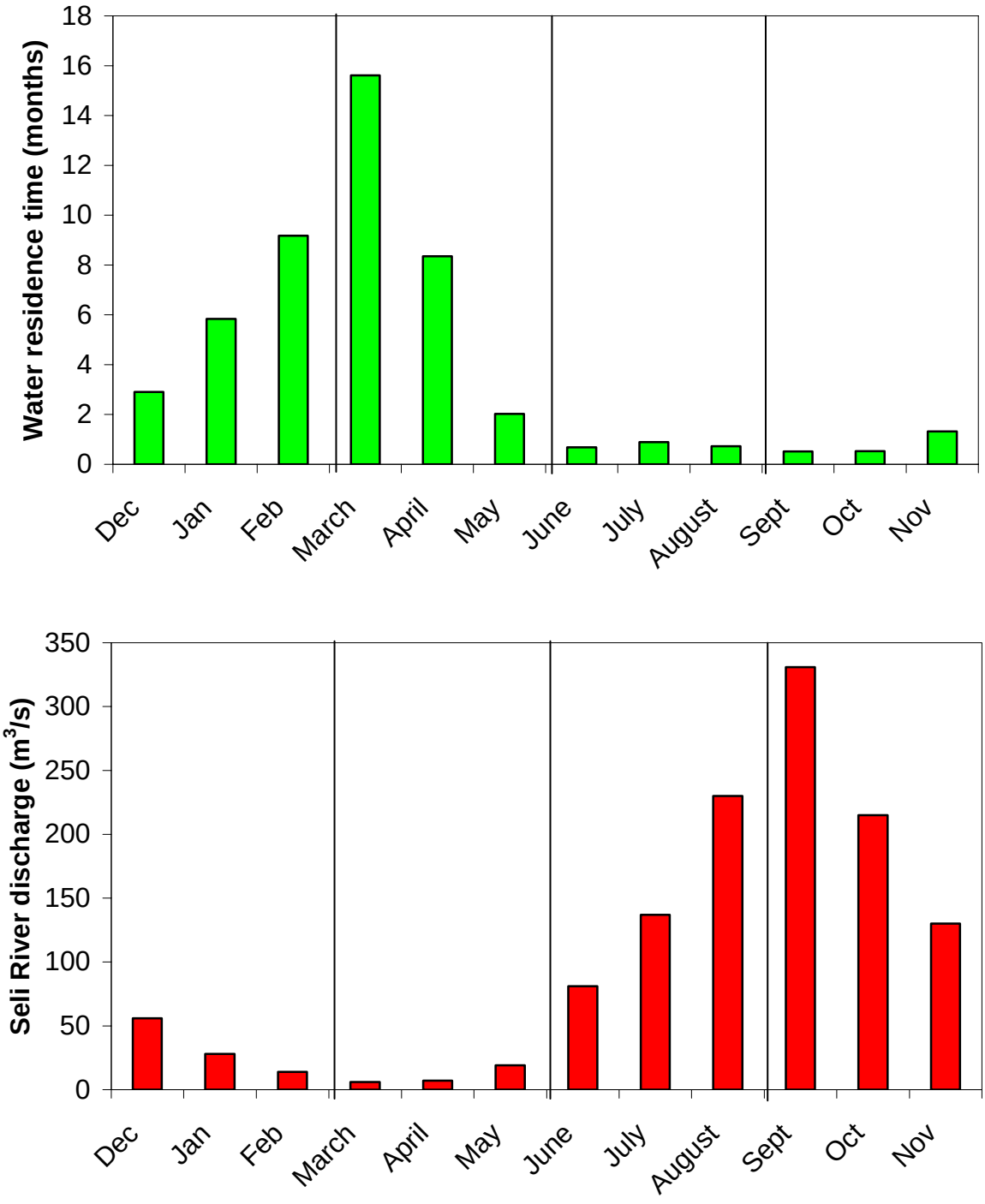
Bubbling fluxes

The GHG emissions from bubbling will be measured following the same seasonal frequency used for the determination of the diffusive emissions (n=4). During each campaign, sampling will occur for a period of 24 h at each station. This will require a certain number of funnels that will be rotated around the reservoir during a given campaign. Time of installation and retrieval must be noted in order to be able to track daily variation/anomalies and to express the fluxes as a function of time.

Gas exportation to downstream aquatic ecosystems

The GHG emissions attributed to the gas export from the reservoir will be measured following the same seasonal frequency used for the determination of the diffusive and bubbling emissions (n=4). During each campaign, sampling will occur once.

FIGURE 3: Water residence time for the proposed Bumbuna reservoir in relation to the Seli River monthly discharge



Data for the calculation of the water residence time are on p. 164 of the Bumbuna hydroelectric project EIA (2004), volume 2

Part III. Methodological Approach

Diffusion

Chamber method

Diffusive fluxes are collected with a floating chamber (Figure 4). Typical floating chambers will have the following characteristics (Lambert and Fréchette, 2005):

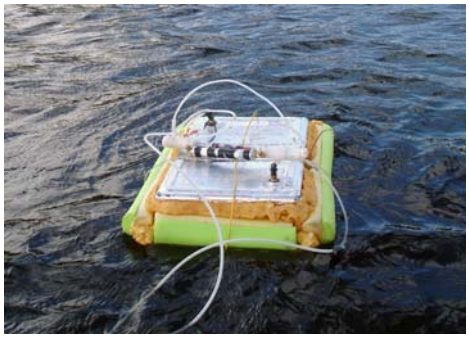
- a surface area in the order of 0.2 m^2;
- a height of 20 to 30 cm;
- a bottom edge that sits approximately 10 cm below the water line;
- a layer of Mylar covering the chamber to prevent overheating inside the chamber;
- Styrofoam collars to keep the floating chamber in position at the water surface;
- an inlet for air sampling at one side of the top of the chamber and connected by Tygon tubing with an internal diameter of approximately 3 mm;
- an outlet for air sampling at the opposite side of the top of the chamber;
- a pressure hole and rubber plug for gentle equilibration at the water-air interface.

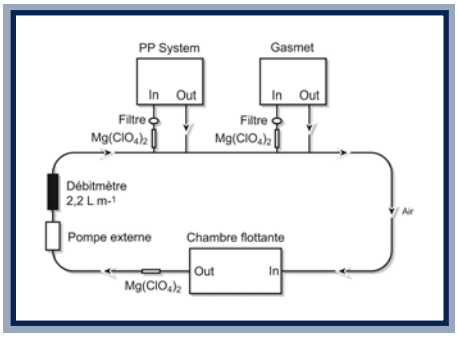
The chamber method gives comparable results to the eddy correlation method, a non-intrusive measurement approach (Guérin et al. 2006). Therefore, it is assumed that this method will not underestimate the diffusive GHG fluxes from reservoirs given the climatic conditions in which it will be used.

The main problem arising from the application of this sampling approach is that it can be used only in calm to moderate wind (< 6.6 m/s at 1.5 m or 8.1 m/s at 10 m height) and wave conditions (< 0.5 m). Furthermore, there is some bias in situations that would promote higher fluxes which maybe underestimated using the chamber method (Guérin et al., 2006). Nonetheless, these conditions are probably not occurring frequently and a good analysis of meteorological records will provide an insight into the representation of this method for each reservoir by assessing the relative importance of periods of high winds.

If windy conditions (> 8.0 m/s) are observed frequently, a correction factor could be applied on the diffusive fluxes. This correction factor can be based on the relationship between the gas exchange coefficient and wind speed. This will imply that hourly wind data are available.

FIGURE 4 — Floating chamber and closed-loop system for continuous gas measurement





Measurements

The concentration of the GHG in the chamber can be measured in two ways, either in line (continuous) using NDIR instrumentation (Non-Dispersive Infrared) or FTIR instrumentation (Fourier Transform Infrared), or using a separate gas chromatograph (non-continuous). In the NDIR/FTIR approach, concentrations are measured in the field as continuous measurements over a given period of a few minutes. In the chromatograph approach, air samples are collected using a series of syringes (grab samples), therefore providing fewer results per replicate. The syringe can then be analyzed in the field using a portable chromatograph or in the laboratory.

A brief description of both methods is presented. The NDIR approach is favoured, but is more expensive due to the cost of the instruments.

NDIR/FTIR approach

- air in the chamber is sampled from the top of the floating chamber;
- air is pumped via the tubing (outlet) through the analytical instrumentation in a loop that returns to the chamber (inlet);
- measurements are done over a period of 5 to 10 minutes;
- typical analytical instrumentation includes a PP System for determination of CO_2 and a Gasmet for determination of CH_4 and N_2O;
- a pump must provide a constant flow through the sampling loop;
- a desiccant (magnesium perchlorate) is placed at the outlet of the floating chamber and before each instrument to prevent condensation in the tubing and defect of the instruments.

- air is analyzed with an automated instrument, a NDIR (Non-Dispersive Infrared) instrument or FTIR (Fourier Transform Infrared) instrument. Typical characteristics of the NDIR and FTIR instruments that can be used are presented in Table 7. The measurement ranges presented should be adequate for tropical reservoirs.

TABLE 7: Characteristics of the NDIR and FTIR instruments

Instrument	Method	Gas	Accuracy	Range (ppm)
PP-System	Infrared (NDIR)	CO_2	< 0,1 % of the measured value[1]	0 – 2 000
Gasmet	Infrared (FTIR)	CO_2	< 1 % of the measured value	0 – 2 000
Gasmet	Infrared (FTIR)	CH_4	< 1 % of the measured value	0 – 20
Gasmet	Infrared (FTIR)	N_2O	< 1 % of the measured value	0 – 20
LI-COR	Infrared (NDIR)	CO_2	1 % or 4-5 ppm at 400 ppm	0 – 3 000

1 The accuracy is better for higher value in the target range; for example, it is 0.07 % at 350 ppm and of 0.03 % at 1 750 ppm.
Source: Lambert et Fréchette (2005).

- Data is collected either on a data logger or on a portable computer. All readings (every 20 seconds) are plotted on a graph of gas concentration as a function of time. The flux (ppm/d or $mg/m^2/d$) is obtained by calculating the slope of the regression line using the following equation:

$$Flux = slope \times F1 \times F2 \times volume / surface$$

where:

F1 is a conversion factor from ppm to mg m^{-3} for TPN conditions,

F2 is a conversion factor of seconds into days,

and where the chamber volume and surface are known.

Chromatograph approach

- With this approach, there is only one tube coming out of the chamber for sampling using a syringe;
- a typical syringe will have a sample volume of 60 ml and a 2-way valve;
- gas samples collected can be analyzed for CH_4 and CO_2 using a gas chromatograph (ex: Shimadzu flame ionization detector gas chromatograph (FID-GC)). More details on the utilization of this instrument can be found in Keller and Stallard (1994) and in Weiss (1981).

Bubbling

Measurements

Bubbling emissions will be measured with inverted collecting funnels. Some designs have the collecting funnels floating at the surface (Galy-Lacaux et al., 1997 and 1999; Keller and Stallard, 1994) or installed at the bottom (Environnement Canada). The former may be easier to handle from small boats. Two examples of funnels are shown in Figures 5 and 6.

The major steps of the sampling procedure using the surface floating funnels are:

- the trap is composed of an inverted funnel (stainless steel or PVC) of known surface area, two are installed at each station to provide duplicate measurements;
- a sample container (syringe, glass bottle with a septum, etc) is connected to the top of the funnel through a 2 way or 3-way valve (sampling from a separate syringe);
- the funnel is maintained near the surface using some flotation device and anchored at the bottom to stay on the station. The funnel can also be used at the bottom of the reservoir;
- sampling is carried out over a 24 h period. Ideally, samples are taken every 2 hours to limit dissolution and microbial oxidation of the gas collected;
- the sample volume must be measured before injection in the chromatograph.

FIGURE 5: Example of a subsurface bubble gas collector (Huttunen et al. 2001).

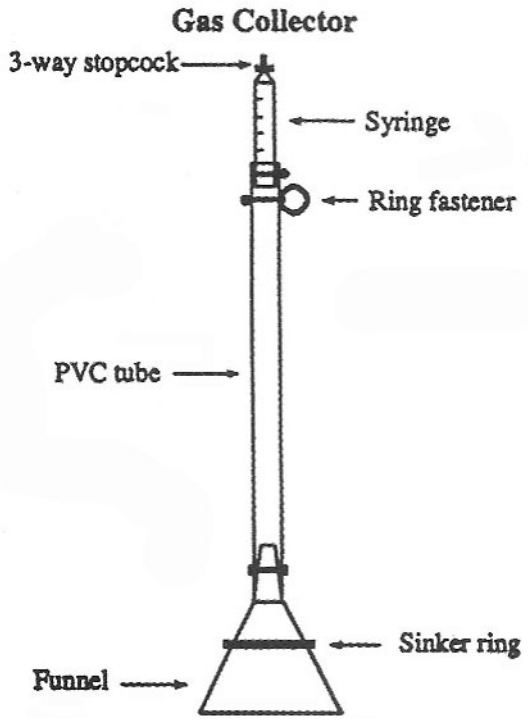


FIGURE 6 : Example of a sediment bubble gas collector

GHG exportation downstream of dam

Measurements

To estimate the total exportation of GHG from a reservoir the following information is required:

- GHG concentrations of the natural river before flooding (best case scenario),
- GHG concentrations from the upstream reach of the river feeding into the reservoir or lakes along the upstream river course,
- Surrounding rivers or lakes (worst case scenario),
- Daily discharge measurements at the dam,
- GHG concentrations of the turbinated water for each campaign (if one cannot directly measure the gas concentration near the turbine, water samples from the water intake or just upstream of the dam at the depth corresponding to the water intake will be appropriate).

The reference GHG concentration will be determined over time (n = 4 campaigns) during one year at the same period than the GHG concentration of the turbinated water. The difference in both concentrations (turbinated water and aquatic system before flooding) corresponding to a given period will be multiplied by the mean daily discharge for that period.

Following are the basic steps for collection of water samples and subsequent gas concentration analysis. The main goal of the water sample collection protocol is to avoid mixing of air within the water samples.

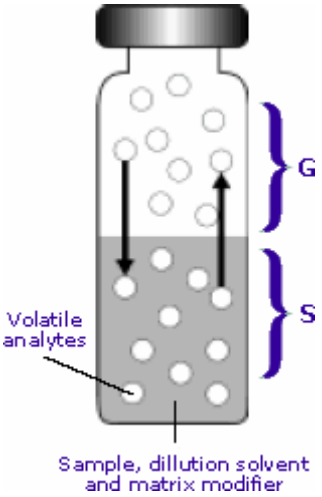
Collection of water samples

- Triplicate water samples are collected at the turbine intake or near the dam at the water intake depth using a water sampler (ex: Niskin bottle);
- Water sample must be collected in a 500 cm^3 volumetric flasks with screw caps which have internal plastic conical liners;
- Water is transferred from the water sampler to the sample bottle with Tygon tubing;
- The sample bottle must be overflowed by at least a half, and preferably a full, bottle volume. This can be done by calculating the time to fill one bottle and by taking 1.5 or 2 times this time;
- A head-space of 1 % of the bottle volume is left to allow for water expansion. This can be achieved by using a pipette with a bulb;
- Mercuric chloride is added to poison the sample and stop bacteriological and phytoplankton activity; the recommended minimum amount is about 0.02 % by volume of saturated aqueous solution;
- The bottle must be sealed and remain gas-tight;
- Samples should be stored in the dark before analysis.

Headspace chromatography

Head-space chromatography is used for the analysis of GHG concentration in water samples. Figure 7 shows the head-space technique principle where G is the gas phase or head-space, and S is the sample phase. Once the sample phase is introduced into the vial and the vial is sealed, volatile components diffuse into the gas phase until the headspace has reached a state of equilibrium as depicted by the arrows. The sample is then taken from the head-space.

FIGURE 7 : Principale of head space technique



G = the gas phase (headspace)
The gas phase is commonly referred to as the headspace and lies above the condensed sample phase.
S = the sample phase
The sample phase contains the compound(s) of interest. It is usually in the form of a liquid or solid in combination with a dilution solvent or a matrix modifier.

Head-space chromatography analysis is done in series and each analysis depends on the previous and the subsequent result (see equation). The

calculation of the change in the number of moles of CO_2 ($\Delta n(CO_2)$), or CH_4, in the equilibrator head-space can be calculated as follow (CDIAC – SOP4):

$$\frac{\Delta n(CO_2) = (p(CO_2)_1 - p(CO_2)_2)V(head - space)}{RT}$$

where:

$(p(CO_2)_1$	pCO_2 value measured before
$p(CO_2)_2$	value measured after the equilibration process
$V(head - space)$	volume of air in the head-space
R	perfect gas constant (8.31 J mol^{-1} K^{-1})
T	temperature in Kelvin degrees

The pCO_2 value is then calculated following some correction factors, including the correction for water vapor pressure (see CDIAC-SOP4 for more details).

Part IV. Calculation of total yearly GHG emissions

Diffusion

At a given station, the diffusive flux is obtained from the slope of the measurements during the sampling period for each replicate (n=3) and then averaged. For each campaign, the mean flux ($mg/m^2/d$) for the entire reservoir will be calculated (n=30). To obtain the average reservoir flux, the mean flux will then be multiplied by the surface area of the reservoir/strata, taking into account the water level at the time of sampling.

The average reservoir fluxes for each campaign (n=4) are summed up to obtain the yearly GHG emission from diffusion calculated as follow for CO_2 and CH_4:

$$Yearly\,Diffusive\,flux_{GHG} = \sum_{C=k\rightarrow n} (F_S * \frac{360 days}{C})$$

where:

F_S is the mean GHG flux for one campaign,

C is the number of campaigns (C_k refers to a specific campaign).

The total diffusive flux is the sum of the diffusive flux of each gas in $CO_{2\,eq}$:

$$Total\,Yearly\,Diffusive\,Flux = F_{CO_2} + (23 * F_{CH_4})$$

where:

F_{CO_2} is the CO_2 flux in mg CO_2 m^{-2} d^{-1},

F_{CH_4} is the CH_4 flux in mg CH_4 m^{-2} d^{-1}.

The CH_4 flux is converted in $CO_{2\,eq}$ by a Global Warming Potential (GWP) of 21.

Bubbling

The bubbling flux for each funnel ($mg/m^2/d$) is calculated with the following equation (Keller and Stallard, 1994):

$$Bubbling\,Flux_{Funnel} = \frac{VC}{A\Delta t}$$

where:

V is the sample volume,

C is the CH_4 concentration of the sample,

A is the collector area,

and Δt is the time interval of collection

In cases where the sample volume is too small to provide an adequate quantification of the CH_4 concentration, a relative concentration of 75% of the total sample volume will be used (Galy-Lacaux et al. 1999, have shown that bubbles contained 50 to 80% CH_4)

The mean bubbling flux at each station will be calculated from the duplicate measurements. The average flux for each transect will then be calculated by integrating the area under the curve of the respective fluxes (1 m, 3 m, 7 m) plotted as a function of depth. The mean of all average fluxes (n = 10) will then be used to provide the bubbling flux for the respective campaigns. To obtain the average reservoir flux, the mean flux will then be multiplied by the surface area of the shallow (0-10 m) portion of the reservoir taking into account the water level at the time of sampling.

The annual contribution of GHG emissions from bubbling will be calculated with the following equation:

$$Yearly\,Bubbling\,flux_{GHG} = \sum_{C=k\rightarrow n} (F_B * \frac{360 days}{C})$$

where:

F_B is the mean GHG flux for one campaign,

C is the number of campaigns (C_k refers to a specific campaign).

The CH_4 flux is converted in $CO_{2\,eq}$ by a Global Warming Potential (GWP) of 21.

GHG exportation downstream of dam

The total amount of GHG exported downstream of the reservoir will be calculated as follow for each gas (CH_4 and CO_2):

$$YearlyExportation_{GHG} = \sum_{w=1\rightarrow 52} Q_w([GHG]_{turbinated} - [GHG]_{BeforeFlooding})$$

where:

Q_w the mean weekly turbinated flow
$[GHG]_{turbinated}$ the GHG concentration of the turbinated water

$[GHG]_{BeforeFlooding}$ the baseline GHG concentration or the reference concentration for the corresponding week.

The total amount of GHG exported from the reservoir is the sum of the exportation calculated for each gas in $CO_{2\,eq}$:

$$TotalYearlyExportation = D_{CO_2} + (21 * D_{CH_4})$$

Where:
D_{CO_2} the export of CO_2 in Tg CO_2 d^{-1}

D_{CH_4} the export of CH_4 in Tg CH_4 d^{-1} converted in $CO_{2\,eq}$ by considering it's global warming potential of 21

Explanation/justification:

The project developers used the best available research on the topic of measuring project emission from reservoirs. The reservoir emissions shall be measured, recorded, and calculated using the best available science and approaches to ensure the total project emission reductions reflect are accurate and conservative.

6. Leakage

Methodology procedure:

The creation of a reservoir may influence development patterns in the area immediately surrounding the new water feature. There is the potential for further land-use changes beyond the inundated area directly resulting from the creation of the reservoir. The project developer will have to monitor the reservoir lake boundaries. While some human activities can be seen as fitting within the context of sustainable development which will be assessed by the host-country DNA's, major deforestation will be considered leakage. The deforested areas will be quantified and calculated in the exact same way described in the baseline section and can utilize the same test plots to measure the impact of the deforestation on the land as a carbon sink or emitter caused by the creation of the reservoir. These impacts will be considered leakage.

Explanation/justification:

The main leakage potential is derived from deforestation resulting from close proximity to the reservoir. The same formulas outlined in the baseline section will be used to quantify the impact in terms of likely carbon emitted or sequestered by the deforested areas.

7. Emission reductions

Methodology procedure:

The emission reduction *ERy* by the project activity during a given year *y* is the difference between baseline emissions (*BEy*) and project emissions and leakage as follows:

$$ERy = BEy - PEy - Ly$$

where:

ERy emission reduction from the project activity during year *y* (tCO_2e)

BEy baseline emissions (tCO_2e)

PEy Project emissions (tCO_2e)

Ly leakage (tCO_2e)

Explanation/justification:

The project emissions reductions are simply the difference between the emissions in the baseline scenario minus the project emissions. In anecdotal terms, it is the fossil fuel avoided minus the cost sequestration and minus the emissions from the reservoir.

8. Changes required for methodology implementation in 2nd and 3rd crediting periods

Methodology procedure:

There would be no changes for the implementation of the monitoring methodology in the second or third crediting periods.

Explanation/justification:

NA

9. Data and parameters not monitored

Methodology procedure:

(Copy this table for each data or parameter)

ID Number:	1
Parameter:	Reservoir Area
Data unit:	Sq kilometre
Description:	Total hectares of different types of vegetation cover in area to be inundated.
Source of data:	Public sources/project developer
Measurement procedures (if any):	Measured using public data sources
Any comment:	Using satellite, mapping or other detailed data on the baseline vegetation cover

ID Number:	2
Parameter:	Global Warming Potential
Data unit:	Global Warming Potential N_2O

Description:	Global Warming Potential
Source of data:	IPCC
Measurement procedures (if any):	Measured using public data sources
Any comment:	

ID Number:	3
Parameter:	Global Warming Potential
Data unit:	Global Warming Potential CH_4
Description:	Global Warming Potential.
Source of data:	IPCC
Measurement procedures (if any):	Measured using public data sources
Any comment:	

Explanation/justification:

All parameters in this methodology are monitored

Section III: Monitoring methodology description

1. Monitoring procedures

A Quality Assurance/Quality Control (QA/QC) program for the measurement of GHG emissions (diffusion, bubbling and GHG exportation downstream of the dam) should include the following points: instrument calibration, special techniques to prevent contamination of samples and to assure good estimation of the measurements and, a posteriori analysis and verification of the data.

Instrument calibration

PP System (CO_2; NDIR)

- zero (in air) done automatically every 20 minutes;
- calibration is checked at the beginning and at the end of each sampling campaigns with a CO_2 (400 ppm) cylinder.

Gasmet (CO_2, CH_4, N_2O; FTIR)

- zero is adjusted every day using a nitrogen cylinder (purity = 99.9 %);
- calibration is checked at the beginning and at the end of each sampling campaigns with two air standards, one CO_2 (400 ppm) cylinder and one CH_4 (90 ppm) cylinder.

Chromatograph

- CH_4 and CO_2 standards are used to calibrate the chromatograph;
- Spectrograms are interpreted using specific commercial solutions;

- Coefficient of variation for a set of replicates should be less than 2.5 %.

Techniques to prevent contamination and loss of samples and to assure the best estimation of the measurements

Diffusive flux sampling

- The exact dimension of the chamber must be known as precisely as possible for the calculation of the GHG fluxes (area and volume). The volume must be calibrated beforehand by adding a known volume of water within the chamber, up to the limit of the water line. Note that the volume off the chamber will depend on the size of the box and its buoyancy;

- The floating chamber must be equilibrated in air for at least 5 minutes before sampling in order to retrieve the gases collected from the previous sample. This is done by putting the chamber upside down in the direction of the wind, the pump allowing circulation of fresh air in the tubing. When atmospheric gas concentrations are reached (can be known on site only if using the continuous approach [NDIR/FTIR], but 5 minutes is usually enough), the chamber is equilibrated. When equilibrating the chamber, care must be taken not to receive flumes from the motor of the boat or from other fuels;

- After equilibration with local air, the chamber must be delicately installed on the water surface with its pressure hole free of the rubber plug. Allowing a few second before positioning the pressure plug will help evacuating the pressure an limit the turbulence at the water-air interface;

- The chamber tubing must be kept free of tension when sampling. If there is any tension in the tubing, it could enhance the turbulence and thus overestimate the fluxes;

- Each flux must be calculated over a period of at least 5 minutes in order to have enough points to calculate the slope of the gas concentration over time. Also, each flux should have take the same time to obtain equivalent precision on each flux;

- Triplicate measurements are done at each station.

Bubbling sampling

- Sub-sampling with a syringe every 2 hours (instead of a longer time interval) will prevent dissolution of the gas bubbles in water;
- Adding a few drops of 0.1 M $HgCl_2$ solution in the gap between the barrel and the plunger of the syringe will prevent diffusive exchange of the gas. The solution also inhibits microbial activity that could affect the gas composition;
- The funnel collecting area and the time interval between samples must be precisely calculated;
- Duplicate bubbling measurements are done at each station;

- Duplicates chromatography analysis for each water samples.

GHG exportation downstream of dam

- $HgCl_2$ is added to poison the sample; the recommended minimum amount is about 0.02 % by volume of saturated aqueous solution;
- Triplicate water samples;
- Duplicate head-space chromatography analysis.

A posteriori analysis and verification of data

Diffusive flux

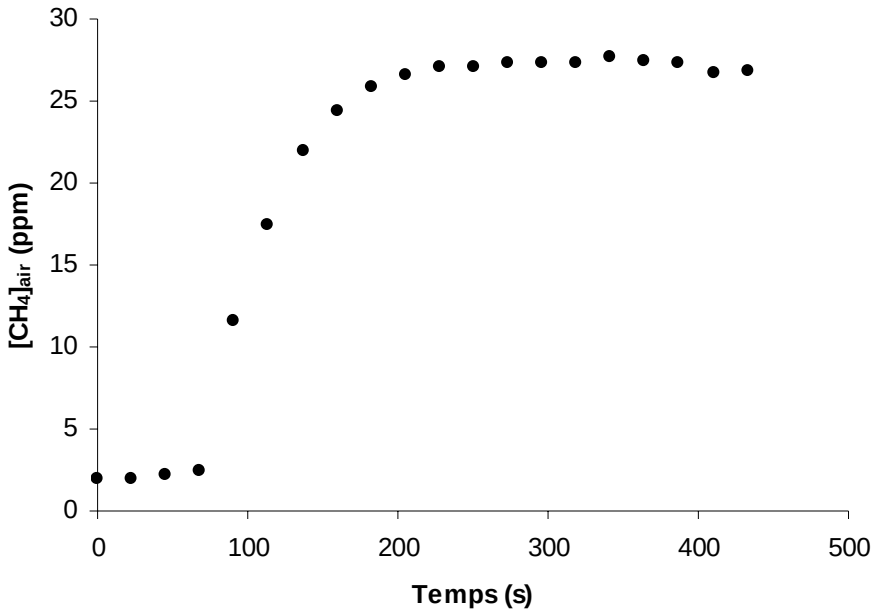
Specific criteria must be established to determine the validity of the fluxes calculated from the slope of each replicate. For the continuous approach (NDIR, FTIR), the criteria is based on the determination coefficient (R^2) of the regression. In general, CO_2 fluxes measured with the PP System that have an $R^2 >$ 0.85 are accepted (Lambert et Fréchette, 2005). Doubtful fluxes attributed to the instrument instability must be removed. In the boreal region where CH_4 and N_2O fluxes are low, all CH_4 and N_2O fluxes obtained from the Gasmet are accepted except for those where gross errors or warning messages are reported and where there are evident signs of bubbling. A criteria based on the R^2 of the regression obtained for CH_4 and N_2O) must be determined for tropical reservoir after the first round of sampling. Other criteria than the r^2 can justify the rejection of some fluxes:

- Invalid reading. For each substance detected by the Gasmet, an error message (OK, Warning or Error) is saved. A reading problem (Error) can be generated in case of interference with other substances than the target gases. In the case of the PP System, the quality of the reading is evaluated by the humidity level detected (should be < 0.15 %) and the atmospheric CO_2 measured by the instrument (should be around 380 ppm).

- Bubbling. Bubbles enriched in CH_4, and less in CO_2, can be monitored by the floating chamber. Those bubbles result in a rapid increase in gas concentration and display a typical S-curve (Figure 8). Bubbling can not be measured representatively by the chamber because of the short measurement time (5-10 minutes). Diffusive fluxes where bubbling is observed are thus "contaminated" and rejected.

- Chamber equilibrium time insufficient. Sometimes, the gas concentration at the beginning of the measurement does not correspond to the atmosphere concentration. Those fluxes are rejected.

FIGURE 8: Typical result of a bubbling artefact during measurement of diffusive fluxes



With the chromatograph approach, there is less points to calculate the slope (usually 3 to 5 measurements) compared to the continuous in situ approach (NDIR/FTIR; 20-25 measurements) although those measurements are more precise. The lesser number of data points is such that one must accept all data, except when there is a clear outlier. Therefore, the in-situ measurement of the gas concentrations will permit a better QA/QC evaluation.

Physical and chemical variables

GHG emissions depend on a large set of temporal, physical and chemical variables (Table 2). This is why it is important to take note of the date, the time and of the physical/biological/chemical environment at every sampling site. When analysing the data, some correlation can be made and could help to refine the future sampling plan. Also, as mentioned earlier, wind and rain can lead to an overestimation of the diffusive fluxes. The fluxes could be corrected if the condition (wind or rain) was observed frequently during sampling but is known not to be typical of the region. Ideally, wind and rain conditions should be known hourly for all the sampling year in order to evaluate the difference between the periods sampled and the rest of the year.
Physical and chemical variables that can be measured include:

8. Depth (m)
9. Water transparency (m, Secchi disk)
10. Water and air temperature (^{o}C)
11. pH
12. Alkalinity (mg $CaCO_3$/L determined by titration)
13. Conductivity (µS/cm)
14. Dissolved oxygen (mg/L)
15. Atmospheric pressure (Kpa)
16. Wind speed and direction , wind gust (ex: Krestel, Extech Instruments 407112)

17. Cloud coverage
18. Presence and importance of precipitation
19. Wave height
20. Drifting speed under the floating chamber (m/s)
21. Water color
22. Physiographic environment nearby: near/far from the shore, type of shore (forested, denuded), slope of the shore (flat, mountainous), presence of pounds, marsh, etc.

Methodology procedure:

The main monitoring procedure is described in the section dealing with project emissions

Explanation/justification:

See project emissions section

2. Data and parameters monitored

Baseline emissions
(Copy this table for each parameter)

Data / Parameter:	**2**
Data unit:	TCO2/MWH
Description:	Tons of CO2 emitted per MWH of baseline electricity generation – generation that will be displaced by the project.
Source of data:	Power company
Measurement procedures (if any):	Use of combined margin, as described in ACM002
Monitoring frequency:	Same as ACM002
QA/QC procedures:	QA/QC procedures same as in ACM002
Any comment:	

Data / Parameter:	**3**
Data unit:	TCO2 equivalent
Description:	annual change in carbon stocks from land ΔCFF
Source of data:	Project participants
Measurement procedures (if any):	Measured using sample plots of similar vegetation type, density, and species composition adjacent to the area to be
Monitoring frequency:	Each project year
QA/QC procedures:	Project developers will follow QA/QC procedures from GPG LULUCF and ARN-AM001.
Any comment:	Each sample plot will be maintained and measured for carbon sequestered using the IPCC approved practices

Data / Parameter:	**4**
Data unit:	TCO2 equivalent

Description:	Annual change in carbon stocks in living biomass ΔCFFLB
Source of data:	Project participants
Measurement procedures (if any):	Measured using sample plots of similar vegetation type, density, and species composition adjacent to the area to be inundated
Monitoring frequency:	Each project year
QA/QC procedures:	Project developers will follow QA/QC procedures from GPG LULUCF and ARN-AM001.
Any comment:	

Data / Parameter:	**5**
Data unit:	TCO2 equivalent
Description:	Annual change in carbon stocks in dead organic matter (includes dead wood and litter) ΔCFFDOM
Source of data:	Project participants
Measurement procedures (if any):	Measured using sample plots of similar vegetation type, density, and species composition adjacent to the area to be inundated
Monitoring frequency:	Each Project Year
QA/QC procedures:	Project developers will follow QA/QC procedures from GPG LULUCF and ARN-AM001.
Any comment:	Each sample plot will be maintained and measured for carbon sequestered using the IPCC approved practices

Data / Parameter:	**6**
Data unit:	TCO2 equivalent
Description:	Annual change in carbon stocks in soils ΔCFFSoils
Source of data:	Project participants
Measurement procedures (if any):	Measured using sample plots of similar vegetation type, density, and species composition adjacent to the area to be inundated
Monitoring frequency:	Each Project Year
QA/QC procedures:	Project developers will follow QA/QC procedures from GPG LULUCF and ARN-AM001.
Any comment:	Each sample plot will be maintained and measured for carbon sequestered using the IPCC approved practices

Project Emissions

Data / Parameter:	**7**
Data unit:	Number
Description:	Different categories to measure in flux testing
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Every Other Month
QA/QC procedures:	The reliability of testing will be ensured by frequent and repetitive tests. A QA/QC program for the measurement of GHG emissions (diffusion, bubbling and GHG exportation downstream of the dam) will include the following points: instrument calibration, special techniques to prevent contamination of samples and to assure good estimation of the measurements and, a posteriori analysis and

	verification of the data. Data will be verified and acceptance criteria are proposed so that outliers are excluded and contamination of samples are identified. Certified calibration gases are used to verify and calibrate the measurement instrumentation. Techniques to prevent contamination and loss of samples and to assure the best estimation of the measurements are proposed. Additional physico-chemical variables are measured to explain possible departure from expected trends. Proper training of personnel doing the testing must also be provided.
Any comment:	

Data / Parameter:	**8**
Data unit:	Milligrams of gas emitted per sq. meter
Description:	Emissions of CH4 at each testing site in each category to be tested
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Every other month
QA/QC procedures:	See # 7
Any comment:	

Data / Parameter:	**9**
Data unit:	Milligrams of gas emitted per sq. meter
Description:	Emissions of CO2 at each testing site in each category to be tested
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Every other month
QA/QC procedures:	See # 7
Any comment:	

Data / Parameter:	**10**
Data unit:	Sq. meters
Description:	Sq. meters of reservoir surface area fitting each category
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Every other month
QA/QC procedures:	See # 7
Any comment:	

Data / Parameter:	**11**
Data unit:	Milligrams of gas in concentration per liter or cubic meter
Description:	For degassing, concentration of CH4 in water at point of intake
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Every other month
QA/QC procedures:	See # 7
Any comment:	

Data / Parameter:	12
Data unit:	Cubic meters
Description:	Total volume of water moving through dam during testing period
Source of data:	Project participant
Measurement procedures (if any):	See Project emissions section
Monitoring frequency:	Daily
QA/QC procedures:	
Any comment:	

Explanation/justification:

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Annex:

Annex 1: Diffusive and bubbling CO_2 and CH_4 emissions (mg m^{-2} d^{-1}) from tropical reservoirs (See attachment)

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