

Scoping paper

Assessment of the GHG Status of Freshwater Reservoirs

Draft 15/02/2008

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PREFACE

Two workshops on the Greenhouse Gas Status of Freshwater Reservoirs have been organized in 2006 and 2007. One of the conclusions from the workshop in Paris, France 5-6 December 2006, was to focus more research on, and to improve understanding of, processes and key parameters that lead to the emission of methane from tropical reservoirs.

The workshop held in Foz do Iguaçu, Brazil, 4-5 October 2007 recommended the following: *“An analytical process will be developed to determine whether GHG emissions from future reservoir sites are likely to be a significant issue. This process will use a small number of key indicators, for example hydrology, reservoir type, climate and organic load. Where this process indicates the potential for significant GHG emissions, more detailed analysis will be applied. To support this process, at least 20 representative tropical/sub-tropical reservoir schemes will be selected. At each of these sites, data will be collected within the context of developing a process based model, including a number of sites where more intensive process measurements will be made.”*

In order to develop this report, the appointed working group (WG) prepared two drafts through correspondence, before its formal meeting in Paris on 10-11 January 2008, where the group discussed and updated the report and its contents, and nominated the WG Chair and Coordinator to prepare this draft for wider circulation. This document is offered as a basis for further dialogue by the forum of participants who attended the Paris and Iguaçu Falls workshops and other organizations engaged in this matter, including: research organizations, governments, NGOs and industry organizations.

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1. BACKGROUND

Freshwater reservoirs are used to regulate flow for many purposes, including: water supply, irrigation, flood mitigation, drought protection, navigation and hydropower. The conversion of land surface areas to create these water bodies and some flux rate measurements from related water surfaces has indicated that the emission of carbon dioxide (CO₂) and methane (CH₄) may be relevant to global inventories of greenhouse gas (GHG) exchanges. However, there is insufficient information and tools to support sound decisions about the GHG status of existing and new reservoirs and mitigation measures that may be necessary.

To quantify the net change of GHG exchange in a river basin caused by the creation of a reservoir, it is necessary to consider exchanges before and after the construction of the reservoir. The difference between pre- and post-reservoir emissions from the whole river basin will indicate the GHG status of the reservoir. The study period of emissions should be calculated for 100 years (IPCC, 2006).

Data from the limited number of tropical reservoirs that have been studied indicates that methane emissions vary not only among reservoirs, but also within each reservoir, as a function of many aspects, including: type and density of the drowned vegetation, aquatic macrophyte growth, wind speed, temperature, oxygen saturation and water level.

2. OBJECTIVES, OUTPUTS AND GOALS

The overall objective is the evaluation of GHG exchange¹ due to the construction of a freshwater reservoir and potential mitigation measures.

The main issues that require resolution with regard to the contribution or potential contribution of reservoirs as sources of GHG to the atmosphere are the following:

- *What is the observed range of fluxes of the primary GHG (carbon dioxide and methane) from reservoirs?*
- *What is the observed storage of carbon in the accumulating sediments and net primary production in a reservoir?*
- *What fraction of GHG fluxes and carbon storage is a result of the construction of the reservoir, i.e. what is the net 'carbon footprint' of the reservoir?*
- *If necessary, is it possible to mitigate emissions from existing or planned reservoirs?*

The expected output of future work scoped by this paper includes:

- (i) Development of tools, including measurement methodologies and models, required to meet the objectives.
- (ii) Development of guidance based on representative data for planning and managing reservoirs in order to mitigate those that might elevate GHG emissions.

It is estimated that these outputs could be completed in a 2 to 3 year timeframe.

3. CONCEPT

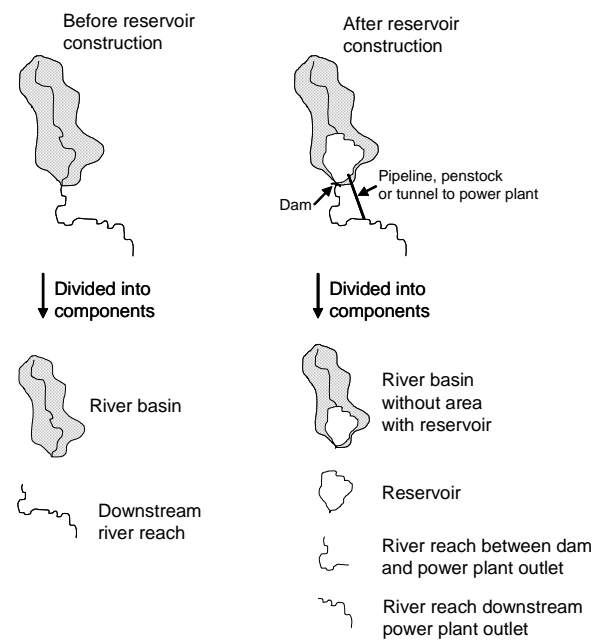
As stated, to quantify the GHG exchange caused by a reservoir, it is necessary to study emissions before and after the construction of the reservoir. The study period of emissions should be calculated for 100 years. The difference between pre- and post-reservoir emissions from the whole river basin will be the true net GHG emission. Transport processes of carbon from the river basin to the downstream river, lake or sea must be considered together with storage changes in the reservoir and

¹ This is often referred to as *the carbon footprint* or *net GHG emission*, which for the purpose of this program is the resulting positive/negative change in GHG emission in the river basin caused by the creation of the reservoir.

1 river. It is important to incorporate the total geographical area where emissions might change due to
 2 the construction of a reservoir. Possible geographical study units are shown in Figure 1.

3 Measurements, studies and models for GHG emissions must take into account emissions or uptake
 4 from all kinds of land-use, including reservoirs and river reaches as well as different terrestrial land-
 5 uses. Transport processes and storage changes to and from these different areas or geographical units
 6 or sub-units must be included. Input to the system may be derived from measurements, literature or
 7 models. Important factors that control the emissions and the transport and storage changes must be
 8 included for all units. These factors might be *drivers* like air temperature, rainfall or light, or *key*
 9 *parameters* like dissolved oxygen content, carbon load, residence time or primary production. The
 10 geographical units which might be used for measurements, calculations and modelling are shown in
 11 Figure 1. A general concept for modelling these geographical units is shown in Figure 2. All arrows
 12 representing fluxes and transport in Figure 2 must be considered.

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15 **Figure 1. Geographical units for a model for net emissions from constructing a reservoir in a river basin.**

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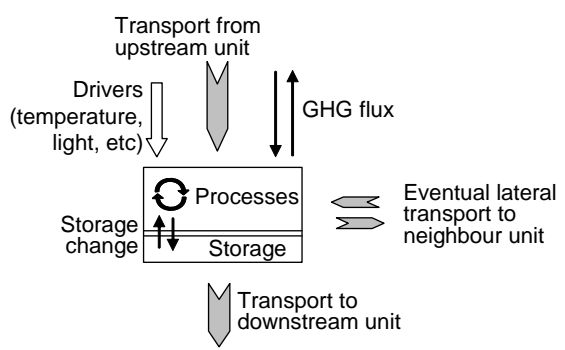
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25 **Figure 2. General concept for all units in a GHG emission study. Key parameters must be included in**
 26 **“drivers” and “transport”. “Processes” must include important processes for key parameters, or**
 27 **empirical relationships.**

28

4. PREVIOUS WORK

In the last decade, freshwater reservoirs have been investigated as potential sources of carbon dioxide and methane emissions to the atmosphere, in boreal (Rudd et al., 1993; Duchemin et al., 1995; Kelly et al., 1997; Huttunen et al., 2002), temperate (Soumis et al., 2004, Casper et al. 2000) and tropical (Keller and Stallard, 1994; Rosa and Schaeffer, 1994; Galy-Lacaux et al., 1997, 1999; Delmas et al., 2001, 2004; Rosa et al., 2003; Abril et al., 2005; Santos et al., 2006, Kemenes et al. 2007) regions. GHG emissions from reservoirs at the global scale are subject to large uncertainties, and there is a strong need for more observations and better understanding of the processes included. Simulation models may play an important role in understanding and analysing GHG emissions due to the construction of a reservoir in a river basin.

Flux measurements from the water-atmosphere or land-atmosphere interface seem to be the only type of measurements reported in the literature. Very few measurements of transported material into or out of the river basin or reservoir have been reported. Also, even though sedimentation in reservoirs can involve significant volumes, very few studies have quantified carbon accumulation through this process. Of all the pathways (arrows) in Figure 2, only the GHG flux in the water-atmosphere interface tends to be available at the reservoirs that have been studied.

Fluxes of carbon dioxide and methane have been measured in a limited number of temperate and tropical reservoirs (Table 1). Methane emission from South American reservoirs has been measured in hydroelectric reservoirs including four Amazonian sites (Samuel, Balbina, Curua-Una, Tucurui), Petit-Saut (French Guyana), eight sites in north-eastern Brazil (Serra da Mesa, Manso, Corumba, Itumbira, Furnas [cascade], Peixoto, Estreito and Funil), and several reservoirs in southern Brazil. Measurements are not available from reservoirs in other regions of the tropics or subtropics. For most of the studied reservoirs, only two GHG pathways from the reservoir to the atmosphere have been studied: ebullition and diffusive fluxes from the surface of the reservoir. Studies at the Petit-Saut and Balbina reservoirs have investigated methane emissions downstream of the dam.

Table 1: Range of average carbon dioxide and methane emissions from hydroelectric freshwater reservoirs in boreal, temperate and tropical regions. Numbers in parentheses are the number of studied reservoirs for each gas and each GHG pathway.

GHG pathway	Boreal & temperate		Tropical	
	CO ₂ mmol m ⁻² d ⁻¹	CH ₄ mmol m ⁻² d ⁻¹	CO ₂ mmol m ⁻² d ⁻¹	CH ₄ mmol m ⁻² d ⁻¹
Diffusive fluxes	-23—145 (107)	-0.3—8 (56)	-19—432 (15)	0.3—51 (14)
Bubbling	0	0—18 (4)	0	0—88 (12)
Degassing [§]	~0.1 (2)	n.a.	4—23 (1)	4—30 (2)
River below the dam	n.a.	n.a.	500—2500 (3)	2—350 (3)

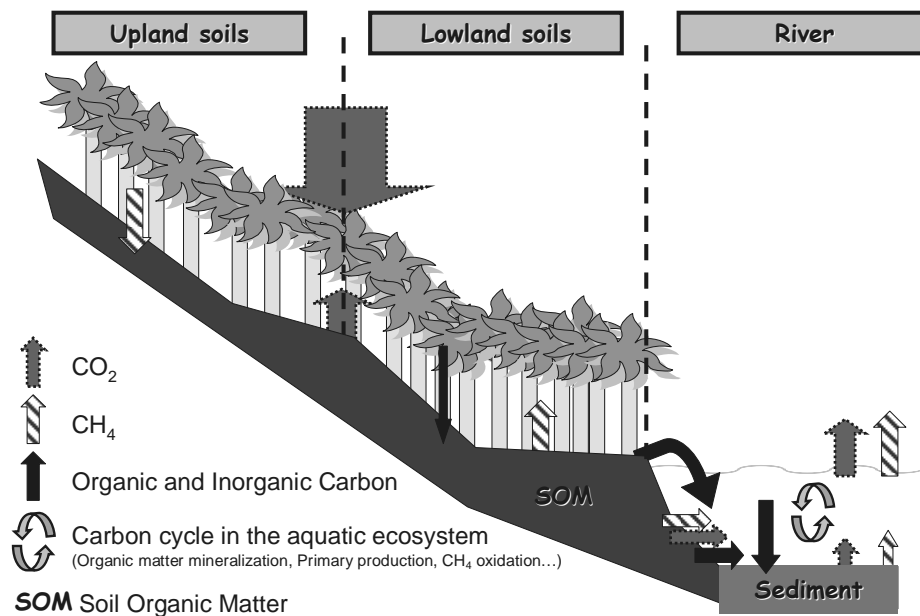
[§]The degassing (generally in Mg d⁻¹) is attributed to the surface of the reservoir and is expressed in the same unit as the other fluxes (mmol m⁻² d⁻¹)

1 5. KEY PROCESSES AND PARAMETERS

2 Carbon cycle in a pristine catchment

3 In terrestrial ecosystem, the main source of carbon is atmospheric carbon dioxide. The carbon dioxide
4 is fixed by plants during photosynthesis for the primary production of organic matter (OM). A part of
5 the produced OM is either directly incorporated in the soil organic matter (SOM) via processes
6 occurring in the rhizosphere or stored in the living biomass until the plant decays. During pedogenesis,
7 the OM is respired in oxic and anoxic conditions and the produced carbon dioxide returns to the
8 atmosphere. During mineralization of OM in anoxic soils, methane is produced. Methane is oxidized
9 by methanotrophic bacteria when diffusing from the anoxic part of the soil to the oxic part. In upland
10 soils, the high drainage often favours oxic conditions and thus aerobic methane oxidation. Generally,
11 the well drained soils act as a sink of atmospheric methane (Conrad, 1989). In lowland soils, anoxic
12 conditions may prevail due to limited drainage and methane production may be higher than methane
13 oxidation. Therefore, these soils may act as a source of atmospheric methane (Conrad, 1989, Figure 3).

14



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16 **Figure 3: Carbon dioxide and methane emissions from a pristine watershed (Conrad, 1989).**

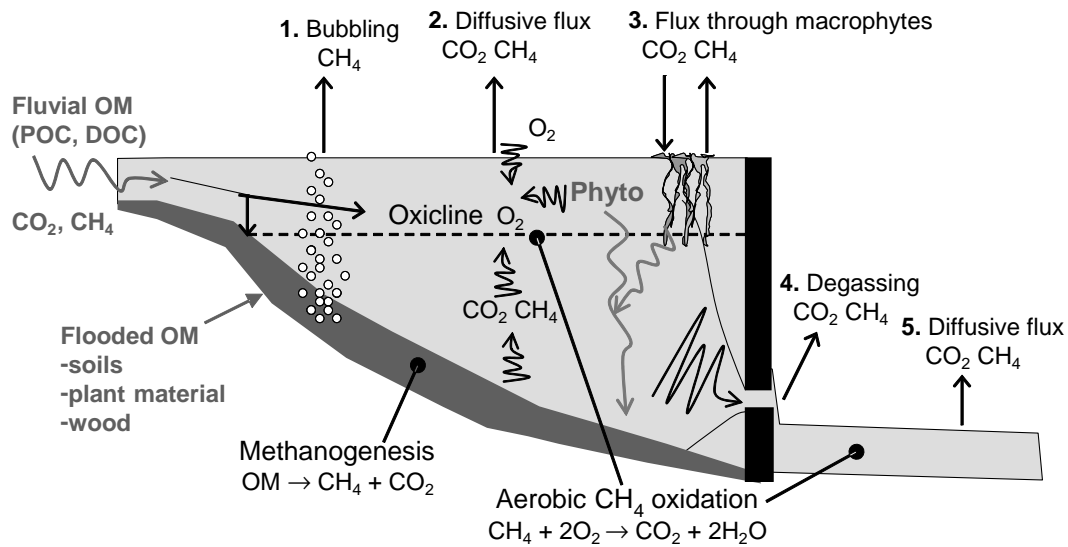
17 Recently, Keppler et al. (2005) showed that methane could be produced by plants in aerobic
18 conditions. The occurrence and the extent of this process remains unsolved (Houwelling et al., 2006;
19 Kirschbaum et al., 2006; Dueck et al., 2007; Ferreti et al., 2007; Miller et al., 2007).

20 The different carbon moieties (organic and inorganic carbon) reach the aquatic ecosystems of the river
21 basin (river, lakes and wetlands) by surface or sub-surface runoff. The carbon dioxide and the
22 dissolved inorganic carbon are either consumed for aquatic primary production or follow the pathways
23 indicated in Figure 2. The methane is either oxidized in the water column or emitted to the
24 atmosphere. The OM, which may have previously been stored in soils for a long period, may be
25 released in aquatic ecosystems when the organic carbon is respired in the water or in the sediment and
26 released as carbon dioxide and methane. The fraction that is not out-gassed is either buried in the
27 aquatic ecosystem or exported to the ocean (Cole et al., 2007).

28 Limited work has been conducted to estimate the significance of the carbon dioxide out-gassing from
29 aquatic ecosystems compared to the carbon dioxide uptake by vegetation at the watershed level. In
30 some temperate and tropical watersheds, carbon dioxide out-gassing from the aquatic ecosystems have
31 been shown to be close to balancing the carbon dioxide uptake by the surrounding forest (Cole and
32 Caraco, 2001; Richey et al., 2002).

1 **Pathways in reservoirs**

2 Emissions of carbon dioxide and methane from freshwater reservoirs result from decomposition of the
3 organic matter in plants and soils flooded during reservoir impoundment and from decomposition of
4 the organic matter produced in the reservoir and that imported into it from its catchment. Carbon
5 dioxide is produced in oxic and anoxic conditions in the water column and in the flooded soils and
6 sediments of the reservoir and is consumed by aquatic primary producers in the euphotic zone of the
7 reservoir. Methane is produced under anaerobic conditions, primarily in the sediments; some is
8 oxidized to carbon dioxide by methanotrophic bacteria in the water and sediments under aerobic
9 conditions (Figure 4). Pathways for methane and carbon dioxide emissions to the atmosphere from
10 reservoirs include: (1) bubble fluxes (ebullition) from the shallow water; (2) diffusive fluxes from the
11 water surface of the reservoir; (3) diffusion through plant stems; (4) degassing just downstream of the
12 dam; and (5) the diffusive fluxes along the river course downstream of the dam (Figure 4).
13



14
15 **Figure 4: Carbon dioxide and methane pathways in a freshwater reservoir with an anoxic hypolimnion.**
16 **For reservoirs with a well oxygenated water column, the processes are similar but restricted to the flooded**
17 **organic water.**

1 **Key processes**

2 Based on the guidelines of the Workshops on the GHG Status of Freshwater Reservoirs, this paper
3 identifies key indicators for significant GHG emissions and is focused on tropical and subtropical
4 reservoirs. Therefore, this section presents parameters and processes likely to be important in such
5 systems, and may not include terms specific to reservoirs in high latitudes where frozen ground, ice
6 cover or large reserves of peat may occur. The two GHG gases considered are *carbon dioxide and*
7 *methane*.

8 Key processes *influencing emission of GHGs* to the atmosphere include the following:

9 I. Processes supplying organic carbon to the reservoir or its sediments:

- 10 a. Inputs of organic matter via groundwater, streams and rivers that depend on the
11 discharge rate and the concentrations of organic matter in the catchment.
- 12 b. Net primary productivity of aquatic macrophytes, periphyton and phytoplankton
13 growing in or on the water or in the drawdown zone around the reservoir, depending
14 on the supply of nutrient and light.
- 15 c. Entrainment of terrestrial organic matter in living plants, litter and soils during
16 impoundment.

17 II. Processes producing conditions conducive to the production of dissolved carbon dioxide and
18 methane:

- 19 a. Decomposition of the various types of organic matter entering the system, depending
20 on the organisms present, temperature, dissolved oxygen and nutrients.
- 21 b. Anoxia in the sediment and water column, relating to the physical stratification,
22 temperature and amount of organic matter.

23 III. Processes influencing the distribution of dissolved carbon dioxide and methane within the
24 reservoir:

- 25 a. Mixing and transport processes that can lead to the movement of carbon dioxide and
26 methane to the surface.
- 27 b. Withdrawal via spillways or subsurface turbines.
- 28 c. Methane oxidation within the water or sediments, depending on the physical
29 stratification, dissolved oxygen and nutrient levels and temperature.
- 30 d. Primary production in the euphotic zone of the reservoir water column that consumes
31 carbon dioxide and depends mainly on light and nutrient availability.

32 IV. Carbon dioxide and methane pathways between the reservoir and the atmosphere:

- 33 a. Ebullition (bubbling)
- 34 b. Transport via plants stems
- 35 c. Diffusive gas exchange between the atmosphere and the reservoir or downstream
36 river.

1 **Key parameters**

2 Key parameters that alter the rates of these processes include the following:

3 I. Parameters that modulate the rates of biological processes such as organic matter production,
4 respiration, methanogenesis and methane oxidation:

5 a. Concentrations of dissolved oxygen

6 b. Temperature

7 c. Organic matter concentrations and C/N ratios in water and in sediments

8 d. Supply of nutrients

9 e. Light

10 f. Biomass of plants, algae, bacteria and animals in the reservoir

11 g. Methane concentration (substrate for methane oxidation)

12 II. Parameters that modulate gas exchange between the atmosphere and the reservoir or
13 downstream river:

14 a. Wind

15 b. Rainfall

16 c. Current speeds in rivers and streams

17 d. Surficial temperatures

18 e. Stability of density stratification in the water

19 f. Water depth and changes in water depth

20 g. Residence time of water in the reservoir

21 h. Reductions in hydrostatic pressure as water is released through reservoir outlets

22 i. Increased turbulence downstream of the dam associated with ancillary structures

23 Most of these parameters and processes must be placed in a geographic and temporal context and need
24 to be expressed on an areal basis. Therefore, it is necessary to have accurate information on the areal
25 extent of the upland catchment and its land cover and land uses, the temporally varying areal extent of
26 aquatic habitats within the reservoir and downstream river, and the bathymetry of the reservoir. We
27 also need information on the terrestrial carbon stocks present in the area before impoundment and on
28 the net emissions of GHG's from the original ecosystem.

29

1 **6. MEASUREMENTS**

2 **Key parameters and processes in reservoirs**

3 Meteorological instrumentation is routinely used to measure and record wind speed, air temperature,
4 rainfall and incoming solar radiation. For measurements within reservoirs, thermistors, current meters
5 and oxygen sensors are available. Concentrations of dissolved and particulate organic matter and
6 nutrients are determined with laboratory analyses on samples collected from the reservoir, inflow from
7 the catchment and downstream river course. Hydrological measurements of discharge and water depth
8 are performed with current meters and pressure transducers or stage gauges.

9 Carbon loading occurs via internal inputs from primary productivity and from flooded soil and plant
10 biomass and via external load from rivers and streams. Measurement of primary productivity requires
11 sequential determination of biomass of woody and herbaceous vegetation growing in the reservoir, and
12 of uptake of dissolved inorganic carbon or evolution of oxygen by algae. Biomasses of macrophytes
13 growing in the reservoir are determined by direct sampling. Biomass of the flooded soils and plant
14 biomass can be measured directly or estimated using the carbon density databases, such as the Carbon
15 Dioxide Information Analysis Center (CDIAC). External loads are the product of water discharge rate
16 and the concentration of dissolved and particulate organic carbon.

17 Methane and carbon dioxide production rates during the mineralization of these different pools of
18 organic matter can be measured by incubation in anoxic conditions. In natural lake sediments, the
19 degradation rates of organic matter and the resulting carbon dioxide and methane benthic fluxes can be
20 obtained by vertical profiles in sediment pore waters or from benthic chamber experiments. The
21 sampling of the flooded organic matter and interstitial water can be difficult due to the presence of
22 tangled trunks and branches that preclude the use of box cores and benthic chambers. Taking into
23 account these difficulties, carbon dioxide and methane production rates during the degradation of the
24 flooded organic matter can be investigated by an in vitro approach. Soils and vegetal samples similar
25 to those which were flooded are retrieved from the river basin and are incubated with water in anoxic
26 conditions. Carbon dioxide and methane potential production rates are then followed over one to two
27 years. Measurements of carbon dioxide production under aerobic conditions are also required for the
28 estimation of heterotrophic respiration in the epilimnion of the reservoir and in the river below the
29 dam. During these experiments, the release of nutrients must be monitored.

30 In aquatic ecosystems, aerobic methane oxidation is an important factor controlling methane fluxes to
31 the atmosphere. This process has a significant impact on the balance between methane and carbon
32 dioxide emissions. The kinetics of this process are determined by incubations under aerobic conditions
33 of water and sediments from the reservoir epilimnion and the river downstream of the dam.

34 **Change in storage in the reservoir**

35 Most reservoirs act as sediment traps, and by accumulating carbon in the sediments they can trap a
36 significant amount of carbon. Sediments can also provide anoxic conditions leading to methane
37 production. The total flux of carbon, carbon dioxide and methane between the reservoir sediments and
38 the atmosphere through the water body must be assessed. If possible, these fluxes should be
39 measured. They can also be calculated as the difference between measurements of carbon input and
40 output.

41 **Output from the reservoir**

42 Diffusive carbon dioxide and methane fluxes at the air-water interface of the reservoir and the river
43 below a dam can be determined using floating chambers or, it could be calculated, based on the partial
44 pressure gradient at the air-water interface and an exchange coefficient that depends on wind speed,
45 water current velocity, rainfall, and temperature gradients at the air-water interface. Methane fluxes
46 through the vegetation and carbon dioxide exchanges by plants are measured with transparent and dark
47 chambers. Methane bubble fluxes from the reservoir are determined using inverted funnels filled with
48 water. Bubble fluxes mainly occur in shallow parts of lakes and reservoirs (<10m) where the

1 hydrostatic pressure is not high enough to dissolve methane in the interstitial water. Since ebullition is
2 episodic, it is difficult to accurately quantify.

3 Degassing below the dam has been estimated as the difference between the gas concentration up- and
4 down-stream of the dam multiplied by the turbine discharge. The surface and the vertical profile of
5 methane and carbon dioxide concentrations can be determined by the headspace method followed by
6 gas chromatography analysis.

7 In addition to downstream degassing of carbon dioxide and methane, dissolved and particulate organic
8 carbon and dissolved carbon dioxide and methane are discharged through the dam and transported by
9 river. This output has been calculated as the product of the water discharge rate and the concentration
10 of dissolved gases. However, for this calculation the out-gassing of carbon dioxide and methane, the
11 production of carbon dioxide by the respiration in the river of the organic matter produced in the
12 reservoir, and the oxidation of methane to carbon dioxide have all to be considered. This is necessary
13 to properly quantify the atmospheric emissions by this pathway and the export of organic matter below
14 the dam.

15 **Temporal and spatial resolution**

16 For an accurate estimation of the atmospheric emissions from a reservoir, the seasonal variation of the
17 fluxes by the whole reservoir system (including the lake, the degassing and the river downstream)
18 must be studied. As shown at the Petit Saut and Balbina reservoirs, atmospheric emissions vary by
19 more than one order of magnitude within a year because of the seasonal variations of organic carbon
20 supply, thermal stratification, irregular convective mixing, depth, hydro operations and flushing rates
21 in the reservoir. As shown at the Petit Saut reservoir with a monthly dataset over ten years, seasonal
22 variations of gross emissions were higher than inter-annual variations. This shows that estimations
23 based on just one or two surveys per year should be taken with caution. Therefore, at least a monthly
24 monitoring of key parameters and carbon dioxide and methane fluxes may be required to encompass
25 the seasonal variability and provide robust mass balance measurements for the studied reservoirs.

26 The monitoring of reservoirs should be compartmentalized to reflect the distinct regions and
27 predominant processes quantified in each of these regions. Six types of sampling stations might need
28 to be chosen for long-term monitoring:

- 29 • Stations at the upstream reach, and other points of inflow.
- 30 • Stations located along the longitudinal axis of the reservoir.
- 31 • Stations located in vegetated and non-vegetated littoral zones of the reservoir.
- 32 • Stations located in embayments (when they exist).
- 33 • Stations close to the dam to understand the mixing of the water column upstream of the dam.
34 Samples may also be taken from the outlet/turbine passageways.
- 35 • Stations in the river below the dam. Emissions must be studied along the river course until
36 carbon dioxide and methane partial pressure reach the natural background levels. The number
37 of sampling stations must be determined depending on the length of the river course impacted
38 by the dam.

39 **Standardization of units**

40 In a modelling framework, amounts of chemical substances (for concentrations, fluxes,
41 biogeochemical reaction rates, etc.) must be expressed in *moles* for stoichiometric calculations. Fluxes
42 of carbon dioxide and methane can be expressed in grams of carbon (g C). All other measurements
43 must be expressed using the International System of Units (SI).

44

1 7. PREDICTION AND MODELLING

2 Emissions from a reservoir can be evaluated by undertaking measurements after it has been
3 constructed or by making predictions before it is constructed. The prediction can be developed through
4 simple empirical relationships among variables and parameters and by modelling the processes in the
5 basin and the reservoir.

6 Initially, empirical models should be developed in order evaluate reservoir net emission. This requires
7 systematic measurements and a standardized assessment of existing data to develop an empirical
8 relationship. Process-based models should also be included in order to improve predictive capacity.
9 For pre-impoundment modelling of catchments, existing land-use or catchment models may be used to
10 calculate pre-impoundment fluxes of GHG. Such models or empirical relationships may be used for
11 the river basin upstream of the reservoir in the post-impoundment modelling process as well.

12 The major problem with predicting emissions is that the processes are complex and the information
13 available before a reservoir is constructed is usually incomplete. Whilst process-based models are
14 available and can be used for existing reservoirs provided sufficient data availability, the uncertainty
15 associated with using such models in a predictive mode is likely to be large.

16 Based on these issues, it is suggested that an empirical modelling approach analogous to that used to
17 model eutrophication and phosphorus loading be considered. It was found to be relatively successful
18 when used for the equally challenging task of predicting eutrophication of lakes and reservoirs in
19 response to phosphorus loading, using simple, empirically derived, relationships among residence
20 time, phosphorus loading and degree of eutrophication. The Working Group therefore developed the
21 following hypothesis:

22 *“Gross greenhouse gas emissions can be described based on the residence time and organic carbon*
23 *loading of a lake or reservoir”.*

24 The proposed model is detailed in the technical appendix, and has the following key characteristics:

- 25 • although simple, a similar approach has been successful in describing a similarly complex
26 problem in the same type of ecosystem;
- 27 • the proposed approach considers potential mitigation measures, in particular the reduction of
28 carbon loading;
- 29 • it can be relatively easily applied in a predictive fashion; and
- 30 • it should be equally applicable to all freshwater systems, including lakes and reservoirs.

31 Currently, the data available to construct such a model are limited. However, it is felt that such data
32 could be collected and analysed over the period of a proposed research program and procedures
33 updated in order to test the above hypothesis.

34 A process-based model for gross GHG emissions from a reservoir is likely to require:

- 35 • the quantification of three sources of organic carbon: (i) loading from the catchment; (ii) the
36 inundated soils and vegetation; (iii) organic matter produced within the reservoir by carbon
37 fixation by photosynthetic aquatic organisms;
- 38 • the potential carbon dioxide and methane production rates during the mineralization of the
39 above listed material under aerobic and anaerobic conditions. The production rates obtained
40 from different incubations can be plotted *versus* organic carbon content or the C:N ratio of the
41 incubated material. These relationships are then used together with the total carbon load
42 (flooded organic matter, autochthonous and allochthonous organic matter) of the reservoir and
43 the river below the dam to extrapolate the total production of methane and carbon dioxide over
44 the desired time scale (e.g., 100 years).
- 45 • Carbon dioxide and methane consumption by photosynthesis and aerobic methane oxidation,
46 respectively. Empirical relationships between net primary production that consumes carbon
47 dioxide and the nutrient load or the residence time of water must be established. In the same

1 way, empirical relationships between the efficiency of aerobic methane oxidation and the
2 mean depth of the reservoir, the nutrient load, the residence time of water or total methane
3 production in the reservoir have to be established.

4 This gross GHG emission model must be used in combination with empirical data, measurements or a
5 similar modelling process for pre-impoundment estimations of GHG emissions in the river basin.
6 Combined with assessments of carbon storage change within the reservoir, net GHG emissions may
7 then be estimated.

8

1 **8. FURTHER WORK**

2 The Working Group suggests that further work is carried out in a research program. Figure 6 shows
3 the proposed framework for further work. The main parts of such a research program are described
4 briefly below.

5 **Guidance for measurement methodology**

6 In order to have reliable measurements of variables and parameters, a guide is required to create
7 standards to be followed when making new measurements. It is also necessary to develop guidance in
8 how to use existing measurements and assessments.

9 **Site selection for representative measurements**

10 Several indicators, such as geographical areas and gradients in characteristics, should guide the
11 selection of sites for measurements and model development and testing. Sites should include all
12 continents in the tropical region, Africa, Asia, Oceania, as well as Latin America. A research program
13 should define the site selection criteria in detail. Possible important criteria include:

- 14 • Carbon loading varying from low natural conditions to large anthropogenic inputs
 - 15 • Reservoir area: large – small
 - 16 • Reservoir depth: deep – shallow
 - 17 • Residence time: long – short
 - 18 • Reservoir age: young – old
 - 19 • Engineering issues such as intake level and location of gates
 - 20 • Flooded soil and vegetation: low to high carbon density
 - 21 • Climate: tropical – sub-tropical – temperate
 - 22 • Hypolimnion: oxic – anoxic
- 23

24 Since all combinations of gradients cannot be represented, it is recommended to select one or two
25 parameters as the primary criteria and to determine how representative the chosen reservoirs are
26 according to the other criteria. Based on these criteria and practical issues like accessibility to the
27 reservoir, political situation in the current country, local facilities, manpower available and the need of
28 a willing host, approximately 10 sites should be selected for measurements.

29 **Conducting measurements in reservoirs**

30 After having developed guidance in how to conduct measurements and having selected sites,
31 measurement teams must be contracted in order to carry out measurements. The co-ordination of these
32 teams may require special focus since there is an urgent need to produce data in a systematic way.

33 **Potential mitigation options**

34 Potential mitigation options may be suggested for sites where net GHG emissions are considered
35 unsatisfactory. These sites may act as case studies for mitigation (See also, Appendix D). More
36 detailed general advice may also be developed in a special report.

37 **Predictive modelling tools**

38 As described in chapter 7, both empirical and process-based models should be developed. Empirical
39 models must use existing data found in the literature and in on-going studies prepared in a
40 standardized way and following guidance described above. Empirical models should also use data
41 from new measurements developed within the research program.

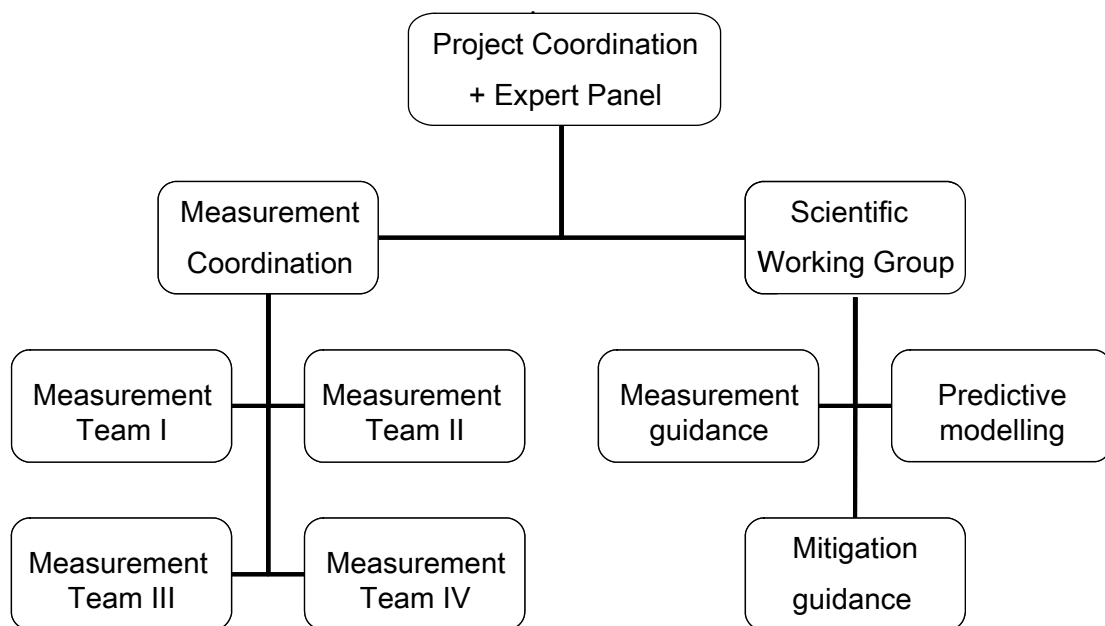
1 Parallel to the development of an empirical model, process-based models should be developed based
2 on one or several existing models.

3 **Reporting**

4 Guidance for measurements must be reported in a manual/handbook type of report, giving clear advice
5 in how, when and where to conduct what types of measurements. Guidance in how to use existing data
6 may be given in a technical report. Mitigation potentials may also be given in a technical report, but
7 should also be generalised in a peer-reviewed scientific paper. All measurements, local and global
8 estimates of GHG emissions and predictive model development should be reported by peer-reviewed
9 scientific papers.

10 **Program organization**

11 The organization of a research program needs to be considered carefully, allowing both administrative
12 co-ordination and scientific guidance throughout the program. A suggested organization chart is
13 shown in Figure 5 and a preparation/development framework is proposed in Figure 6.



32 **Figure 5. A possible organization chart for a research program.**

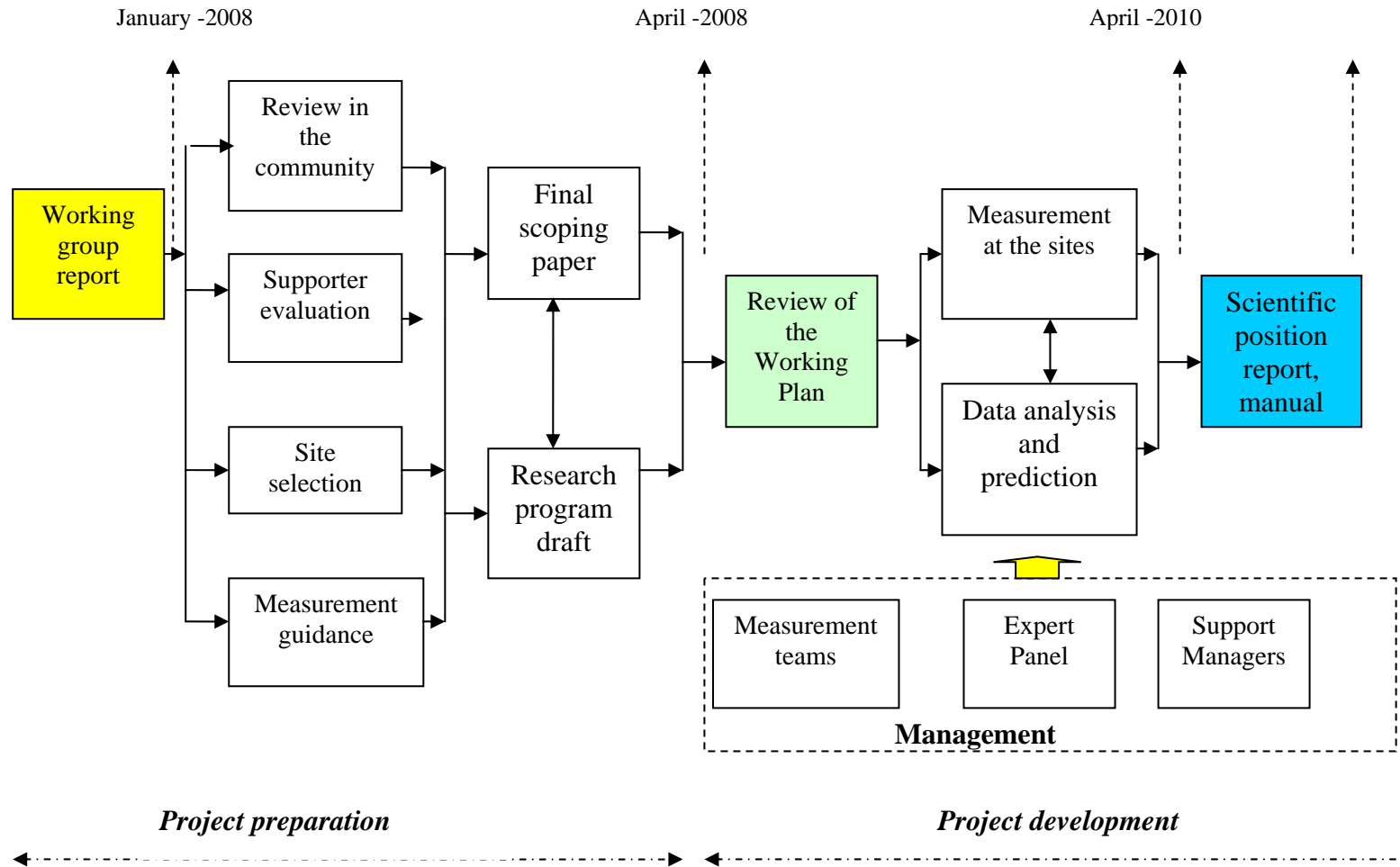


Figure 6. Program framework.

9. REFERENCES

- Abril G., Commarieu M.-V and F. Guérin (2007) Enhanced methane oxidation in an estuarine turbidity maximum. *Limnol. Oceanogr.* 52: 470-475.
- Abril, G., F. Guérin, S. Richard, R. Delmas, C. Galy-Lacaux, P. Gosse, A. Tremblay, L. Varfalvy, M. A. dos Santos, and B. Matvienko (2005), Carbon dioxide and methane emissions and the carbon budget of a 10-years old tropical reservoir (Petit-Saut, French Guiana), *Global Biogeochem. Cycles*, 19, GB 4007, doi:10.1029/2005GB002457.
- Abril G., S. Richard, and F. Guérin (2006), In situ measurements of dissolved gases (CO₂ and CH₄) in a wide range of concentrations in a tropical reservoir using an equilibrator, *Sci. Tot. Env.*, 354, 246-251.
- Borges, A. V., Vanderborght, J.P., Schiettecatte, L.-S., Gazeau, F., Ferron-Smith, S, Delille, B., and Frankignoulle, M., 2004b. Variability of the Gas Transfer Velocity of CO₂ in a Macrotidal Estuary (the Scheldt). *Estuaries*, 27:593-603.
- Casper, P., S.C. Maberly, G.H. Hall, P.J. Finlay (2000), Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere, *Biogeochem.*, 49: 1-19.
- Chanton, J.P., Martens, C.S., 1988. Seasonal variations in the isotopic composition and rate of methane bubble flux from a tidal freshwater estuary. *Global Biogeochemical Cycles* 2, 289–298.
- Chanton, J.P., Martens, C.S., Kelley, C.A., 1989. Gas transport from methane-saturated tidal freshwater and wetland sediments. *Limnology and Oceanography* 34, 807–819.
- Chanton, J.P., Whiting, G.J., Showers, W., Crill, P., 1992b. Methane flux from *Peltandra virginica* - stable isotope tracing and chamber effects. *Global Biogeochemical Cycles* 6, 15–33.
- Dannenberg S., Wulder J., Conrad R. 1997. Agitation of anoxic paddy soil slurries a effects the performance of the methanogenic microbial community. *FEMS Microbiology Ecology*. 22 : 257-263.
- Dumestre, J.-F., J. Guézennec, C. Galy-Lacaux, R. Delmas, S. Richard, and L. Labroue, (1999), Influence of light intensity on methanotrophic bacterial activity in Petit-Saut reservoir, French Guiana, *Appl. Env. Microbiol.*, 65, 534-539.
- Fearnside, P.M. (2002), Greenhouse gas emissions from a hydroelectric reservoir (Brazil's Tucuruí dam) and the energy policy implication, *Water Air Soil Pollut*, 133, 69-96.
- Frankignoulle, M., Bourge, I. and Wollast, R., 1996. Atmospheric CO₂ fluxes in a highly polluted estuary (The Scheldt). *Limnol. Oceanogr.*, 41:365-369.
- Galy-Lacaux, C., R. Delmas, C. Jambert, J. F. Dumestre, L. Labroue, S. Richard, and P. Gosse (1997), Gaseous emissions and oxygen consumption in hydroelectric dams: A case study in French Guiana, *Global Biogeochem. Cycles*, 11, 471-483.
- Galy-Lacaux, C., R. Delmas, G. Kouadio, S. Richard, and P. Gosse (1999), Long term greenhouse gas emission from a hydroelectric reservoir in tropical forest regions, *Global Biogeochem. Cycles*, 13, 503-517.
- Glaser, P.H., J.P. Chanton, D.O. Rosenberry, et al. (2004), Surface Deformations as Indicators of Deep Ebullition Fluxes in a Large Northern Peatland, *Global Biogeochem. Cycles*, 18: 1-15.
- Guérin F., and G. Abril (2007), Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir, *J. Geophys. Res.*, 112, G03006, doi:10.1029/2006JG000393.
- Guérin F., G. Abril, D. Serça, C. Delon, S. Richard, R. Delmas, A. Tremblay, and L. Varfalvy (2007), Gas transfer velocities of CO₂ and CH₄ in a tropical reservoir and its river downstream, *J. Mar. Syst.*, 66, 161-172.
- Harrits, S. M., and R. S. Hanson (1980), Stratification of aerobic methane-oxidizing organisms in Lake Mendota, Madison, Wisconsin, *Limnol. Oceanogr.*, 25, 412-421.
- Joyce J, Jewell PW. Physical controls on methane ebullition from reservoirs and lakes. *Environ Engineer Geoscience* 2003; 9: 167-178.
- Keller M. and Stallard R.F. (1994) Methane emissions by bubbling from Gatun Lake, Panama. *J. Geophys. Res.* 99, 8307-8319.
- Kemenes, A., Forsberg, B. R. and Melack, J. M. 2007, Methane release below a tropical hydroelectric dam. *Geophys. Res. Lett.*, 34, L12809, doi:10.1029/2007GL029479.

- 1 Lidstrom, M. E., and L. Somers (1984), Seasonal study of methane oxidation in Lake Washington,
2 Appl. Environ. Microbiol., 47, 1255-1260.
- 3 Martens, C.S., J.V. Klump (1980), Biogeochemical Cycling in an organic rich coastal marine basin. 1.
4 Methane sediment-water exchange processes, Geochim. Cosmochim. Acta, 44: 471-490.
- 5 McGinnis, D.F.; Greinert, J.; Artemov, Y.; Beaubien, S.E.; Wüest, A. (2006), Fate of rising methane
6 bubbles in stratified waters: How much methane reaches the atmosphere? J. Geophys. Res.-
7 Oceans, 111, C9, C09007.
- 8 Roehm C. and A. Tremblay (2006) Role of turbines in the carbon dioxide emissions from two boreal
9 reservoirs, Québec, Canada. J. Geophys. Res., 111, doi:10.1029/2006JD007292
- 10 Rudd, J. W., R. D. Hamilton, and N. E. R. Campbell (1974), Measurements of microbial oxidation of
11 methane in lake water, Limnol. Oceanogr., 19, 519-524.
- 12 Scranton, M.I., Crill, P., DeAngelis, M.A., Donaghay, P.L., Sieburth, J.M., 1993. The importance of
13 episodic events in controlling the flux of methane from and anoxic basis. Glob. Biogeochem.
14 Cycles 7, 491–507.
- 15 Smith, L.K., W.M. Lewis Jr, J.P. Chanton, et al. (2000), Methane emissions from the Orinoco River
16 floodplain, Venezuela, Biogeochem., 51: 113–140.
- 17 Soumis, N., Duchemin E., Canuel R., and M. Lucotte (2004), Greenhouse gas emissions from
18 reservoirs of the Western United States. Global Biogeochem. Cycles 18
19 doi:10.1029/2003GB002197.
- 20 Ward B., Wanninkhof R., McGillis W. R., Jessup A. T., DeGrandpre M. D., Hare J. E., Edson J. B.
21 2004. Biases in the air-sea flux of CO₂ resulting from ocean surface temperature gradient. J.
22 Geophys. Res., doi: 10.1029/2003JC001800.
- 23 Weiss RF., 1974. Carbon dioxide in water and seawater: the solubility of a non-ideal gas. Mar. Chem.,
24 2:203 – 15.
- 25 Yamamoto S, Alcauskas JB, Crozier TE., 1976. Solubility of methane in distilled water and
26 seawater. J. Chem. Eng. Data., 21:78 – 80.

TECHNICAL APPENDIX

A. Indicators

Age – This can be a good indicator of GHG emissions. Reservoirs older than 20 years of age tend to have low emissions (and in some cases, have been found to be a net sink for carbon).

Flooded vegetation – The highest levels of GHG emissions occur in situations where forests were not removed before impoundment. Fluctuating water levels in operating reservoirs may seasonally add organic carbon that has grown on the littoral drawdown zone.

Land use and carbon load – The land use in the catchment has a major impact on the amount of carbon which is received by the reservoir. Reservoirs in catchments with little erosion and negligible dumping of effluents receive small amounts of allochthonous carbon. Conversely, those in catchments with intensive human use can receive large amounts of carbon and nutrients, and this can affect the carbon load and the level of primary production in the reservoir. Human effluents may also be more labile than natural runoff.

Lake area – The larger the air-water interface, the larger the volume of GHG emissions is likely to be. There is a considerable spatial variability in the area of reservoirs, conditioned by the power installed, by operating procedures, by social and environmental restrictions and by the water regime.

Drainage ratio – In an upstream basin the drainage ratio is easily defined. However, there is no easy solution to the problem of determining the “representative catchment area” of a reservoir placed downstream from another reservoir.

Residence time – Greenhouse gas concentrations are dependent on the water residence time in the reservoir, but the nature of the relationships involved are not yet clear. Further examination under a range of conditions is required.

Climatic variability – Assessing climatic variability requires examination of meteorological, climatological and geographic parameters.

Mean depth – Volume divided by surface area. This indicator evaluates the spatial variability of the reservoir (surface area) with the reservoir water volume, giving an idea of the vertical dimension.

The likely range for each of the indicators above is preliminary described in Table A.1.

Table A.1 Characteristics of the reservoirs

	Range	Higher GHG emissions	Lower GHG emissions
Age	0-100	0-5 years	10+ years
Flooded Vegetation	Thin cover – Thick cover	Thick cover, without previous deforestation	Thin cover, or previous deforestation
Land Use	Pristine – Heavily anthropic	Heavily anthropic	Pristine
Lake Area	Few square kilometers – hundreds of square kilometers	Few square kilometers (emission / sq Km)	Hundreds of square kilometers (emission / sq Km)
Drainage Ratio	?	High (emission / sq Km)	Low (emission / sq Km)
Residence Time	weeks – years	Years	Weeks
Climatic variability	days - weeks	weeks	days
Depth	meters	Smaller	higher

1 **B. Measuring and predicting GHG emissions**

2 This technical appendix outlines details of the proposed approach to measuring and predicting the
3 GHG emissions from a lake or reservoir.

4 **Methods for the determination of net greenhouse gas emissions from freshwater reservoirs**

5
6
7 *Diffusive CO₂ and CH₄ fluxes at the air-water interface* of the reservoirs and the river below the dams
8 are determined using the floating chamber technique. Measurements are performed with a chamber
9 with wall extension below the water surface (2-5 cm) while drifting with the water mass
10 (Frankignoulle et al., 1996). Compared with the eddy covariance method, both methods have been
11 found to give similar results. Thus, the floating chamber appears to be a reliable and inexpensive
12 technique to determine the gas transfer velocity in various aquatic environments (lakes, estuaries,
13 rivers) (Guerin et al., 2007). In general terms, diffusive emission of GHGs depends primarily on the
14 magnitude and direction of the concentration gradient at the air-water interface. The gas exchange is
15 also influenced by physical processes that enhance the turbulence and the transport of the gases across
16 this interface. These physical processes are wind speed (e.g., Borges et al., 2004; Guerin et al., 2007),
17 water current velocity in rivers (e.g., Borges et al., 2004), rainfall (e.g., Guerin et al., 2007) and
18 temperature gradient at the air-water interface (e.g., Ward et al., 2005). All parameters must be
19 determined during flux measurements in order to derive relationships between the fluxes and the
20 controlling factors. When the relationships are known for a given reservoir and river below the dam, it
21 becomes possible to normalize fluxes to values representative of the average meteorological and
22 hydrodynamical conditions for extrapolations to the reservoir scale.

23 *CH₄ fluxes through the vegetation and CO₂ pumping by plants:* CO₂ and CH₄ fluxes are measured with
24 transparent and dark chambers in order to integrate fluxes at the daily scale (night and day). In the
25 littoral zone, chambers are mounted on collars inserted in the soil. As these chambers are high (~1 m
26 in height), a fan is installed inside to circulate air and homogenise GHG concentrations from the top to
27 the bottom of the chamber (Chanton et al., 1992). Fluxes through plants depend on both temperature
28 and on the humidity, thus chambers are shaded to control the temperature and humidity is also
29 controlled (Chanton et al., 1992).

30 *CH₄ bubbling fluxes* from the reservoir are determined using inverted funnels filled with water (Keller
31 and Stallard, 1994). The funnels must be deployed over long periods (24h) at different sites with
32 various depths encompassing the bathymetry of the reservoir. Ebullition is episodic and thus it is
33 difficult to accurately quantify. Bubble fluxes from aquatic ecosystems are probably always
34 underestimated (e.g., Glaser et al., 2004), thus they must be determined as often as possible. When
35 CH₄ accumulates in the flooded soils, CH₄ bubbles can develop if the CH₄ concentration in the
36 interstitial water becomes higher than the solubility of this gas in water. Bubble fluxes correspond to a
37 direct transfer of CH₄ from the sediment to the atmosphere without significant interaction with the
38 processes occurring within the water column. Bubble fluxes mainly occur in shallow parts of lakes and
39 reservoirs (<10m) (Keller and Stallard, 1994; Galy-Lacaux et al., 1997; Abril et al., 2005) where the
40 hydrostatic pressure is not high enough to dissolve CH₄ in interstitial water. However, bubbles can
41 also be released from the sediment in deeper parts of lakes and reservoirs, but these bubbles tend to
42 dissolve into the water during their transport through the water column and so do not reach the
43 atmosphere (McGinnis et al., 2006). The release of bubbles is triggered by atmospheric pressure
44 variations (e.g., Casper et al., 2000), variations in water current velocity (Martens and Klump, 1980;
45 Chanton et al., 1989; Scranton et al., 1993), shear stress at the sediment surface (Joyce and Jewell,
46 2003), variation of hydrostatic pressure associated with rapid changes of the water level above the
47 sediment (e.g., Smith et al., 2000), increase of temperature that makes the CH₄ solubility decrease
48 (Chanton and Martens, 1988) and strong wind events (Keller and Stallard, 1994). For correct
49 extrapolation of bubble fluxes at the reservoir scale, relationships between the fluxes and the
50 controlling factors must be established.

51 *Degassing below the dam:* Degassing is commonly estimated by calculating the difference between
52 the gas concentration up- and down-stream of the dam, multiplied by the turbine discharge (Galy-

1 Lacaux et al., 1997, 1999; Fearnside, 2002; Soumis et al., 2004; Abril et al., 2005; Kemenes et al.,
2 2007; Rohem et Tremblay, 2006). This method may give realistic estimates with the concentration of
3 water entering the turbines (or in the turbines whenever it is possible) and water in the downstream
4 river. An empirical model for the efficiency of degassing depending on the water turbulence below the
5 dam and the variation of water pressure up- and down-stream of the dam must be developed.

6 *The surface and the vertical profile of CH₄ and CO₂ partial pressure* are determined by the headspace
7 method followed by gas chromatography (GC) analysis. Surface water can be sampled with a sampler
8 that limits gas exchange (Abril et al., 2007). The sampler is gently submerged and kept for a few
9 seconds below the water surface, with the open part facing in the direction of the water current. For
10 vertical profiles of partial pressure, waters can be sampled with a peristaltic pump or with sampling
11 bottles equipped with a tube (Abril et al., 2006). Water is transferred through the tube to serum glass
12 bottles with an overflow of at least three bottle volumes. Only the water that had no contact with air is
13 used for further analysis. After removing the tubing gently, the bottles should be immediately capped
14 without allowing an air bubble, using a butyl rubber stopper which is secured with aluminum crimps.
15 Duplicate bottles must be immediately poisoned with NaOH or HgCl₂. In the laboratory, a headspace
16 must be created by injecting N₂ through the stopper, keeping the bottle bottom-up while
17 simultaneously expelling water in excess through a second needle. All bottles must be weighed when
18 empty, and before and after the creation of the headspace in order to determine gravimetrically the
19 volume of gas and water. In order to equilibrate the CH₄ between the water and the headspace, the
20 bottles are given a vigorous shaking and are left to equilibrate at ambient temperature (25°C) for ~1
21 hour. The partial pressure in the headspace is measured (on duplicate bottles) using a GC with a flame
22 ionization detector (GC-FID) for CH₄ and a thermal conductivity detector (TCD) for CO₂. The
23 concentrations must be computed with solubility coefficients as a function of temperature (Yamamoto
24 et al. 1976 for methane and Weiss, 1976 for CO₂). Collection of samples for dissolved gas analysis
25 that maintains the samples from deeper water under pressure should be incorporated.

26 **Aerobic methane oxidation** - In aquatic ecosystems, aerobic methane oxidation is an important
27 process controlling methane fluxes to the atmosphere. At the Petit Saut reservoir, this microbiological
28 process that consumes methane and oxygen (O₂) reduces methane emissions by 85-90% (Guerin and
29 Abril, 2007). Part of the methane is oxidized to CO₂. Potential methane oxidation rates are determined
30 at variable concentrations for different sampling stations in the reservoir and in the river below the
31 dam throughout the hydrological cycle. Methane and oxygen (O₂) are added to water samples and the
32 decrease of methane concentration is followed by GC-FID analysis. Aerobic methane oxidation rates
33 can also be assayed by the uptake of ¹⁴C- CH₄ (Rudd et al., 1974). Analyses are made on triplicates, at
34 least.

35 For these incubations, 6 parameters must be considered:

- 36 • the volume of the headspace must be great enough to take several samples in the headspace
37 without creating a depression;
- 38 • in order not to modify significantly the methanotrophic population within the sample, the
39 increase of the CH₄ concentration compared to *in situ* must be lower than a factor of 4;
- 40 • the oxygen concentration in the water phase must be always higher than 80-100 mmol.L⁻¹, a
41 value higher than the O₂ half-saturation constant for aerobic CH₄ oxidation (Harrits and
42 Hanson, 1980; Lidstrom and Somers, 1984; Rudd et al., 1974);
- 43 • the bottles are incubated at a temperature close to *in situ*;
- 44 • the bottles are incubated under constant agitation in order to maintain the equilibrium between
45 the gas and the liquid phase;
- 46 • incubation is performed in the dark as methanotrophic bacteria are inhibited by light
47 (Dumestre et al., 1999)

48 These experiments provide potential aerobic methane oxidation rates. *In situ* oxidation rates (mol m⁻³
49 s⁻¹) must be corrected for *in situ* CH₄ and O₂ concentration and for inhibition by light as described in
50 Guerin and Abril (2007). Aerobic CH₄ oxidation can be depth integrated in order to obtain areally
51 averaged rates (mol m⁻² s⁻¹).

1 **CO₂ and CH₄ production** - CO₂ and CH₄ production during the mineralization of the flooded organic
2 matter, particulate organic matter from the watershed and particulate organic matter produced in the
3 reservoir is determined during incubation under anaerobic conditions. Slurries containing deionized
4 water and organic material (1:1 w/w) are filled in serum bottles and incubated in the dark without
5 agitation (Dannenberg et al., 1997), with a N₂ headspace and at a constant temperature close to the *in*
6 *situ* temperature at the bottom of the reservoir. The production rates (mmol g C⁻¹ s⁻¹) are the slope of
7 the linear correlation between CO₂ and CH₄ concentration in the headspace determined over time.
8 Using the carbon loads of the different pools of organic matter (g C m⁻²), the GHG production rates
9 are areally averaged (mmol m⁻² s⁻¹).

10 CO₂ production during the mineralization of organic matter in oxic water is determined by the
11 incubation of water under aerobic conditions and constant agitation to prevent settling of the
12 particulate organic matter. The production rates are determined as above.
13

C. Preliminary description of proposed empirical model that predicts GHG emissions from freshwater reservoirs

Residence time, mean depth and/or hydraulic load

The Vollenweider and OECD models consider residence time and mean depth as the main descriptors of the lake physics. Residence time can be simply defined as the average volume of the lake divided by the average inflow rate. Whilst it is recognised that this is an incomplete descriptor of the flushing of a lake or reservoir, it is easily calculated ahead of construction. Hydraulic load is the mean depth divided by the residence time.

For the purposes of this investigation, we define residence time T_R as

$$T_R = V/Q_I$$

where V is the average annual lake volume [m^3], and Q_I is the average annual inflow rate [$m^3 s^{-1}$]. This assumes that the inflows balance the hydraulic outflow over the year. If this is not the case, corrections can be made to include both inflow and outflow volumes to ensure the timescale gives a realistic representation of the hydraulic flushing time of the system.

Mean depth z_m is simply determined as the average lake volume divided by the average lake area. Hydraulic load q_s is defined as T_R / z_m .

Carbon load

The formation of methane requires the presence of carbon and the absence of oxygen. It is hypothesised that the average carbon concentration in a lake or reservoir is a function of the carbon load. The carbon load is presumed to consist of three components:

1. External load from rivers/streams C^E
2. Internal load from flooded vegetation and soils prior to inundation C^I
3. Internal load from net primary production from macrophytes, periphyton and phytoplankton C_{NPP}^I

External load from rivers and streams:

- A full carbon load model would consider both organic carbon load (dissolved and particulate) and inorganic carbon load. Given that we are recommending a relatively simple model, with a focus on methane, the load calculations focus solely on organic carbon load.
- Load needs to be areally averaged (over the surface area of the reservoir).
- It is recognised that the surface area of the reservoir may change considerably throughout the year. Surface area should therefore be calculated as the mean surface area (\pm one standard deviation).
- Inflow concentrations can be determined either by measurement or by classification of catchment land-use and vegetation types.

$$C^E = \frac{\sum_{i=1}^N C_i^{TOC} Q_i}{A}$$

where N is the number of inflows, C_i^{TOC} is the total organic carbon (TOC) in inflow i consisting of particulate and dissolved forms [$g m^{-3}$], Q_i is the volume of inflow i [$m^3 d^{-1}$], A is the mean annual

1 surface area [m²] and the overbar represents an average. This gives the average daily inflow carbon
2 flux with units of [g C m⁻² d⁻¹].
3

4 **Internal load from flooded vegetation and soils:**

- 5
- 6 – In many cases, the inundated area of a reservoir includes inundated vegetation and soils. It is
7 recognised that these components represent a significant potential source of carbon in a reservoir,
8 and so it is included in the calculations.
- 9 – This calculation requires the total mass of inundated vegetation as well as a first-order decay rate
10 of that vegetation and the different types of soils. More complexity can be considered by
11 including additional decay rates to compartmentalize vegetation into, for example, leaves,
12 branches and trunks, and soils into several compartments depending on their organic carbon
13 content or their C:N ratio.
- 14 – To convert this to the same units as previous components, the values need to be areally averaged.
- 15 – The breakdown of the mass of flooded vegetation and soils can be approximated as a first order
16 decay process

$$17 \quad M^t = M \exp[-kt]$$

18 where M represents the initial mass [g] of organic carbon, k represents the decay rate of that
19 component [d⁻¹] and t is the time since inundation [d].

20 The decay rate coefficient can be determined by following the CO₂ and CH₄ production rates and the
21 loss of organic carbon during the mineralization of the different compartments of this pool of organic
22 matter under anoxic conditions.

23 As an indicator, reducing the inundated biomass to 50% of the original biomass over a 10 year period
24 (3650 days) gives a decay rate coefficient of 1.9e-4 d⁻¹.

25 **Internal load of TOC from primary productivity:**

26 Primary productivity can be a significant source of organic carbon to the reservoir, and includes
27 production by macrophytes, periphyton and phytoplankton. No equation is required, as it is the annual
28 average net primary productivity (NPP), in units of g C m⁻² d⁻¹. Determination of these rates requires
29 either measurement or comparison with similar systems. NPP of woody vegetation can be determined
30 by incremental changes in biomass usually derived from measurements of diameter and height
31 followed by application of allometric equations and by collection of litterfall. NPP of herbaceous
32 aquatic vegetation can be determined by regular collections of above- and below-water plant material
33 throughout the growing season. NPP of phytoplankton and periphyton is usually assayed by measuring
34 changes in dissolved oxygen in dark and transparent containers or by measuring uptake of isotopic
35 tracers of dissolved inorganic carbon.
36
37
38
39
40
41

1 **D. Preliminary thoughts on possible mitigation measures**

2
3 A relatively simple list of potential measures to reduce the greenhouse gas emissions from a reservoir
4 is presented here, in the full knowledge that the list is neither comprehensive nor cross-checked for
5 effectiveness. Some of the methods to reduce emissions may not be compatible with other operational
6 objectives for the reservoir in question.

7 The mitigation measures focus on the reduction of the production of methane in the water column.
8 They can therefore be separated into two groups: measures to reduce carbon loading to the reservoir
9 (that is, the source material for methane production), and measures to reduce stratification (or to draw
10 water from methane-saturated zones). It is assumed that the reduction of stratification will lead to
11 increased oxygen concentrations and therefore less likelihood that methane will be produced.

12 **Methods to reduce carbon loading**

- 13 • Deforesting reservoir area prior to inundation. This very expensive method was tried at Nam
14 Theun 2 in some areas. Actually, it decreases the biomass of tree trunks which are not very
15 labile and it increases the growth of terrestrial herbaceous species, which are composed of
16 very labile carbon. This method should therefore be taken with caution.
- 17 • Controlling nutrient inputs from rivers (for example, through the construction of sewage
18 treatment plants upstream) to reduce primary production. The effect of this option could be
19 minor if the main source of carbon is flooded soils and biomass. On the other hand, human
20 activity in the catchment (agricultural, industrial and domestic) could significantly influence
21 the emissions observed at a reservoir downstream.

22 **Methods to reduce stratification**

- 23 • Manipulate water level to minimise hypolimnetic volume during periods of high methane
24 production. For example, depending on the depth/volume relationship for the reservoir, it may
25 be possible to maintain the water level at a position where the hypolimnion volume is
26 significantly decreased (say by 20%) without significantly impacting power production.
27 However, since methane is produced in the sediments and diffuses into the hypolimnion,
28 reducing the volume of the hypolimnion may not reduce the downstream fluxes or bubble
29 fluxes.
- 30 • For a chain of reservoirs, manipulate upstream releases to ensure underflows of high oxygen
31 concentration. This can be used to replenish the hypolimnion in the downstream reservoir with
32 oxygenated water, if feasible.
- 33 • Install an artificial destratification system. This is typically done using compressed air or
34 mechanical mixers. However, careful design is required to ensure that the system functions
35 efficiently with minimal power consumption.
- 36 • Artificially oxygenate the hypolimnion, through the direct injection of oxygen into the
37 hypolimnion. This is potentially an expensive option, but it favours methane oxidation in the
38 hypolimnion and this way it decreases downstream emissions.
- 39 • It may be possible to strip methane from the hypolimnetic water above the dam or just below
40 the dam and use it directly for power production; this would release carbon dioxide, a less
41 intensive greenhouse gas. This technique has been proposed but not implemented.
- 42 • The use of withdrawal uptakes that retrieve surface waters will favour the discharge of “CH₄
43 and CO₂ depleted waters” and thus decrease the downstream emissions.

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