

**Scoping paper**

**Assessment of the GHG Status of Freshwater Reservoirs**

**Revision 20 April 2008**

## 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 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 Foz do Iguaçu 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 (CO<sub>2</sub>) and methane (CH<sub>4</sub>) may be relevant to global inventories of greenhouse gas (GHG) exchanges. Research suggests that emission levels in cold and temperate climates are generally low, and that elevated emissions appear to be related to tropical systems with persistent anoxia. However, it is important to improve available information and tools in order 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). Limited published data from tropical reservoirs 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 exchange<sup>1</sup> 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 major GHGs (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

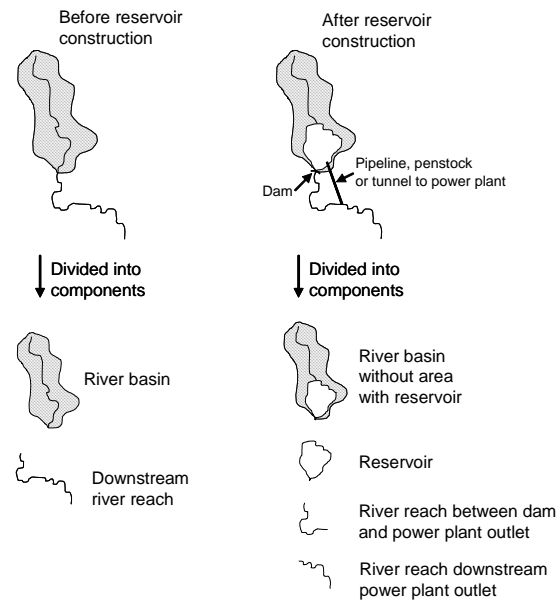
To quantify the GHG exchange caused by a reservoir, it is necessary to study emissions before and after the construction of the reservoir. The period of emissions should be calculated for 100 years. The

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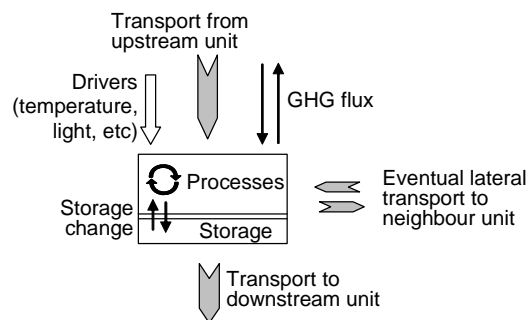
<sup>1</sup> This is often referred to as *the carbon footprint* or *net GHG emission*, which for the purpose of this program is the resulting positive or negative change in GHG emission in the river basin caused by the creation of the reservoir.

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

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



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



**Figure 2. General concept for all units in a GHG emission study.**

#### 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; Tremblay et al. 2005), temperate (Therrien et al. 2005; 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; Rosa et al., 2003; Abril et al., 2005; Sikar et al. 2005; Santos et al., 2006; Guerin 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. Few measurements of transported material into or out of the river basin or reservoir have been reported. Also, even though sedimentation in reservoirs can be significant, 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), and additional sites in central and southern Brazil (Serra da Mesa, Manso, Corumba, Itumbira, Furnas, Mascarenhas de Moraes, L.C.B. Carvalho, Funil, Itaipu, Xingó, Miranda, Segredo, Barra Bonita, Ribeirão das Lajes, Três Marias). Measurements are not available from reservoirs in other regions of the tropics or subtropics except for Lake Gatun, Panama. 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, Samuel and Balbina reservoirs have investigated methane emissions downstream of the dam.

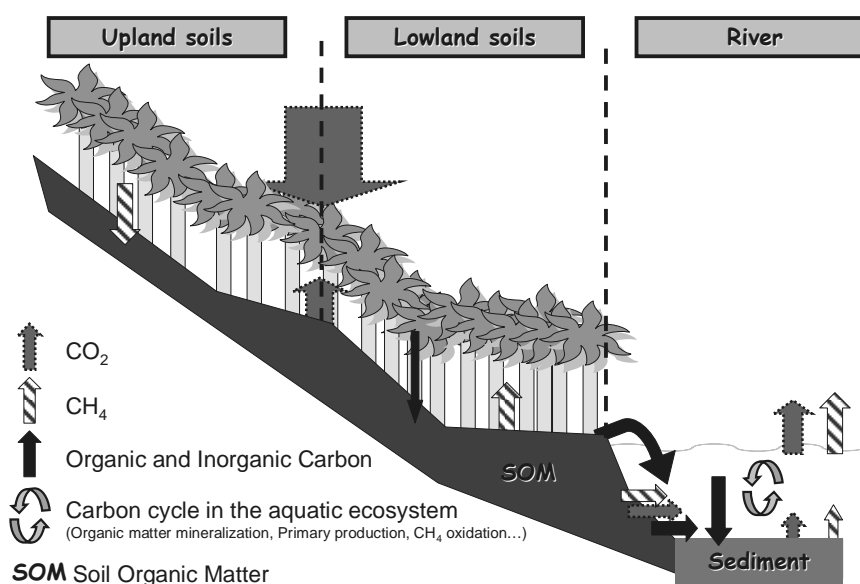
**Table 1: Range of average carbon dioxide and methane emissions from hydroelectric freshwater reservoirs in boreal, temperate and tropical regions. Numbers in parentheses are the number of reservoirs studied for each gas and each GHG pathway. Sources of data cited in paragraph above.**

GHG pathway	Boreal & temperate		Tropical	
	CO <sub>2</sub> mmol m <sup>-2</sup> d <sup>-1</sup>	CH <sub>4</sub> mmol m <sup>-2</sup> d <sup>-1</sup>	CO <sub>2</sub> mmol m <sup>-2</sup> d <sup>-1</sup>	CH <sub>4</sub> mmol m <sup>-2</sup> d <sup>-1</sup>
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)
River below the dam	n.a.	n.a.	500—2500 (3)	2—350 (3)

## 5. KEY PROCESSES AND PARAMETERS

### Carbon cycle in a natural catchment

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



**Figure 3: Carbon dioxide and methane emissions from a natural watershed (adapted from concepts in Conrad 1989 and Cole et al. 2007).**

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

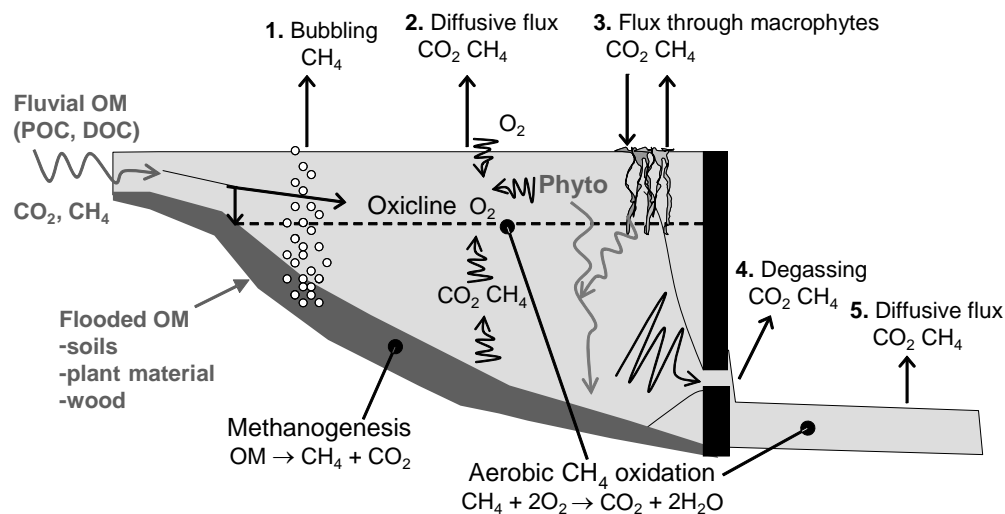
The different carbon moieties (organic and inorganic carbon) reach the aquatic ecosystems of the river basin (river, lakes and wetlands) by surface or sub-surface runoff. The carbon dioxide and the dissolved inorganic carbon are either consumed for aquatic primary production or follow the pathways indicated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

Limited work has been conducted to estimate the significance of the carbon dioxide out-gassing from aquatic ecosystems compared to the carbon dioxide uptake by vegetation at the watershed level. In some temperate and tropical watersheds, carbon dioxide out-gassing from the aquatic ecosystems has

been shown to be close to balancing the carbon dioxide uptake by the surrounding forest (Cole and Caraco, 2001; Richey et al., 2002).

### Pathways in reservoirs

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



**Figure 4: Carbon dioxide and methane pathways in a freshwater reservoir with an anoxic hypolimnion. For reservoirs with a well-oxygenated water column, methane emissions through pathways (2), (4) and (5) are reduced.**

## Key processes

Based on the guidelines of the Workshops on the GHG Status of Freshwater Reservoirs, this paper identifies key precursors for significant GHG emissions and is focused on tropical and subtropical reservoirs. Therefore, this section presents parameters and processes likely to be important in such systems, and may not include terms specific to reservoirs in high latitudes where frozen ground, ice cover or large reserves of peat may occur.

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

- I. Processes supplying organic carbon to the reservoir or its sediments:
  - a. Inputs of organic matter via groundwater, streams and rivers that depend on the discharge rate and the concentrations of organic matter in the catchment.
  - b. Net primary productivity of aquatic macrophytes, periphyton and phytoplankton growing in or on the water or in the drawdown zone around the reservoir, depending on the supply of nutrient and light.
  - c. Entrainment of terrestrial organic matter in living plants, litter and soils during impoundment.
- II. Processes producing conditions conducive to the production of dissolved carbon dioxide and methane:
  - a. Decomposition of the various types of organic matter entering the system, depending on the organisms present, temperature, dissolved oxygen and nutrients.
  - b. Anoxia in the sediment and water column, relating to the physical stratification, temperature and amount of organic matter.
- III. Processes influencing the distribution of dissolved carbon dioxide and methane within the reservoir:
  - a. Mixing and transport processes that can lead to the movement of carbon dioxide and methane to the surface.
  - b. Withdrawal via spillways or subsurface turbines.
  - c. Methane oxidation within the water or sediments, depending on the physical stratification, dissolved oxygen, inhibition by light, nutrient levels and temperature.
  - d. Primary production in the euphotic zone of the reservoir water column that consumes carbon dioxide and depends mainly on light and nutrient availability.
- IV. Carbon dioxide and methane pathways between the reservoir and downstream river and the atmosphere:
  - a. Ebullition (bubbling)
  - b. Transport via plants stems
  - c. Diffusive gas exchange between the atmosphere and the reservoir or downstream river
  - d. Degassing immediately after water passes through turbines and in spillways
- V. Processes leading to release of carbon dioxide and methane from above water to the atmosphere
  - a. Aerobic decay of dead emergent vegetation
  - b. Methane released by termite activity
  - c. Fires that consume vegetation in drawdown zones

## Key parameters

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

- I. Parameters that modulate the rates of biological processes such as organic matter production, respiration, methanogenesis and methane oxidation:
  - a. Concentrations of dissolved oxygen
  - b. Water temperature
  - c. Organic matter concentrations and C/N, C/P and N/P ratios in water and in sediments
  - d. Supply of nutrients
  - e. Light
  - f. Biomass of plants, algae, bacteria and animals in the reservoir and in drawdown zone
  - g. Methane concentration (substrate for methane oxidation)
- II. Parameters that modulate gas exchange between the atmosphere and the reservoir or downstream river:
  - a. Wind
  - b. Rainfall
  - c. Current speeds in rivers and streams
  - d. Surficial temperatures
  - e. Stability of density stratification in the water
  - f. Water depth and changes in water depth
  - g. Residence time of water in the reservoir
  - h. Reductions in hydrostatic pressure as water is released through reservoir outlets
  - i. Increased turbulence downstream of the dam associated with ancillary structures, e.g. weirs

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

## **6. MEASUREMENTS**

### **Key parameters and processes in reservoirs**

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

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

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

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

### **Change in storage in the reservoir**

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

### **Output from the reservoir**

Diffusive carbon dioxide and methane fluxes at the air-water interface of the reservoir and the river below a dam can be determined using floating chambers or, it could be calculated, based on the partial pressure gradient at the air-water interface and an exchange coefficient that depends on wind speed, water current velocity, rainfall, and temperature gradients at the air-water interface. Methane fluxes through the vegetation and carbon dioxide exchanges by plants are measured with transparent and dark chambers. Methane bubble fluxes from the reservoir are determined using inverted funnels coupled to gas collectors initially filled with water. Bubble fluxes mainly occur in shallow parts reservoirs where the hydrostatic pressure is not sufficiently high to dissolve methane in the interstitial water. Since ebullition is episodic, it is difficult to accurately quantify.

Degassing below the dam has been estimated as the difference between the gas concentration up- and down-stream of the power plant multiplied by the turbine discharge. If possible, the gas concentrations should be sampled from ports within the conduits leading to the turbines. The surface and the vertical profiles of methane and carbon dioxide concentrations can be determined by the headspace method followed by gas chromatographic analysis.

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

### **Temporal and spatial resolution**

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

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

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

### **Standardization of units**

In a modelling framework, amounts of chemical substances (for concentrations, fluxes, biogeochemical reaction rates, etc.) must be expressed in *moles* for stoichiometric calculations. Fluxes of carbon dioxide and methane can be expressed in grams of carbon per square meter per day ( $\text{g C m}^{-2} \text{d}^{-1}$ ). All other measurements must be expressed using the International System of Units (SI).

## 7. PREDICTION AND MODELLING

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

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

The major problem with predicting emissions is that the processes are complex and the information available before a reservoir is constructed is usually incomplete. Whilst process-based models exist (e.g., Walter and Heimann 2000) and, with some modification, can be used for existing reservoirs provided sufficient data are available, the uncertainty associated with using such models in a predictive mode is likely to be large.

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

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

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

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

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

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

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

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

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

## **8. FURTHER WORK**

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

### **Guidance for measurement methodology**

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

### **Site selection for representative measurements**

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

- Carbon loading varying from low natural conditions to large anthropogenic inputs
- Reservoir area: large – small
- Reservoir depth: deep – shallow
- Residence time: long – short
- Reservoir age: young – old
- Engineering issues such as intake level and location of gates
- Flooded soil and vegetation: low to high carbon density
- Climate: tropical – sub-tropical – temperate
- Hypolimnion: oxic – anoxic
- Drawdown zone: large - small

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

### **Conducting measurements in reservoirs**

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

### **Potential mitigation options**

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

### **Predictive modelling tools**

As described in chapter 7, both empirical and process-based models should be developed for both pre- and post-impoundment conditions. Empirical models must use existing data found in the literature and

in on-going studies prepared in a standardized way and following guidance described above. Empirical models should also use data from new measurements developed within the research program.

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

### Reporting

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

### Program organization

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

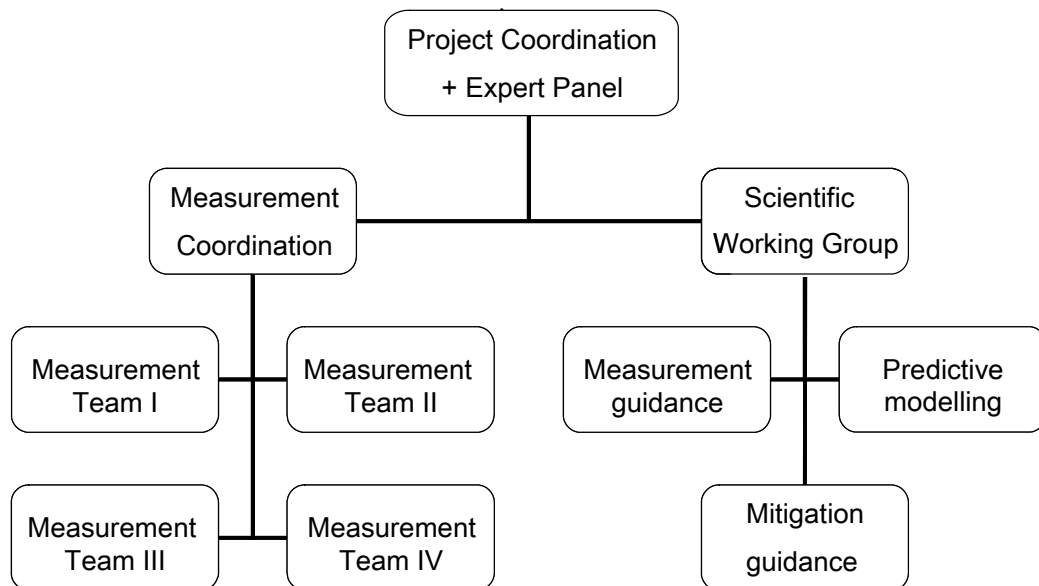


Figure 5. A possible organization chart for a research program.

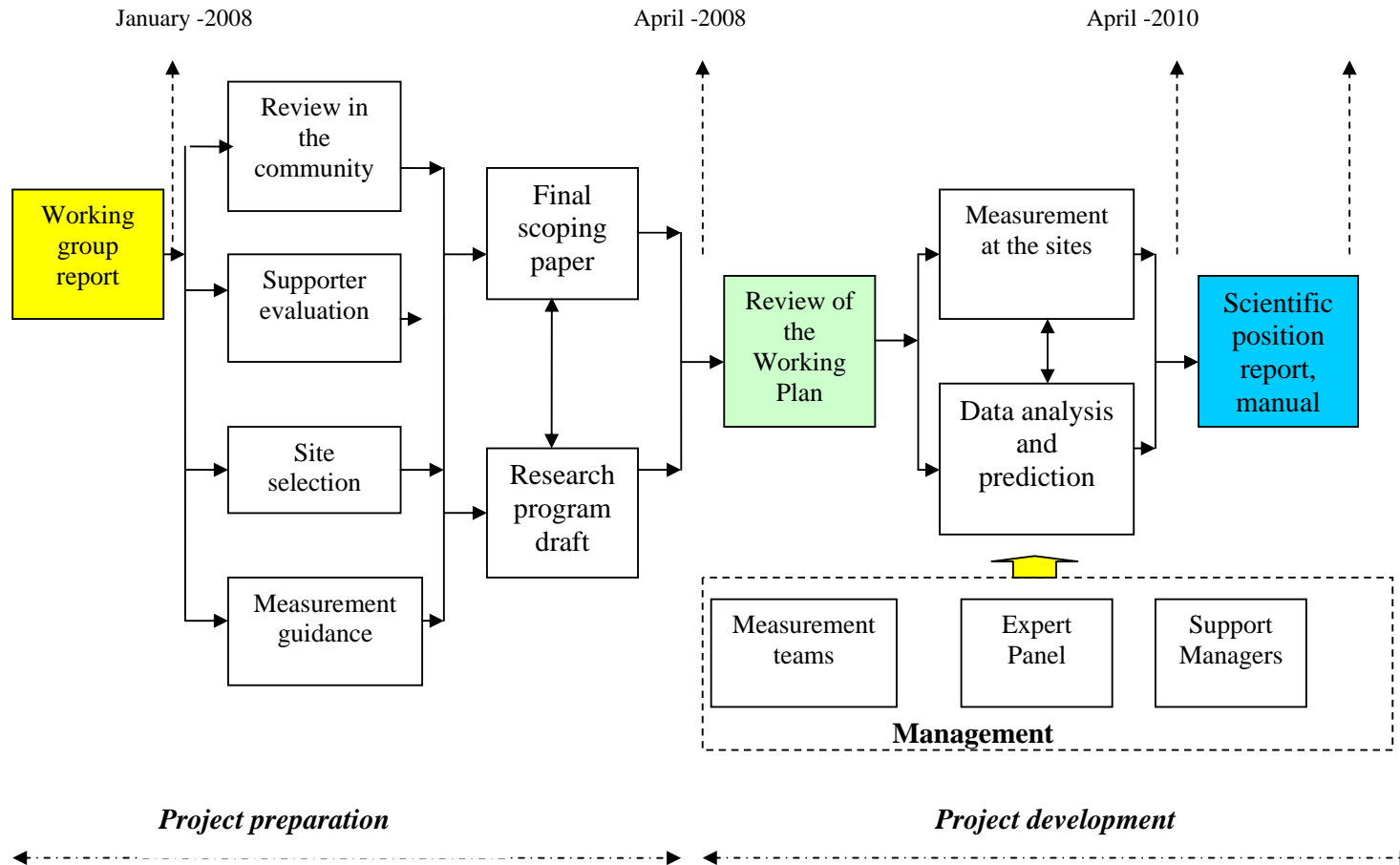


Figure 6. Program framework.

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## TECHNICAL APPENDIX

### A. Predictive Indicators (not ranked in importance)

Age – The relation between age and GHG emissions appears to be variable in tropical reservoirs.

Flooded vegetation and vegetation in drawdown zone – The highest levels of GHG emissions are likely to 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 that is received by the reservoir. Reservoirs in catchments with little erosion and negligible inputs 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 – 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 hydrologic regime.

Drainage ratio – In an upstream basin the drainage ratio is readily defined. Determination of relevant catchment area for a reservoir placed downstream from another reservoir requires further analysis.

Residence time – Greenhouse gas concentrations are dependent on the water residence time in the reservoir, but the nature of the relationships involved are not well established.

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

Mean depth – Volume divided by surface area.

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

Table A.1 Characteristics of the reservoirs

Predictive indicators	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 and Carbon Load	Natural – anthropic	Anthropic and high organic carbon loading	Natural and low organic carbon loading
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

## B. Measuring and predicting GHG emissions

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

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

*Diffusive CO<sub>2</sub> and CH<sub>4</sub> fluxes at the air-water interface* of the reservoirs and the river below the dams are determined using the floating chamber technique. Measurements are performed with a chamber with wall extension below the water surface (2-5 cm) while drifting with the water mass (Frankignoulle et al., 1996). Compared with the eddy covariance method, both methods have been found to give similar results. Thus, the floating chamber appears to be a reliable and inexpensive technique to determine the gas transfer velocity in various aquatic environments (lakes, estuaries, rivers) (Guerin et al., 2007). In general terms, diffusive emission of GHGs depends primarily on the magnitude and direction of the concentration gradient at the air-water interface. The gas exchange is also influenced by physical processes that enhance the turbulence and the transport of the gases across this interface. These physical processes are wind speed (e.g., Borges et al., 2004; Guerin et al., 2007), water current velocity in rivers (e.g., Borges et al., 2004), rainfall (e.g., Guerin et al., 2007) and temperature gradient at the air-water interface (e.g., Ward et al., 2005). All parameters must be determined during flux measurements in order to derive relationships between the fluxes and the controlling factors. When the relationships are known for a given reservoir and river below the dam, it becomes possible to normalize fluxes to values representative of the average meteorological and hydrodynamical conditions for extrapolations to the reservoir scale. Samples for gas analyses can be obtained as discrete samples and analysed in a laboratory (see below) or monitored continuously with systems such as photoacoustic detectors.

*CH<sub>4</sub> fluxes through the vegetation and CO<sub>2</sub> pumping by plants:* CO<sub>2</sub> and CH<sub>4</sub> fluxes are measured with transparent and dark chambers in order to integrate fluxes at the daily scale (night and day). In the littoral zone, chambers are mounted on collars inserted in the soil. As these chambers are high (~1 m in height), a fan is installed inside to circulate air and homogenise GHG concentrations from the top to the bottom of the chamber (Chanton et al., 1992). Fluxes through plants depend on both temperature and on the humidity, thus chambers are shaded to control the temperature and humidity is also controlled (Chanton et al., 1992).

*CH<sub>4</sub> bubbling fluxes* from water bodies are determined using inverted funnels filled with water (Keller and Stallard, 1994). The funnels must be deployed over long periods (24 h) at different sites with various depths encompassing the bathymetry of the reservoir. Ebullition is episodic and thus it is difficult to accurately quantify. Bubble fluxes from aquatic ecosystems are probably always underestimated (e.g., Glaser et al., 2004), thus they must be determined as often as possible. When CH<sub>4</sub> accumulates in the flooded soils, CH<sub>4</sub> bubbles can develop if the CH<sub>4</sub> concentration in the interstitial water becomes higher than the solubility of this gas in water. Bubble fluxes correspond to a direct transfer of CH<sub>4</sub> from the sediment to the atmosphere without significant interaction with the processes occurring within the water column. Bubble fluxes mainly occur in shallow parts of lakes and reservoirs (Keller and Stallard, 1994; Galy-Lacaux et al., 1997; Abril et al., 2005) where the hydrostatic pressure is not high enough to dissolve CH<sub>4</sub> in interstitial water. However, bubbles can also be released from the sediment in deeper parts of lakes and reservoirs, but these bubbles tend to dissolve into the water during their transport through the water column and so do not reach the atmosphere (McGinnis et al., 2006). The release of bubbles is triggered by atmospheric pressure variations (e.g., Casper et al., 2000), variations in water current velocity (Martens and Klump, 1980; Chanton et al., 1989; Scranton et al., 1993), shear stress at the sediment surface (Joyce and Jewell, 2003), variation of hydrostatic pressure associated with rapid changes of the water level above the sediment (e.g., Smith et al., 2000), increase of temperature that makes the CH<sub>4</sub> solubility decrease (Chanton and Martens, 1988) and strong wind events (Keller and Stallard, 1994). For correct extrapolation of bubble fluxes at the reservoir scale, relationships between the fluxes and the controlling factors must be established.

*Degassing below the dam:* Degassing is commonly estimated by calculating the difference between the gas concentration up- and down-stream of the dam, multiplied by the turbine discharge (Galy-Lacaux et al., 1997, 1999; Fearnside, 2002; Soumis et al., 2004; Abril et al., 2005; Kemenes et al., 2007; Roehm and Tremblay, 2006). This method may give realistic estimates with the concentration of water entering the turbines (or in the turbines whenever it is possible) and water in the downstream river. An empirical model for the efficiency of degassing depending on the water turbulence below the dam and the variation of water pressure up- and down-stream of the dam should be developed.

*The surface and the vertical profile of CH<sub>4</sub> and CO<sub>2</sub> partial pressure* are determined by the headspace method followed by gas chromatography (GC) analysis. Surface water can be sampled with a sampler that limits gas exchange (Abril et al., 2007). The sampler is gently submerged and kept for a few seconds below the water surface, with the open part facing in the direction of the water current. For vertical profiles of partial pressure, waters can be sampled with a peristaltic pump or with sampling bottles equipped with a tube (Abril et al., 2006). Water is transferred through the tube to serum glass bottles with an overflow of at least three bottle volumes. Only the water that had no contact with air is used for further analysis. After removing the tubing gently, the bottles should be immediately capped without allowing an air bubble, using a butyl rubber stopper which is secured with aluminum crimps. Duplicate bottles must be immediately poisoned with NaOH or HgCl<sub>2</sub>. In the laboratory, a headspace must be created by injecting N<sub>2</sub> through the stopper, keeping the bottle bottom-up while simultaneously expelling water in excess through a second needle. All bottles must be weighed when empty, and before and after the creation of the headspace in order to determine gravimetrically the volume of gas and water. In order to equilibrate the CH<sub>4</sub> between the water and the headspace, the bottles are given a vigorous shaking and are left to equilibrate at ambient temperature (25°C) for ~1 hour. The partial pressure in the headspace is measured (on duplicate bottles) using a GC with a flame ionization detector (GC-FID) for CH<sub>4</sub> and a thermal conductivity detector (TCD) for CO<sub>2</sub>. The concentrations must be computed with solubility coefficients as a function of temperature (Yamamoto et al. 1976 for methane and Weiss, 1976 for CO<sub>2</sub>). Collection of samples for dissolved gas analysis that maintains the samples from deeper water under pressure should be incorporated. Measurements of CO<sub>2</sub> can also be done with an infrared gas analyser.

**Aerobic methane oxidation** - In aquatic ecosystems, aerobic methane oxidation is an important process controlling methane fluxes to the atmosphere. At the Petit Saut reservoir, this microbiological process that consumes methane and oxygen reduces methane emissions by 85-90% (Guerin and Abril, 2007). Below Balbina dam, in the Uatumã River, oxidation reduces methane emission by 85 % (Kemenes et al., 2007). Part of the methane is oxidized to CO<sub>2</sub>. Potential methane oxidation rates are determined at variable concentrations for different sampling stations in the reservoir and in the river below the dam throughout the hydrological cycle. Methane and oxygen are added to water samples and the decrease of methane concentration is followed by GC-FID analysis. Aerobic methane oxidation rates can also be assayed by the uptake of <sup>14</sup>C- CH<sub>4</sub> (Rudd et al., 1974). Analyses are made on triplicates, at least.

For these incubations, 6 parameters must be considered:

- the volume of the headspace must be great enough to take several samples in the headspace without creating a depression;
- in order not to modify significantly the methanotrophic population within the sample, the increase of the CH<sub>4</sub> concentration compared to *in situ* must be lower than a factor of 4;
- the oxygen concentration in the water phase must be always higher than 80-100 mmol.L<sup>-1</sup>, a value higher than the O<sub>2</sub> half-saturation constant for aerobic CH<sub>4</sub> oxidation (Harrits and Hanson, 1980; Lidstrom and Somers, 1984; Rudd et al., 1974);
- the bottles are incubated at a temperature close to *in situ*;
- the bottles are incubated under constant agitation in order to maintain the equilibrium between the gas and the liquid phase;
- incubation is performed in the dark as methanotrophic bacteria are inhibited by light (Dumestre et al., 1999)

These experiments provide potential aerobic methane oxidation rates. *In situ* oxidation rates ( $\text{mol m}^{-3} \text{ s}^{-1}$ ) must be corrected for *in situ*  $\text{CH}_4$  and  $\text{O}_2$  concentration and for inhibition by light as described in Guerin and Abril (2007). Aerobic  $\text{CH}_4$  oxidation can be depth integrated in order to obtain areally averaged rates ( $\text{mol m}^{-2} \text{ s}^{-1}$ ).

**$\text{CO}_2$  and  $\text{CH}_4$  production** -  $\text{CO}_2$  and  $\text{CH}_4$  production during the mineralization of the flooded organic matter, particulate organic matter from the watershed and particulate organic matter produced in the reservoir is determined during incubation under anaerobic conditions. Slurries containing deionized water and organic material (1:1 w/w) are filled in serum bottles and incubated in the dark without agitation (Dannenberg et al., 1997), with a  $\text{N}_2$  headspace and at a constant temperature close to the *in situ* temperature at the bottom of the reservoir. The production rates ( $\text{mmol g C}^{-1} \text{ s}^{-1}$ ) are the slope of the linear correlation between  $\text{CO}_2$  and  $\text{CH}_4$  concentration in the headspace determined over time. Using the carbon loads of the different pools of organic matter ( $\text{g C m}^{-2}$ ), the GHG production rates are areally averaged ( $\text{mmol m}^{-2} \text{ s}^{-1}$ ).

$\text{CO}_2$  production during the mineralization of organic matter in oxic water is determined by the incubation of water under aerobic conditions and constant agitation to prevent settling of the particulate organic matter. The production rates are determined as above.

The above-water decay of the portions of trees projecting above the water can be calculated from information on the topography, water management and forest inventories of each reservoir, together with information on the vertical distribution of biomass (Fearnside, 1995, 2002). A given percentage of the trunks sinks to the bottom of the reservoir, while the remaining trunks float and are pushed by winds to the edges of the reservoir. The fate of the carbon in each of these components and the time of emission can be calculated based on existing knowledge of wood properties and decay processes.

## C. Proposed empirical model that predicts GHG emissions from freshwater reservoirs

### Residence time, mean depth and/or hydraulic load

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 [ $\text{m}^3$ ], and  $Q_I$  is the average annual inflow rate [ $\text{m}^3 \text{s}^{-1}$ ]. 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 and from annual vegetation flooded in the drawdown zone  $C^I$
3. Internal load from net primary production from macrophytes, periphyton and phytoplankton  $C^I_{NPP}$

### 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 [ $\text{g m}^{-3}$ ],  $Q_i$  is the volume of inflow  $i$  [ $\text{m}^3 \text{d}^{-1}$ ],  $A$  is the mean annual

surface area [m<sup>2</sup>] and the overbar represents an average. This gives the average daily inflow carbon flux with units of [g C m<sup>-2</sup> d<sup>-1</sup>].

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

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

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

where  $M$  represents the initial mass [g] of organic carbon,  $k$  represents the decay rate of that component [d<sup>-1</sup>] and  $t$  is the time since inundation [d].

The decay rate coefficient can be determined by following the CO<sub>2</sub> and CH<sub>4</sub> production rates and the loss of organic carbon during the mineralization of the different compartments of this pool of organic matter under anoxic conditions.

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

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

## **D. Possible mitigation measures**

Mitigation measures may aim to reduce production of methane by reducing carbon loading to the reservoir or may aim to increase methane oxidation in the water column by manipulating stratification. Design and operation of the intakes to hydroelectric turbines may offer mitigation options. It may be possible to strip methane from the hypolimnetic water above the dam or just below the dam and use it directly for power production; this would release carbon dioxide, a less intensive greenhouse gas. This technique has been proposed but not implemented. All these options require careful analysis and further study.