HYDROPOWER AND THE ENVIRONMENT:

Managing the Carbon Balance in Freshwater Reservoirs

IEA Hydro Technical Report

Guidelines for Quantitative Analysis of Net GHG Emissions from Reservoirs

Volume 1 – Measurement Programs and Data Analysis

October 2012

IEA Hydropower Agreement: Annex XII

FINLAND JAPAN NORWAY BRAZIL USA

OVERVIEW OF THE IEA IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

The IEA Hydropower Implementing Agreement (IEA Hydro) is a working group of International Energy Agency member countries and others that have a common interest in advancing hydropower worldwide. Member governments either participate themselves, or designate an organization in their country to represent them on the Executive Committee (ExCo) and on the Annexes, the task forces through which IEA Hydro's work is carried out. Some activities are collaborative ventures between the IA and other hydropower organisations.

Vision

Through the facilitation of worldwide recognition of hydropower as a well-established and socially desirable energy technology, advance the development of new hydropower and the modernisation of existing hydropower

Mission

To encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower.

To accomplish its Mission, the Executive Committee has identified the following programme-based strategy to:

- Apply an interdisciplinary approach to the research needed to encourage the public acceptance of hydropower as a feasible, socially desirable form of renewable energy.
- Increase the current wealth of knowledge on a wide array of issues currently associated with hydropower.
- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
- Bring a balanced view of hydropower to the worldwide debate on its feasibility as an environmentally desirable energy technology.
- Encourage technology development

IEA Hydro is keen to promote its work programmes and to encourage increasing involvement of non-participating countries. All OECD and non-OECD countries are eligible to join. Information about membership and research activities can be found on the IEA Hydro website www.ieahydro.org.

INTERNATIONAL ENERGY AGENCY - IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

Annex XII

Hydropower and the Environment

Task 1: Managing the Carbon Balance in Freshwater Reservoirs

Guidelines for Quantitative Analysis of Net GHG Emissions from Reservoirs

Volume 1 – Measurement Programs and Data Analysis

Member Countries: BRAZIL, JAPAN, FINLAND, NORWAY and USA

October 2012

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ABSTRACT

In the present state of the art on hydropower reservoir GHG emissions, numerous uncertainties and diverging positions preclude their consideration in energy policies, legislations and regulations. Recognizing this fact, the International Energy Agency Implementing Agreement for Hydropower Technologies and Programmes (IEA Hydro) started a new Annex on “Managing the Carbon Balance in Freshwater Reservoirs”, aiming through a comprehensive work program to increase knowledge on processes connected to man-made reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs and standardize GHG flux evaluation methods.

These guidelines provide a reference framework for performing quantitative analysis of net GHG emissions from man-made reservoirs, containing advice and recommended procedures for performing in-situ measurements, data analysis and modeling. The guidelines have been prepared in two volumes: *Volume 1- Measurement Programs and Data Analysis* (this document) and *Volume 2- Modeling*. In this volume, a definition of net GHG emissions for a man-made reservoir is given in terms of differences between post-impoundment balances of GHG emissions and removals, excluding GHG emissions from unrelated anthropogenic sources, and pre-impoundment balances of GHG emissions and removals. A general framework for estimation of net GHG emissions is described using a conceptual model based on the model developed in EPRI (2010) for the description of the system with five components: the inundation area, the reservoir, the upstream watershed, the reservoir outflow facilities and the downstream reach. General procedures for calculation of estimates of net GHG emissions from data obtained in measurement programs, as well as to evaluate their uncertainties, are provided. Advice and procedures are given for planning and executing measurement programs for obtaining estimates of post-impoundment emissions, with associated uncertainties, for existing reservoirs. For estimating pre-impoundment emissions, the advice and procedures are given for both planned and existent reservoirs. This volume also includes a list of environmental and technical descriptors of reservoirs which should be searched and included in net GHG emission quantitative analysis reports.

Keywords:
Carbon balance, Measurement, Data Analysis, Modeling, Net GHG Emissions, Multipurpose Reservoirs.

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The names of contributors and independent reviewers are listed below:

Main Contributors: Jorge Machado Damazio, Electric Energy Research Center (CEPEL), Brazil; Albert Cordeiro Geber de Melo, Electric Energy Research Center (CEPEL), Brazil; Maria Elvira Piñeiro Maceira, Electric Energy Research Center (CEPEL), Brazil; Alexandre Mollica Medeiros, Electric Energy Research Center (CEPEL), Brazil; Mauro Negrini, Electric Energy Research Center (CEPEL), Brazil; Jukka Alm, Finnish Forest Research Institute (FFRI), Finland; Tormod Andre Schei, Statkraft Corp, Norway; Yutaka Tateda, Environmental Science Research Laboratory, (CRIEPI), Japan; Brennan Smith, Oak Ridge National Laboratory, (ORNL), USA and Niels Nielsen, IEA Hydropower Implementing Agreement.

Other Contributors: Marco Aurelio dos Santos, (COPPE/UFRJ), Brazil; Donato Abe, (IIEGA), Brazil; Nelson L Dias, (UFPR), Brazil.

Reviewers: André C. P. Cimbleris, (FURNAS Centrais Eletricas S.A.), Brazil; Ben Miller, (Pacific Northwest National Laboratory), USA; Boualem Hadjerioua, Oak Ridge National Laboratory (ORNL), USA; Joel Goldefum, (IHA), Brazil; Helio S. Migon (DME/UFRJ), Brazil; Kenneth Ham (Pacific Northwest National Laboratory), USA; Masayuki Itoh (Center for Ecological Research, Kyoto University) Japan; Rao Kotamarthi (Argonne National Laboratory) USA; Marco Aurelio dos Santos, (COPPE/UFRJ), Brazil; Rita Christianne Sbrissia, (J. Malucelli Energia), Brazil; Andrew Scanlon, (Hydro Tasmania), Australia and Vinicius P. Israel (DME/UFRJ), Brazil

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Electric Energy Research Center (CEPEL), Brazil, Operating Agent for Annex XII Task 1.

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EXECUTIVE SUMMARY

The scope of the guidelines is to identify best practice to help users obtain a reference framework for performing quantitative analysis of net GHG emissions from man-made reservoirs. From this they can undertake sufficient analysis and study to understand the process of GHG emissions from an existing or planned reservoir.

The knowledge contained in these guidelines was sourced from a range of industry practice and the experience of scientists and academics and experts from hydropower industry.

In the present state of the art on hydropower reservoir GHG emissions numerous uncertainties and diverging positions preclude their consideration in energy policies, legislations and regulations. Recognizing this fact, the IEA Hydropower Implementing Agreement on Hydropower Technologies and Programmes (IEA Hydro) started a new Annex on "Managing the Carbon Balance in Freshwater Reservoirs". The objectives of the Annex, through a comprehensive work program, are to increase knowledge on processes connected to man-made reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs and standardize GHG flux evaluation methods.

These guidelines provide best practice that aims to assist the reader to measure, analyze data and model net GHG emissions from multipurpose reservoirs. Volume 1 addresses measurement programs and data analysis and Volume 2, the modeling.

1.0 INTRODUCTION

1.1 OVERVIEW

Countries and responsible jurisdictions that write and promote sustainable energy policies and develop legislation and regulations for energy projects approval and licensing are facing the major challenge of making reductions to greenhouse gases emissions (GHG) while providing increased levels of energy service. Hydropower, a well-established and socially desirable renewable energy technology is a sound alternative to meet this challenge.

Hydroelectricity enjoys several advantages over most other sources of electrical power. These include a high level of reliability, proven technology, high efficiency[1], very low operating and maintenance costs and the ability to easily adjust to load changes. Because many hydropower plants are located in conjunction with a reservoir, they can provide multi-purpose benefits that include water and irrigation, flood control, fluvial transport and recreation benefits. In addition, hydropower generation produce low amounts of waste products and does not contribute to local air quality problems and acid rain.

There can be some disadvantages to hydropower development, mainly related to environmental and social implications of damming natural watercourses and to the associated upstream artificial man-made reservoir created by the inundation of part of the river valley[2]. The possibility that the role of hydropower plants in global anthropogenic GHG emissions may not be negligible has been indicated by a number of published GHG emission measurements done in hydropower reservoirs (Rosa et al. 1994a). Some studies identified hydropower reservoirs as potential sources of GHG (Rudd et al. 1993; St Louis et al. 2000). At the end of 1990s the broad review performed by World Commission on Dams (WCD) on the development effectiveness of large dams included in its themes the role of dams to enhance the Greenhouse Effect. A report prepared for the WCD by Rosa and Santos (2000) that was included in the WCD-Final Report (2000) prompted much debate on this topic worldwide.

Substantial uncertainty remains on quantifications of CO_2-equivalent emissions from freshwater reservoirs. Internationally agreed current methodologies for estimating national inventories of anthropogenic

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[1] The 2011 IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, (IPCC, 2011) notes that hydropower is the best conversion efficiency of all known energy sources and the highest energy payback ratio. It is also mentioned that hydropower flexibility and short response time facilitate thermal plants to operate at their optimum steady state level thereby reducing their fuel consumption and pollution and that hydropower plants with reservoir are ideal to be used as back up and regulator of intermittent renewable sources (wind, solar and waves).

[2] In these guide the term reservoir is generally used to refer to man-made reservoir created by damming natural water courses. There is some hydropower projects connected to high-altitude natural lakes serving as reservoir via tunnels coming up beneath the lake. This type of project is not covered in this guideline.

emissions and removals of greenhouse gases, in the case of assessing CO_2 and CH_4 emissions from flooded lands, (IPCC, Appendices 2 and 3, 2006) include only a basis for future methodological development, reflecting the limited availability of scientific information on this topic. The report from IPCC/NGGIP Task Force São Paulo 2009 meeting (IPCC 2010) identifies that distinction of anthropogenic fluxes in reservoirs (as in wetlands) is problematic because these areas affect and are affected by neighboring land use. Furthermore, the inter-annual climate variability makes the anthropogenic emission estimation difficult. A recent review of the literature on the subject performed by the Oak Ridge National Laboratory (EPRI 2010) concluded that even though it can be claimed that data clearly indicate that measured emissions of GHG from reservoirs are not zero, whether there is a *net* emission of GHG is less certain because few studies have measured or estimated both emission and removals and assessed emissions or removals prior to reservoir construction. Recent studies reported that freshwater reservoirs may act as carbon sink (Chanudet et al. 2011; Ometto et al. 2010; Sikar et al. 2009)

The Executive Board of UNFCCC agreement for the determination of the eligibility of hydroelectric reservoirs as Clean Development Mechanism (CDM) projects, while noting the scientific uncertainties still surrounding the subject and the fact that those uncertainties will probably not be resolved shortly, uses thresholds in terms of power density (W/m^2) such that hydropower plants with power densities up to 4 W/m^2 cannot benefit from CDM projects, while the emissions from plants with power densities higher than 10 W/m^2 can be neglected. Those projects with power densities in the 4 to 10 W/m^2 interval are penalized with an emission factor of 90 g CO_2eq/ kWh (UNFCCC/CCNUCC, 2006)[3]. On the other hand, the UNFCCC CDM Executive Board highlighted that this guidance does not prevent project activities with reservoirs to submit new methodologies for consideration by the Meth Panel[4].

In the present state of the art on hydropower reservoir GHG emissions numerous uncertainties and diverging positions preclude their consideration in energy policies, legislations and regulations. Recognizing this fact, the IEA Hydropower Implementing Agreement on Hydropower Programmes and Technologies (IEA Hydro) started a new Annex on "Managing the Carbon Balance in Freshwater Reservoirs". The objectives of the Annex, through a comprehensive work program, are to increase

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[3] The 2011 IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, (IPCC 2011) notes that there is little link between installed capacity, the area of a reservoir and the various biogeochemical processes active in a reservoir. Hypothetically, two identical storage projects would, according to the power density, have the same emissions independent of climate zones or of inundated biomass and carbon fluxes. As such, the power density rule may inadvertently impede the development of socially beneficial hydropower projects, while at the same time supporting less beneficial projects.

[4] The Methodologies Panel (Meth Panel) was established to develop recommendations to the UNFCCC CDM Executive Board on guidelines for methodologies for baselines and monitoring plans and prepare recommendations on submitted proposals for new baseline and monitoring methodologies.

knowledge on processes connected to man-made reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs and standardize GHG flux evaluation methods.

These guidelines define Best Practice, as it relates to the measurements of net GHG emissions, as *the process that*:

- *provides the desired outcome for each specific activity in the most expedient manner, taking into account available resources;*
- *meets corporate drivers for technical quality, financial expenditure, safety and risk exposure and environmental and regulatory compliance; and*

'Industry Practice' is the breadth of practice encountered in the project research and 'Best Practice' is based on the combined best of the 'Industry Practice' gathered, as judged and contributed by the authors.

1.2 GUIDELINE OBJECTIVES

The primary objectives of these guidelines are to:

- Provide a reference framework for performing quantitative analysis of net GHG emissions from man-made reservoirs. Net GHG emissions are defined as *"differences between post-impoundment balances of GHG emissions and removals, excluding GHG emissions from unrelated anthropogenic sources, and pre-impoundment balances of GHG emissions and removals"*.
- Develop measurement procedures and protocols for GHG emissions from hydropower reservoirs.
- Improve the scientific basis on the processes associated with hydropower reservoir GHG emissions, as input government energy policies, legislation and regulations.

The advice and procedures contained in these guidelines were developed as a research tool with the specific goal of achieving a better understanding of net GHG emissions at hydropower plants in a global scale. This will be achieved through the application of this guideline for a set of hydropower reservoirs spread in boreal, tropical, semi-arid and temperate climate zones under the activities of the work program of IEA Hydropower Implementing Agreement Annex XII. It should be clear that these guidelines are not directed for routine assessment and monitoring in existing and future reservoirs.

1.3 SCOPE OF WORK

The guidelines have been prepared in two volumes.

Volume 1 – Measurement Programs and Data Analysis, contains advices and recommended procedures for performing measurement campaigns and data analysis to obtain estimates and associated uncertainties of net GHG emissions from man-made reservoirs correspondent to the period of the measurement program.

Volume 2 – Modeling, presents advices and recommended procedures for formulating, calibrating, validating and using models to obtain estimates of net GHG emissions from man-made reservoirs correspondent to long-term horizons.

A number of activities were undertaken as part of the preparation of Volume 1, to achieve the Project Objectives (Section 1.2). These are described below.

1. *Undertake a Literature Review of previous work on the topic*
2. *Review the work of institutions in Brazil, Norway, Finland, Japan, USA, Canada, Australia and France, as well as organizations, such as the IPCC and the IHA as it relates to this subject matter*
3. *Identify and communicate with sources that cover the range of industry practice and the experience of scientists and academics.*
4. *Gather the collected knowledge of the authors and other contributors*
5. *Peer review from an independent group of experts*

1.4 FORMAT OF REPORT AND BEST PRACTICE GUIDE

The framework for identifying best practice for performing measurement campaigns and data analysis to obtain estimates and associated uncertainties of net GHG emissions from multipurpose reservoirs is set out in this volume.

The format is:

Chapter 1: Introduction and Overview - explains the needs, concepts, objectives and scope of this volume. The user will gain an understanding of what the volume contains, whether it will be applicable to the user's needs, and how to use it.

Chapter 2: Quantitative Analysis of Net GHG Emissions for Reservoirs – covers the description of the adopted framework for estimation of net GHG emissions and general rules for calculation of estimates of net GHG emissions, as well as to evaluate their uncertainties. This chapter also includes a list of environmental and technical descriptors of reservoirs which should be searched and included in net GHG emission quantitative analysis reports.

Chapter 3: Pre-Impoundment Analysis – covers advices and procedures for planning and executing measurement programs and for performing literature search for obtaining estimates, with associated uncertainties, of pre-impoundment balances of GHG emissions and removals for existent and planned reservoirs.

Chapter 4: Post-Impoundment Analysis – covers advices and procedures for planning and executing measurement programs for obtaining estimates, with associated uncertainties, of post-impoundment balances of GHG emissions and removals, excluding GHG emissions from unrelated anthropogenic sources, for existent reservoirs.

Appendices - includes a description of the present knowledge on how bigeochemical process governs GHG fluxes and permanent carbon burial rates in surface areas, and details of measurement techniques.

1.5 USING THE GUIDELINE VOLUME

This guideline volume contains generic guidance to assist the reader to efficiently and effectively identify best practice for performing measurement campaigns and data analysis to obtain estimates and associated uncertainties of net GHG emissions from multipurpose reservoirs. It is not prescriptive document and specific site conditions should be factored into the decision making process and project set-up. The user should, therefore, consider the relevance of each section to their particular circumstance and how the guidance applies to their project.

2.0 Quantitative Analysis of Net GHG Emissions for Reservoirs

2.1 Introduction

Construction and operation of any reservoir creates an inundated area and introduces at the area a different regime of mass transport and storage from that prevailing before the impoundment. In particular, when carrying on a quantitative analysis of net GHG emissions for a reservoir, there are two kinds of differences between the pre- and post- impoundment regimes: the difference in GHG fluxes[5] between surface and atmosphere and the difference in the permanent carbon burial rate. For the GHG fluxes, the analysis concentrates on CO_2, CH_4 and N_2O. Thus, the main concern is on processes affecting carbon and nitrogen transport and storage.

Basic biogeochemical processes of concern in carbon balances are the net exchange of CO_2 in photosynthesis and respiration of autotrophic organism like plants and cyanobacteria, and decomposition of dead organic matter by heterotrophic organisms such as animals, fungi, bacteria and archae releasing CO_2 and CH_4. In this sense, phosphorus is also an important element to be gauged, as it may affect primary production and the efficiency of organic matter decomposition. For nitrogen balance the biological processes are biofixation, ammonification, nitrification, and de-nitrification, and the last two can result in a release of N_2O. Physical processes of concern are chemical species advection, turbulent diffusion and gas bubbling; geochemical processes of concern are organic matter chemical decay and combustion. Appendix A provides a description of the present knowledge on how the occurrence of these processes governs CO_2, CH_4 and N_2O emissions and carbon burial rates regimes in different landscapes.

2.2 Conceptual Model

Context

In the general framework adopted in this guideline for quantitative analysis of *net GHG emissions* from reservoirs, the balances of GHG emissions and removals corresponding to the pre-impoundment regime are called *pre-impoundment GHG emissions* and the balances of GHG emissions and removals corresponding to the post-impoundment regime are called *post-impoundment GHG emissions*. In post-impoundment balances, GHG emissions that can be attributed to anthropogenic sources unrelated with the reservoir should be excluded. Finally, *net GHG emissions* are the differences between *post-impoundment* and *pre-*

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[5] A flux is defined as the time rate of mass transfer across a surface. The flux rate is denoted with a positive sign if the mass transfer occurs out of the mass store of interest, e.g. from a reservoir to the atmosphere. Specifically the positive flux is called an emission. In the context of atmospheric change, the term emission is used in situations when the atmospheric mixing ratio (or concentration) for a certain greenhouse gas species increases due to gas release from e.g. land use. Conversely, uptakes from the atmosphere are called removals. If the resulting balance of emissions and removals in space and time for a surface area is positive, the area is called a source, if it is negative; the area is called a sink. Areas can be meaningful sinks or sources for the atmospheric gases only if the resulting balance of emissions and removals persist over more than one annual cycle.

impoundment GHG emissions. Estimates of *pre-impoundment GHG emissions*, *post-impoundment GHG emissions* and of *net GHG emissions* for a certain reservoir are obtained by a conceptual model which follows the model presented in EPRI (2010). In this model the studied system is described with five components:

- the inundation area,
- the reservoir,
- the upstream watershed,
- the reservoir facilities which convey water downstream, and
- the downstream reach where the water is released.

Best Practice Guideline

A. The conceptual model should be used as the basis for the quantitative analysis of net GHG emissions from reservoirs

B. The studied system should be sub-divided into five components; inundation area, reservoir, upstream watershed, dam discharge works, and downstream reaches

Commentary

A. The conceptual model should be used as the basis for the quantitative analysis of net GHG emissions from reservoirs

The assessment model for reservoir GHG emissions take into account all the GHG flux pathways resulting from reservoir operations[6] focusing on diffusion and bubble emissions of GHG from the surface of reservoirs and, in addition to these surface pathways, the possible GHG emissions that result from passage of water through low level outlets. GHG emissions also may be changed (enhanced or reduced) in the river downstream of dams (tailwater) for some considerable distance, enhanced as a result of discharge of GHG-laden deep waters or reduced due to sediments trapped in the reservoir.

Three pathways of GHG emissions should be accounted for in assessments of reservoir GHG status: (1) emissions from the reservoir surface (diffusion and via bubbles), (2) emissions at dams as water passes through spillways and turbines, and (3) emission in the tailwater downstream of dams for some distance until GHG fluxes return to ambient river values in the absence of the dam.

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[6] This guideline doesn't take into account the GHG emissions related to the construction phase

The conceptual models for assessment of net GHG emissions from man-made reservoirs covers flux of GHG in ecosystems both prior to reservoir construction and during reservoir operation. The model for net GHG emissions, forms the basis of Figures 1 to 3 in Item 2.3

B. The studied system should be sub-divided into five components; inundation area, reservoir, upstream watershed, dam discharge works, and downstream reaches

Inundation area

In the pre-impoundment period, reflecting local environmental conditions, different compartments of the inundation area present different regimes of GHG fluxes between surface and atmosphere and of permanent carbon burial rates. For the purpose of analyzing net GHG emissions, the inundation area can be schematically divided in three compartments: water bodies, floodplain, and upland. The water bodies compartment includes all those portions of the inundation area which are flooded throughout the year, as river reaches, streams and lakes. The floodplain compartment corresponds to the inundation area where the soil is either flooded or saturated only during high flow periods, and the upland compartment covers the balance of the inundation area. It may prove convenient to further subdivide any of the above three compartments in order to better represent its heterogeneity in the inundation area. For example, when a substantial portion of the water bodies comprises lakes, the compartment should be subdivided in rivers/streams and lakes sub compartments.

In the pre-impoundment period, regimes of transformations, transport and storage of carbon- and nitrogen-containing compounds are established at each of the compartments. At the upland compartment, the biomass of vegetation and surface soil/peat layer cover may make it a sink area of CO_2. The floodplain may be a significant source of CH_4 where permanent carbon burial may occur at a significant rate. In the water bodies compartment, the river reaches and streams transport water and sediments collected by the drainage network in the upstream watershed. This is combined, in the downstream reaches, to the water and sediments collected by the drainage network in the floodplain and from the upper land compartments of the inundation area. Moreover, within the stream flow, GHG emissions are constantly produced as a result of the microbial community activity. In general, the water bodies compartment is conceived to act in the pre-impoundment period as a source area for CO_2, CH_4 and N_2O, whereas at the lakes sub-compartment substantial permanent carbon burial rate can be present.

All GHG fluxes between surface and atmosphere and permanent carbon burial rates at the inundation area compartments should be estimated in order to calculate estimates of pre-impoundment balance of emissions and removals. Chapter 3 provides guidance on recommended methods[7] for their estimation for any specific reservoir.

After the reservoir filling, the inundation area environment is replaced by the reservoir, where new regimes of transformations, transport and storage for carbon- and nitrogen- compounds are established. The new established regimes are influenced by flooded biomass and organic matter stored at the inundation area at the time of the reservoir filling and for several years thereafter. The measurements of flooded biomass and organic matter are important for the understanding, model calibration and prediction of the post-impoundment GHG fluxes between surface and atmosphere and permanent carbon burial rates regime. Volume 2 provides guidance on recommended methods for estimation of flooded biomass and organic matter.

Reservoir

In the post-impoundment period, reservoir filling introduces a new regime for the GHG fluxes between surface and atmosphere and permanent carbon burial rates at the inundation area. Pathways for GHG fluxes across the reservoir air-water interface to be considered are diffusive and ebullitive fluxes. Ebullitive fluxes (mainly CH_4) occur mostly at shallow zones of the reservoir. A new regime of permanent carbon burial rate is established at the reservoir sedimentation zone. For the purpose of analyzing GHG emissions, the reservoir can be schematically divided in compartments reflecting different hydrodynamics characteristics and thus, the relative impact on water quality. For example, for analyzing diffusive fluxes it is common to take into account a stratification of the reservoir surface with four strata: upstream, mid, coves and forebay.

GHG emissions through all reservoir air-water interface pathways and reservoir permanent carbon burial rates should be estimated in order to calculate post-impoundment balances of GHG emissions and removals. Chapter 4 provides guidance on recommended methods for their estimation for any specific reservoir.

Upstream watershed

Carbon- and nitrogen- containing compounds that are collected by the upstream watershed drainage network are conveyed through the river system to the reservoir, where microbial activity eventually

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[7] For recommended methods we consider methods that aim to ensure that estimates are systematically neither over- nor underestimates so far as can be judged, and that uncertainties are reduced toward a target level so far as possible.

converts them to GHG. The measurements of these influxes are important for the understanding, model calibration and prediction of the post-impoundment regime of GHG fluxes between surface and atmosphere. Volume 2 provides guidance on recommended methods for obtaining estimates of inputs to the reservoir of carbon- and nitrogen- containing compounds from upstream watershed.

Outflow structures

The GHG emissions from water discharged downstream through outflows structures due to abrupt changes in the hydrostatic pressure ("degassing") is a path for GHG emissions introduced by the reservoir and should be considered when estimating post-impoundment balances of GHG emissions and removals. Chapter 4 provides guidance on recommended methods for the estimation of degassing GHG fluxes for any specific reservoir.

Downstream Reach

The GHG fluxes between surface and atmosphere regime in the downstream reach of the watercourse can be altered through reservoir operation practices that can in turn modify concentrations of dissolved gases in the downstream water releases. These fluxes should be considered for calculations of pre-impoundment and post-impoundment balances of GHG emissions and removals. Guidance on recommended methods for the estimation of downstream reach GHG fluxes between surface and atmosphere for any specific reservoir for the pre-impoundment period are provided at Chapter 3, and for the post-impoundment period in Chapter 4.

Moreover, measurements of the amounts of carbon- and nitrogen- compounds leaving the reservoir water body through the river system are important for the understanding, model calibration and prediction of the post-impoundment GHG fluxes between surface and atmosphere regime. Guidance on recommended methods for estimation of outputs from the reservoir of carbon- and nitrogen- containing compounds for any specific reservoir for the post-impoundment period are provided in Volume 2.

2.3 General Procedure for Quantification of Net GHG Emissions

Context

The general procedures for the quantification of net GHG emissions can be separated into three components, as follows:

- Time Horizon, Measurement Campaigns and Modeling
- General Rules for Calculation of Estimates
- General Rules for Evaluation of Uncertainties

Best Practice Guideline

A. Estimates of net GHG emissions for reservoirs should be obtained for specified time horizons, depending on the objectives of the study

B. Calculation of estimates of net GHG emissions for reservoirs should be based on a set of rules

C. Estimates of emissions should be reported as central values together with 95% confidence intervals

D. Practical quantification of net GHG emissions of a reservoir should take into consideration Decision Trees 1, 2 and 3

Commentary

A. Estimates of net GHG emissions for reservoirs should be obtained for specified time horizons

Time horizon, Measurement Campaigns and Modeling

In studies with the objective of gathering information for scientific knowledge improvement, short time horizons can provide valuable information, although a minimum of one year is necessary to observe seasonal effects (intra-annual variability). Multi-year climate fluctuations and flooded biomass decomposition process can be appraised by considering multi-year horizons. For these short time horizons studies, with temporal and spatial distributions carefully planned, well-conducted measurement campaigns at the reservoir site provide valuable data, which can be used, together with simple modeling assumptions for time and space interpolation, to estimate pre-impoundment or post-impoundment GHG fluxes between surface and atmosphere and permanent carbon burial rates which occurred during the field campaign time period, as described in this guideline. If the objective is to provide information for a life-cycle analysis (LCA) of the plant, the chosen time horizon should be as great as 100 years (ISO 2006; Guinée, J. 2002), and should be considered as starting on the date of impoundment. In these studies, estimates of future reservoir GHG fluxes between surface and atmosphere and permanent carbon burial rates (and past, for existent reservoirs) can be obtained by the application of models with parameters and constants obtained from specific measurements, literature searches or by calibration with estimates of short periods emissions obtained from measurement campaigns at reservoir sites. Estimates obtained with these models are usually called *predictions*. Recommendations for formulating, calibrating and using these models are given in Volume 2 of this guideline.

B. Calculation of estimates of net GHG emissions for reservoirs should be based on a set of rules

General Rules for Calculation of Estimates

- Calculations are done separately for each gas and for pre- and post- impoundment conditions.

- Estimates of permanent carbon burial rates are considered together with estimates of CO_2 fluxes[8].
- The balance of estimates of all fluxes between surface and atmosphere of a specific gas for the pre-impoundment condition provides the estimate of the *pre-impoundment emissions* for that gas.
- The balance of estimates of all fluxes between surface and atmosphere of a specific gas for the post-impoundment condition provides the estimate of the *post-impoundment emissions* for that gas.
- Estimates of emissions of a specific gas that can be attributed to anthropogenic sources unrelated with the reservoir should be taken out in the balance of fluxes for the estimate of post-impoundment emissions for that gas.
- Estimates of *net emissions* are calculated by differences between estimates of *post-impoundment emissions* and *pre-impoundment* emissions.

Figure 1 illustrates the application of the rules for calculation of *net emissions* respectively for CO_2, with the conceptual model described in Item 2.2. The upper part represents the estimate of the CO_2 *pre-impoundment emissions* (CPRE), given by:

$$\mathrm{CPRE} = \mathrm{C1} + \mathrm{C2} + \mathrm{C3} + \mathrm{C4} + \mathrm{C5} - (44/12)(\mathrm{C6} + \mathrm{C7}) \qquad (1)$$

where,

C1 is the balance of estimates of CO_2 emissions and removals at the upland compartment
C2 is the balance of estimates of CO_2 emissions and removals at the flood plain compartment
C3 is the balance of estimates of CO_2 emissions and removals at the lake sub compartment
C4 is the balance of estimates of CO_2 emission and removals at the river sub compartment
C5 is the balance of estimates of CO_2 emissions and removals at the downstream reach.
C6 is the estimate of permanent carbon burial at the flood plain
C7 is the estimate of permanent carbon burial at the lake

The middle part of Figure 1 represents the estimates of the CO_2 *post-impoundment emissions* (CPOSTBE) before taken out emissions attributed to unrelated anthropogenic sources given by:

$$\mathrm{CPOSTBE} = \mathrm{C8} + \mathrm{C9} + \mathrm{C10} - (44/12)\mathrm{C11} \qquad (2)$$

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[8] In pre-impoundment regime, all buried carbon in lake and flood plain sediments at the inundation area can be conceived as originated from CO_2 removals from the atmosphere and we may take the carbon burial rate as an abatement parcel in the balance of CO2 exchange fluxes between the inundation area and the atmosphere. In post-impoundment regime, the reservoir increases the carbon burial rate, interfering with carbon destination. Although other criterion can be suggested, we opted to suggest the same criterion used in the pre-impoundment regime.

where,

C8 is the balance of estimates of CO_2 emissions and removals at the air-water interface in the reservoir
C9 is the estimates of CO_2 degassing emissions
C10 is the balance of estimates of CO_2 emissions and removals at the downstream reach
C11 is the estimate of permanent carbon burial at the reservoir sedimentation zone

The lower part of Figure 1 represents the estimates of the CO_2 emissions attributed to anthropogenic sources unrelated with the reservoir (CUAS), given by:

$$\mathrm{CUAS} = \mathrm{C12} + \mathrm{C13} + \mathrm{C14} \tag{3}$$

where,

C12 is the estimate of CO_2 emissions attributed to unrelated anthropogenic sources (UAS) at air-water interface in the reservoir
C13 is the estimate of degassing CO_2 emissions attributed to unrelated anthropogenic sources (UAS)
C14 is the estimate of CO_2 emissions attributed to unrelated anthropogenic sources (UAS) at the downstream reach

Note that in all the balances of fluxes, emissions should be expressed by positive values and removals by negative values.

The estimate of the *CO_2 post-impoundment emissions* is given by

$$\mathrm{CPOST} = \mathrm{CPOSTBE} - \mathrm{CUAS} \tag{4}$$

or

$$\mathrm{CPOST} = [\mathrm{C8} + \mathrm{C9} + \mathrm{C10} - (44/12)\mathrm{C11}] - [\mathrm{C12} + \mathrm{C13} + \mathrm{C14}] \tag{5}$$

The estimate of the *net CO_2 emission* is given by:

$$\mathrm{CNET} = \mathrm{CPOST} - \mathrm{CPRE} \tag{6}$$

or,

$$\mathrm{CNET} = C8 + C9 + C10 - (44/12)C11 - C12 - C13 - C14 - C1 - C2 - C3 - C4 - C5 + (44/12)(C6 + C7) \tag{9}$$

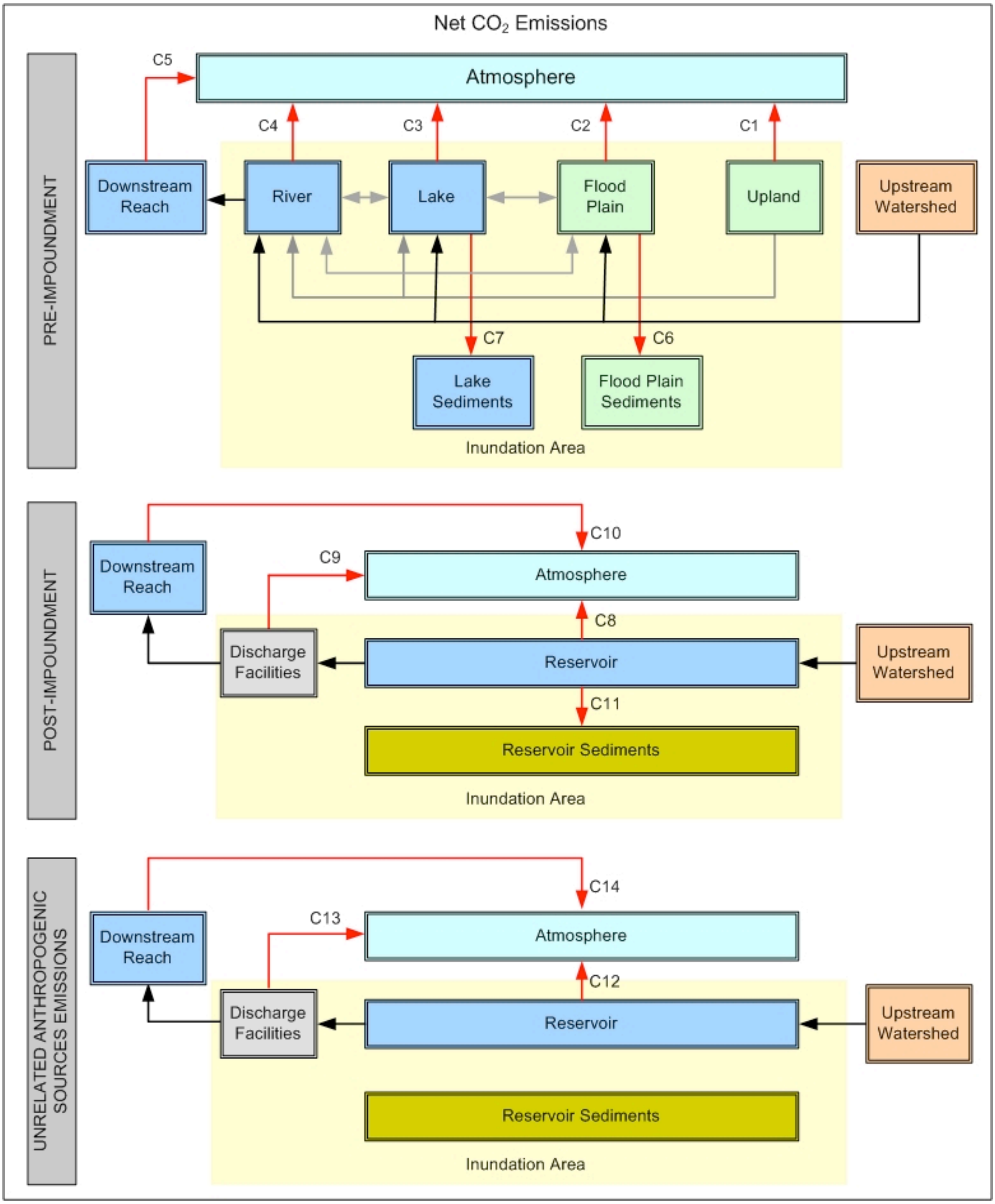

Figure 1: Application of the rules for net CO_2 emission estimation

Figure 2 illustrates the application of the rules for calculation of *net emissions* for CH_4. The upper part represents the estimate of the *CH_4 pre-impoundment emissions* (MPRE), given by:

$$\mathrm{MPRE} = \mathrm{M1} + \mathrm{M2} + \mathrm{M3} + \mathrm{M4} + \mathrm{M5} \qquad (10)$$

where,

M1 is the balance of estimates of CH_4 emissions and removals at the upland compartment
M2 is the balance of estimates of CH_4 emissions and removals at the flood plain compartment
M3 is the balance of estimates of CH_4 emissions and removals at the lake sub compartment
M4 is the balance of estimates of CH_4 emission and removals at the river sub compartment
M5 is the balance of estimates of CH_4 emissions and removals at the downstream reach.

The middle part of Figure 2 represents the estimates of the CH_4 *post-impoundment emissions* (MPOSTBE) before taken out emissions attributed to unrelated anthropogenic sources given by:

$$\mathrm{MPOSTBE} = \mathrm{M6} + \mathrm{M7} + \mathrm{M8} \qquad (11)$$

where,

M6 is the balance of estimates of CH_4 emissions and removals at the air-water interface in the reservoir
M7 is the estimates of CH_4 degassing emissions
M8 is the balance of estimates of CH_4 emissions and removals at the downstream reach

The lower part of Figure 2 represents the estimates of the CH_4 emissions attributed to anthropogenic sources unrelated with the reservoir (CUAS), given by:

$$\mathrm{MUAS} = \mathrm{M9} + \mathrm{M10} + \mathrm{M11} \qquad (12)$$

where,

M9 is the estimate of CH_4 emissions attributed to unrelated anthropogenic sources (UAS) at air-water interface in the reservoir
M10 is the estimate of degassing CH_4 emissions attributed to unrelated anthropogenic sources (UAS)
M11 is the estimate of CH_4 emissions attributed to unrelated anthropogenic sources (MUAS) at the downstream reach

The estimate of the *CH_4 post-impoundment emissions* is given by

$$\mathrm{MPOST} = \mathrm{MPOSTBE} - \mathrm{MUAS} \tag{13}$$

or

$$\mathrm{MPOST} = [\mathrm{M6} + \mathrm{M7} + \mathrm{M8}\,] - [\mathrm{M9} + \mathrm{M10} + \mathrm{M11}] \tag{14}$$

The estimate of the *net CH_4 emission* is given by:

$$\mathrm{MNET} = \mathrm{MPOST} - \mathrm{MPRE} \tag{15}$$

or,

$$\mathrm{MNET} = \mathrm{M6} + \mathrm{M7} + \mathrm{M8} - \mathrm{M9} - \mathrm{M10} - \mathrm{M11} - \mathrm{M1} - \mathrm{M2} - \mathrm{M3} - \mathrm{M4} - \mathrm{M5} \tag{16}$$

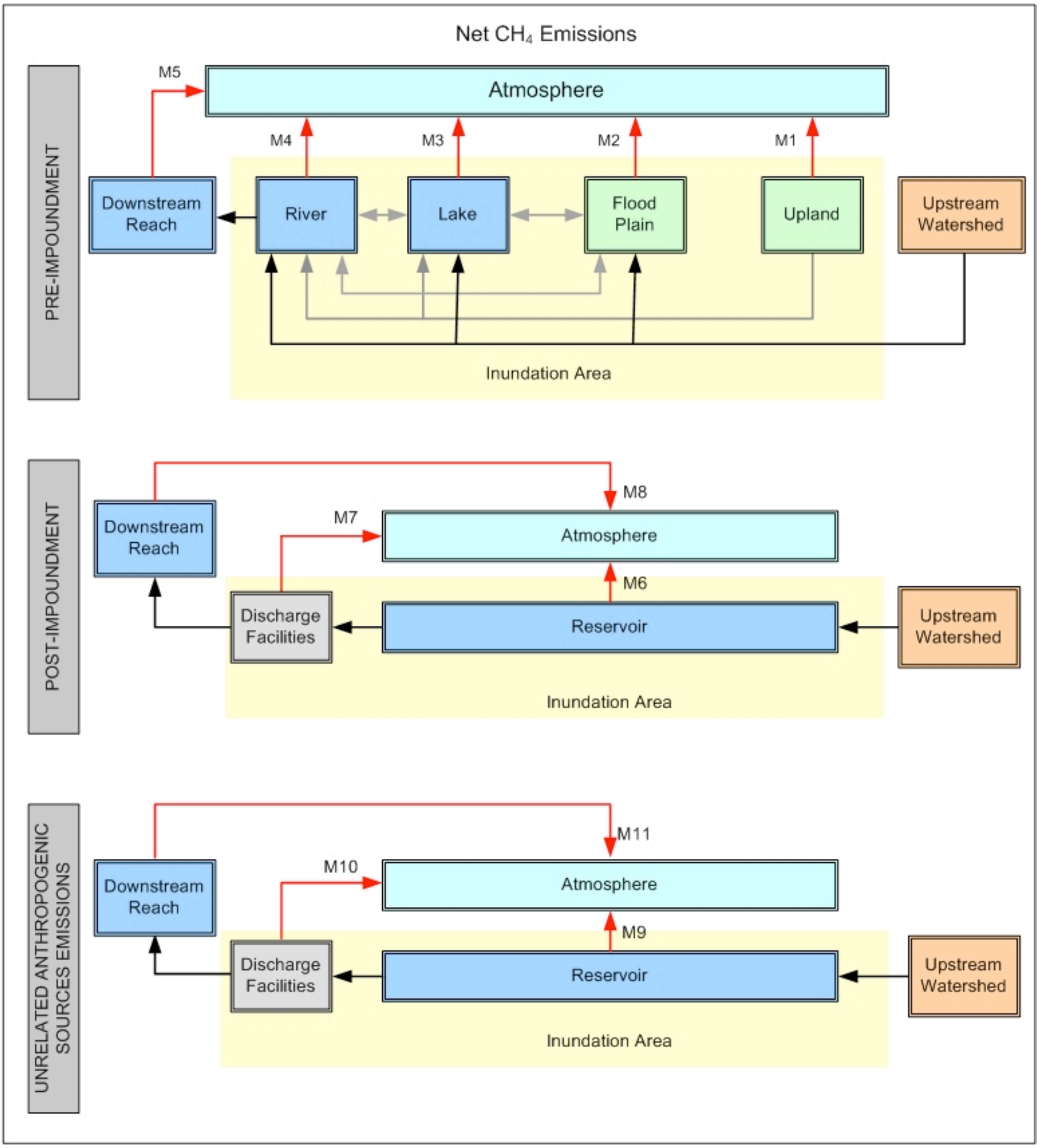

Figure 2: Application of the rules for net CH_4 emission estimation

Figure 3 illustrates the application of the rules for calculation of *net emissions* for N_2O. The upper part represents the estimate of the N_2O *pre-impoundment emissions* (NPRE), given by:

$$NPRE = N1 + N2 + N3 + N4 + N5 \quad (17)$$

where,

N1 is the balance of estimates of N_2O emissions and removals at the upland compartment
N2 is the balance of estimates of N_2O emissions and removals at the flood plain compartment
N3 is the balance of estimates of N_2O emissions and removals at the lake sub compartment
N4 is the balance of estimates of N_2O emission and removals at the river sub compartment
N5 is the balance of estimates of N_2O emissions and removals at the downstream reach.

The middle part of Figure 3 represents the estimates of the N_2O *post-impoundment emissions* (NPOSTBE) before taken out emissions attributed to unrelated anthropogenic sources given by:

$$\mathrm{NPOSTBE} = \mathrm{N6} + \mathrm{N7} + \mathrm{N8} \tag{18}$$

where,

N6 is the balance of estimates of N_2O emissions and removals at the air-water interface in the reservoir
N7 is the estimates of N_2O degassing emissions
N8 is the balance of estimates of N_2O emissions and removals at the downstream reach

The lower part of Figure 3 represents the estimates of the N_2O emissions attributed to anthropogenic sources unrelated with the reservoir (NUAS), given by:

$$\mathrm{NUAS} = \mathrm{N9} + \mathrm{N10} + \mathrm{N11} \tag{19}$$

where,

N9 is the estimate of N_2O emissions attributed to unrelated anthropogenic sources (UAS) at air-water interface in the reservoir
N10 is the estimate of degassing N_2O emissions attributed to unrelated anthropogenic sources (UAS)
N11 is the estimate of N_2O emissions attributed to unrelated anthropogenic sources (UAS) at the downstream reach

The estimate of the N_2O *post-impoundment emissions* is given by

$$\mathrm{NPOST} = \mathrm{NPOSTBE} - \mathrm{NUAS} \tag{20}$$

or

$$\mathrm{NPOST} = [\mathrm{N6} + \mathrm{N7} + \mathrm{N8}] - [\mathrm{N9} + \mathrm{N10} + \mathrm{N11}] \tag{21}$$

The estimate of the *net* N_2O *emission* is given by:

$$\mathrm{NNET} = \mathrm{NPOST} - \mathrm{NPRE} \tag{22}$$

or,

$$\mathrm{NNET} = \mathrm{N6} + \mathrm{N7} + \mathrm{N8} - \mathrm{N9} - \mathrm{N10} - \mathrm{N11} - \mathrm{N1} - \mathrm{N2} - \mathrm{N3} - \mathrm{N4} - \mathrm{N5} \tag{23}$$

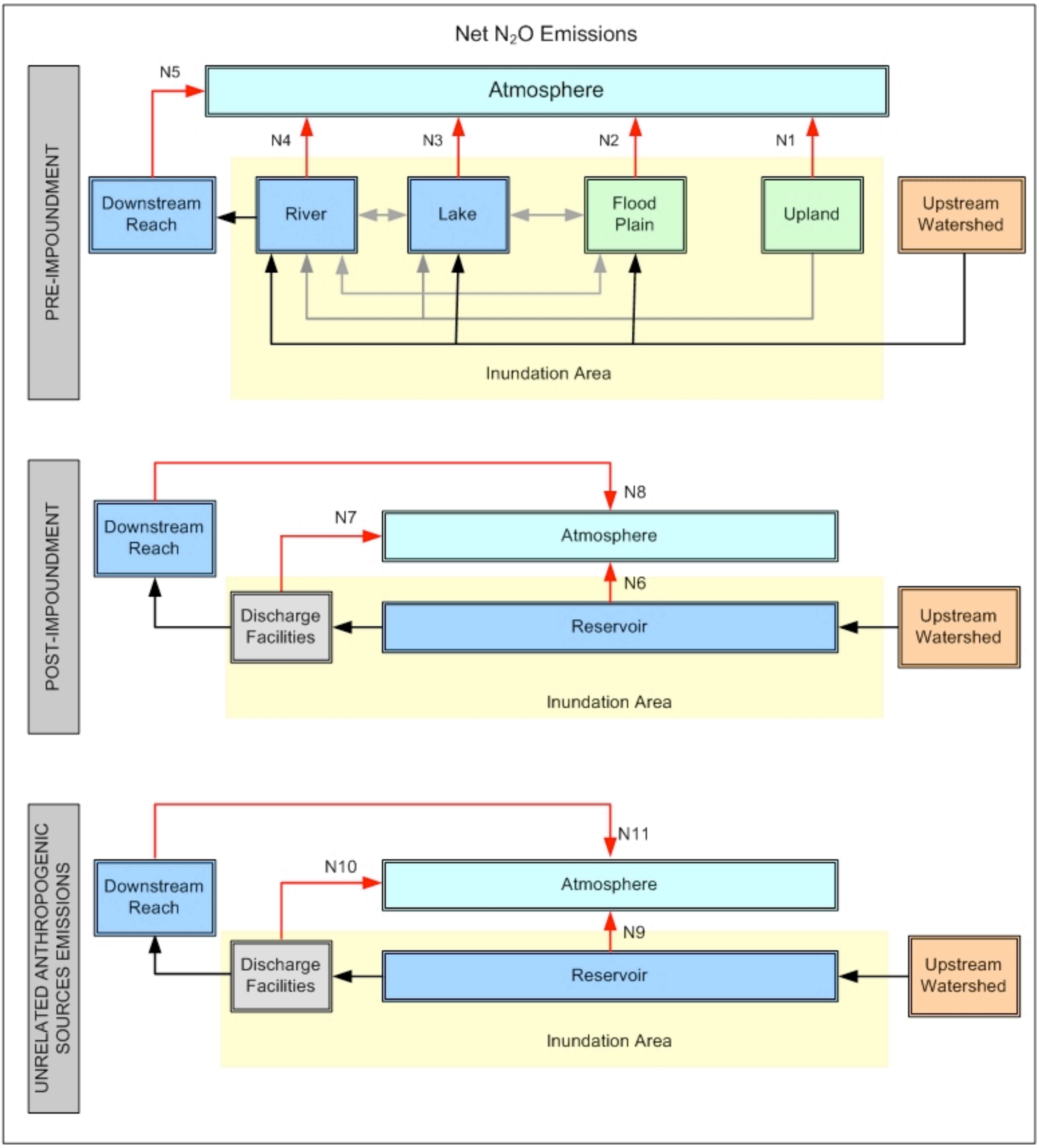

Figure 3: Application of the rules for net N_2O emission estimation

Estimates of CO_2 equivalence net emissions

The estimates of *net emissions* of each gas are usually combined using the CO_2 reference, yielding an estimated of CO_2eq *net emissions.* The combination is done by summing the estimates of *net emissions* of each gas multiplied by coefficients:

$$\mathrm{CO2eqNET} = \mathrm{CNET} + \lambda_M \cdot \mathrm{MNET} + \lambda_N \cdot \mathrm{NNET} \tag{24}$$

The values of the □ ´s coefficients in (24) should reflect the relativeness of the contributions over time of CH_4 and N_2O emissions to climate changes when compared with CO_2 emissions contributions. One option is the use of Global Warming Potentials (GWP), the index adopted for use in the Kyoto Protocol, which is calculated on time-integration over a time horizon of the global mean radiative forcing[9] of a pulse emission of 1 kg of the gas relative to that of 1 kg of CO_2 (IPCC, 1994). Another option is the Global Temperature Potential (GTP) metric which focus on global mean temperature changes at the end of the chosen time horizon. As stated in IPCC, 2007, "…C*ompared to the GWP, the GTP gives equivalent climate response at a chosen time, while putting much less emphasis on near-term climate fluctuations caused by emissions of short-lived species (e.g., CH4)*…".

C. Estimates of emissions should be reported as central values together with 95% confidence intervals

General Rules for Considering Uncertainties

The recommended approach is to model estimation errors (differences between estimates and "true values") as random variables with zero mean (free of systematic errors) and finite variances, and adopt standard procedures for reporting uncertainties in measurements (JCGM 2008). In this approach, the uncertainties in estimates are evaluated in terms of two numeric values:

a) the standard uncertainty, a numeric characterization of the dispersion of possible estimates around the true value, defined as:

$$u(\hat{x}) = \sqrt{\int_{-\infty}^{\infty} (v - x)^2 f_{(\hat{x}-x)}(v - x)\,dv} \tag{25}$$

---

[9] Radiative forcing is the defined as 'the change in net (down minus up) irradiance (solar plus longwave; in W m^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values' (IPCC, 2007).

where

$\hat{x}$ is the estimate of the “true value” x,

$u(\hat{x})$ is the standard uncertainty of the estimate

$f_{(\hat{x}-x)}(.)$ is the probability density function for the estimation errors,

b) the degrees of freedom, a numeric characterization of the uncertainty in the estimation of the standard uncertainty, given by half of the square of the inverse of the standard proportional uncertainty in the standard uncertainty[10] :

$$\upsilon_{\hat{x}} = \frac{1}{2}\left(\frac{u(u(\hat{x}))}{u(\hat{x})}\right)^{-2} \tag{26}$$

Approximated symmetric 95% intervals[11] around the estimate are built using:

$$\hat{x} \pm t_{97.5\%,\upsilon_{\hat{x}}}\, u(\hat{x}) \tag{27}$$

where

$t_{97.5\%,\upsilon_{\hat{x}}}$ is the 97.5% quantile of the Student´s t distribution with $\upsilon_{\hat{x}}$ degrees of freedom.

The interval in (27) should be interpreted as having 95% of probability of containing the “true value” x :

$$P\left[\hat{x} - t_{97.5\%,\upsilon_{\hat{x}}} u(\hat{x}) \le x \le \hat{x} - t_{97.5\%,\upsilon_{\hat{x}}} u(\hat{x})\right] = 95\%$$

Propagation of uncertainties can be done by considering only first-order derivatives (JCGM, 2008). As an example, 95% intervals for net N_2O emissions, consistent with equation (22), are calculated by combining standard uncertainties and degrees of freedom of uncorrelated pre-impoundment and post-impoundment N_2O emission estimates (F. E. Satterthwaite, 1946 and B. L. Welch, 1947) by:

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[10] A justification for the use of this definition and equation (26) can be found in appendix G of JCGM (2008) and in Kirkup L. and Frenkel, R.B. (2006) pages 160 to 161

[11] Details of the limits of this approximation can be found in DeGroot and Schervish (2002) and Migon and Gameraman (1999)

$$u(\mathrm{NNET}) = \sqrt{u^2(\mathrm{NPOST}) + u^2(\mathrm{NPRE})} \tag{28}$$

$$\upsilon_{\mathrm{NNET}} = \frac{u^4(\mathrm{NNET})}{\dfrac{u^4(\mathrm{NPOST})}{\upsilon_{\mathrm{NPOST}}} + \dfrac{u^4(\mathrm{NPRE})}{\upsilon_{\mathrm{NPRE}}}} \tag{29}$$

The 95% interval for NNET is then calculated as:

$$\mathrm{NNET} \pm t_{97.5\%,\upsilon_{\mathrm{CO2NET}}}\, u(\mathrm{NNET}) \tag{30}$$

D. Practical quantification of net GHG emissions of a reservoir should take into consideration Decision Trees 1, 2 and 3

For quantification of net GHG emissions of a reservoir it should be considered the Decision Trees 1, 2 and 3, shown respectively in Figures 4, 5 and 6[12].

Decision Tree 1 (Fig. 4) corresponds to the general procedures for evaluation of the variables needed to quantify net GHG emissions considering the differences between pre and post impoundment conditions. This decision tree intends to help by showing a rational workflow in information collection, and pointing out decisions to be made in certain key conditions. It contains a link to further evaluation if unrelated anthropogenic sources may contribute to the net GHG emissions from the reservoir (Decision Tree 2, Fig. 5 and Decision Tree 3, Fig. 6). Basically summarizes the net GHG estimation procedure of this Guideline. It also helps to identify if there is a risk for GHG emissions due to unrelated anthropogenic sources (UAS).

Decision tree 2 (Fig. 5) helps to identify the conditions when UAS related GHG emissions may increase emissions in the post-impoundment period.

Decision tree 3 (Fig. 6) further shows the situations when it may be relevant to estimate UAS related GHG emissions and those situations when there are no significant UAS related GHG emissions and

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[12] The approaches suggested by this set of decision trees may be a part of an advanced level assessment of GHG emissions from reservoirs, corresponding to IPCC Tier 3 of 2006 Guidelines, where countries possess or collect new data, and may use sophisticated models. The trees can also aid in focusing the research by identifying the conditions that are critical for selecting an extensive or more restricted monitoring program.

therefore is no practical interest in their estimation. In any case, a scientifically transparent method for evaluation of the UAS related emission components is needed in all cases.

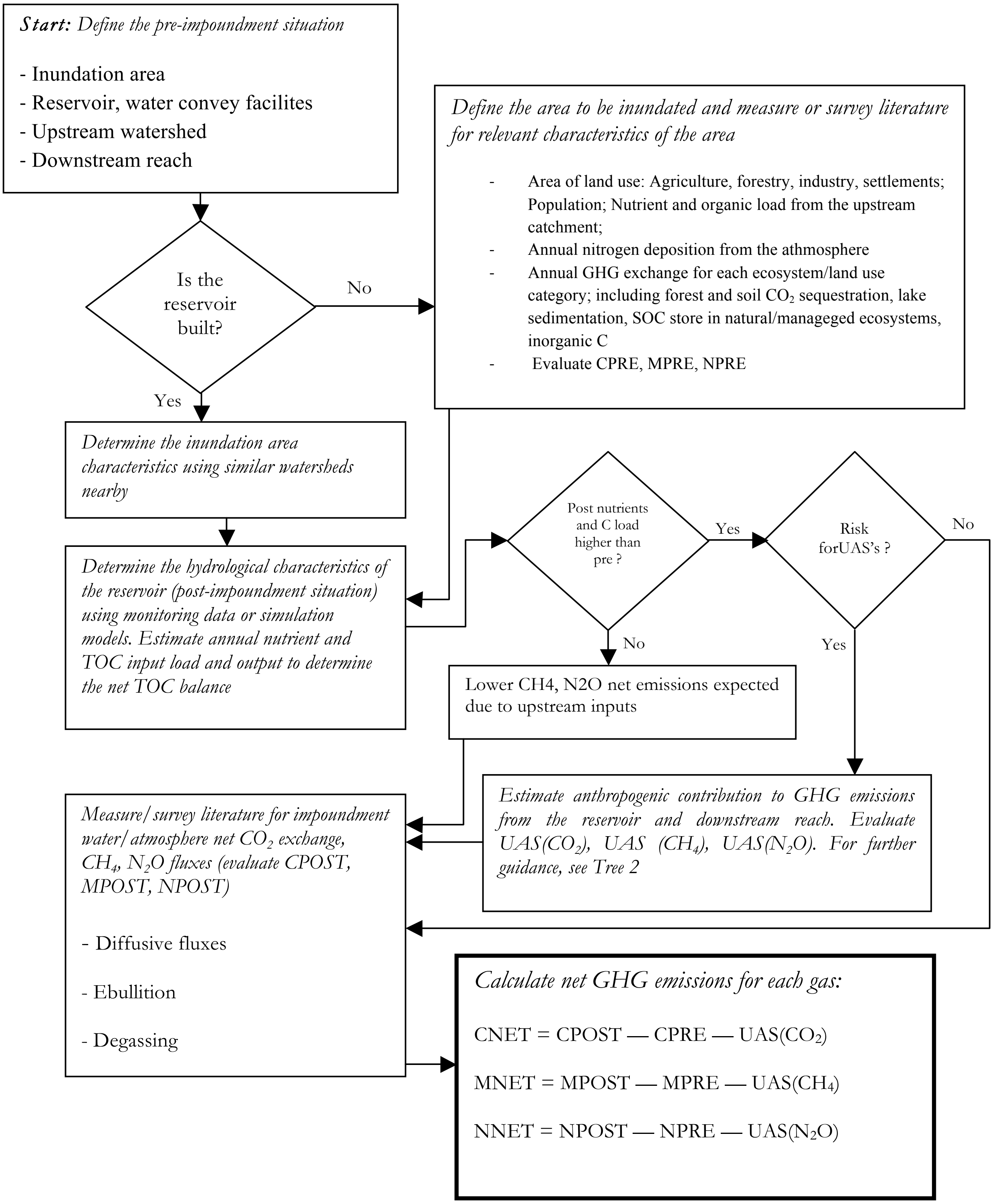


Figure 4 – Decision tree 1

Decision Tree 1

For reservoirs already built, much of the data about the reservoir needed in the Decision Tree 1 may be routinely monitored during the reservoir management so it can be characterized using measured data. On the other hand, the characteristics of the inundation area before the impoundment have to be obtained indirectly by studying historical land use or similar watersheds nearby. In the case of reservoirs which aren't already built, during the planning phase the data about the inundation area are usually collected directly whereas data about the reservoir are obtained through simulation.

The procedure first diverts in two branches depending if the reservoir has already been built or is just in the planning stage. In the planning stage the inundation area can be inventoried for C stores in biomass and soil, land use types and the typical annual GHG balance for each land use category or natural ecosystem. Knowledge of the direct exchange of CO_2, CH_4 and N_2O in the impoundment area provides means to estimate the fluxes of these gases in this area. These fluxes can be positive (emissions to the atmosphere) or negative (removals from the atmosphere). Impounding will cut the terrestrial removals and, by affecting the biogeochemistry of the landscape, will eventually enhance the emissions to the atmosphere. On the other hand, sedimentation of organic matter in the reservoir can at least partly compensate for the emissions. Organic sediments can be formed from the upstream organic load or from biomass produced within the impoundment area. While the decomposing organic sediments in the reservoir can give raise to GHG emissions, some organic matter may exit the reservoir through the downstream reaches.

Anthropogenic activity (agriculture, dairy production, forestry, industry, community sewage) upstream of the inundation area may contribute to GHG emissions from the impoundment. Leaching of nutrients or organic matter from any of those activities may constitute an UAS to the GHG emissions from the reservoir. An inventory of such activities gives means to identify cases where in post-impoundment conditions such loads are higher than in the pre-impoundment conditions. Note that if in the pre-impoundment conditions there were no relevant anthropogenic activities upstream or in the inundation area, pre-impoundment condition can be considered as "natural" and, for these cases, any load significantly higher than expected in natural conditions may constitute an UAS worth to investigate. Determination of the risk of UAS increasing the GHG emissions is more detailed in Decision Tree 2.

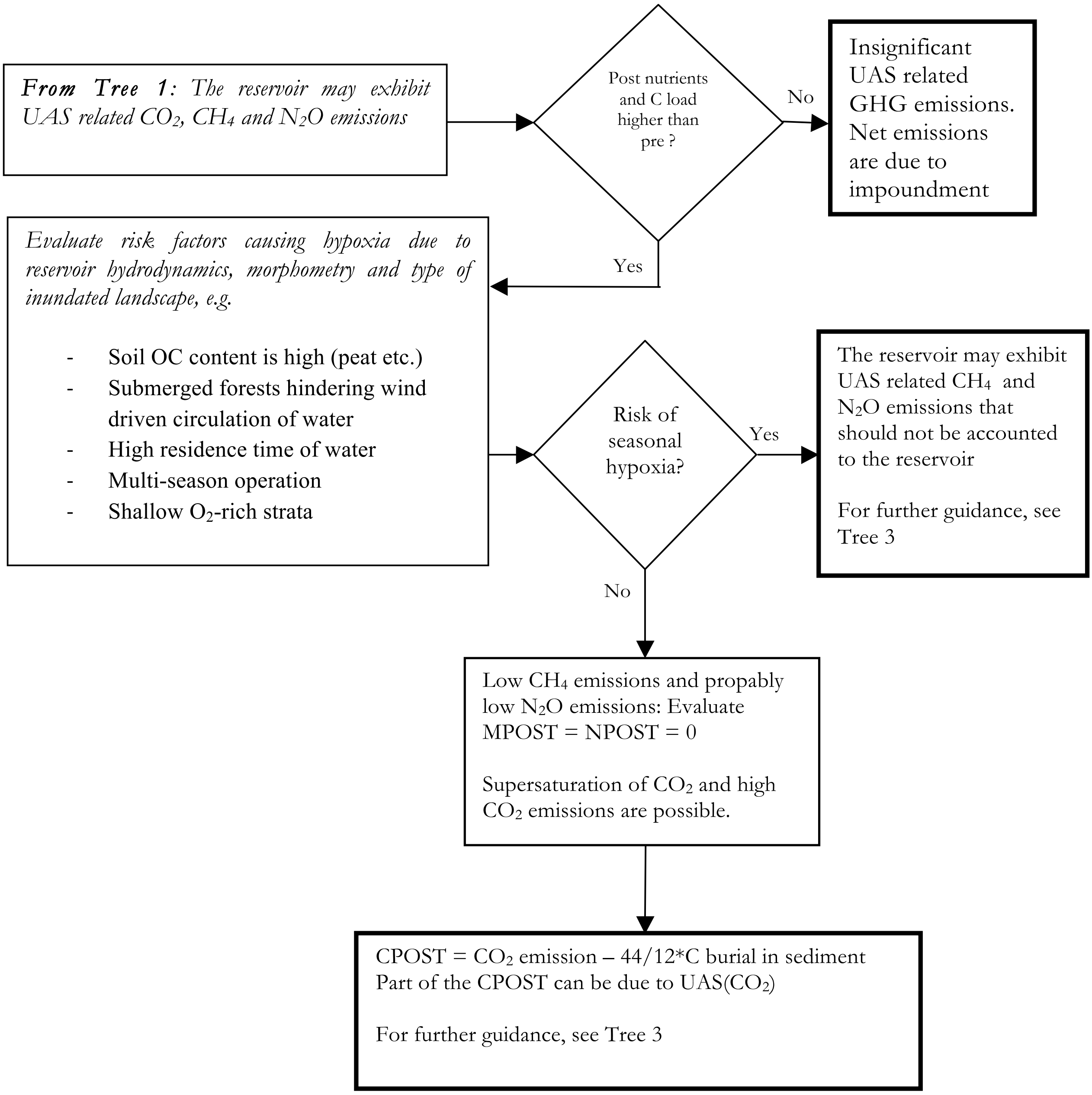
Post-impoundment emissions of CO_2 may be originated in carbon loads already present in the pre-impoundment conditions. These loads include dissolved inorganic carbon (DIC) provided, for example, by limestone areas in the upstream catchment, and dissolved organic carbon (DOC) provided, for example, by leaching of forest soils in the upstream catchment. Only the difference between post-impoundment and pre-impoundment emissions should be addressed to the reservoir. The reservoir may create conditions where organic matter decomposing under hypoxia is released as CH_4 instead of CO_2, as it would be in aerated environments. A large C and nutrient load could e.g. raise the trophic state of the reservoir, and cause eutrophication which would increase the occurrence of hypoxia and particularly affect the emissions of CH_4 and in some cases of N_2O.

Decision Tree 2

The purpose of the Decision Tree 2 is to help to identify situations when the UAS actually contributes to the post-impoundment GHG emissions from the reservoir. The contribution depends on the oxic conditions in the reservoir. From the characteristics of the catchment and of the reservoir it may be possible to identify the occurrence of hypoxia in the reservoir. In hypoxic conditions CH_4 and N_2O emissions may occur. If the hypoxia risk can be ruled out from monitoring data, in the case of existent reservoir or from simulation, in the case of planned reservoir, it is probable that there are low risks for CH_4 and N_2O emissions from the reservoir. Similarly, the UAS contribution to CH_4 and N_2O emissions must be small. In this condition high CO_2 release may take place.

If a high load of C or nutrients, exceeding those suggested by pre-impoundment conditions, has been found to enter the reservoir from the catchment upstream, then UAS may have a significant contribution to GHG emissions from the reservoir. If no such load is found, then UAS is insignificant for the reservoir GHG emissions and can be ignored. The risk of enhanced CH_4 or N_2O emissions due to UAS may be realized if the reservoir hydrodynamics and other characteristics support hypoxic conditions. Analysis of possible risk factors is needed.

In case no hypoxia, the contribution of UAS may still lead to enhanced CO_2 emissions or higher C burial rate by sedimentation. In case hypoxic conditions emerge at least seasonally, higher seasonal CH_4 and N_2O emissions may appear. Note that the Decision Tree 2 is only followed in case there is a high anthropogenic load to the impoundment. Therefore the enhanced emissions are either due to UAS or only due to the reservoir. The latter is true if there were no lake system before the reservoir, or if there was an already eutrophic in the inundation area. More guidance is given in Decision Tree 3 on how to distinguish the UAS derived GHG emissions from the reservoir emissions.



From Tree 1: *The reservoir may exhibit UAS related CO_2, CH_4 and N_2O emissions*

Insignificant UAS related GHG emissions. Net emissions are due to impoundment

Evaluate risk factors causing hypoxia due to reservoir hydrodynamics, morphometry and type of inundated landscape, e.g.

- Soil OC content is high (peat etc.)
- Submerged forests hindering wind driven circulation of water
- High residence time of water
- Multi-season operation
- Shallow O_2-rich strata

The reservoir may exhibit UAS related CH_4 and N_2O emissions that should not be accounted to the reservoir

For further guidance, see Tree 3

Low CH_4 emissions and propably low N_2O emissions: Evaluate MPOST = NPOST = 0

Supersaturation of CO_2 and high CO_2 emissions are possible.

CPOST = CO_2 emission – 44/12*C burial in sediment
Part of the CPOST can be due to UAS(CO_2)

For further guidance, see Tree 3

Figure 5 – Decision tree 2

Decision Tree 3

This tree is entered only if risks of UAS (C and/or nutrient load from the upstream catchment) derived GHG emissions have been identified in Decision Tree 2. In Decision Tree 2 there are two alternative entry points to Decision Tree 3. The first implies a risk of seasonal hypoxia with possible CH_4 or N_2O emissions, and the second considers possible CO_2 emissions under permanently oxic conditions. The aim of the Decision Tree 3 is to help in judgment when UAS may be strong enough to merit an evaluation. If the UAS is deemed weak then it may be wise to evaluate UAS derived GHG emissions as zero.

There can be several potential sources for UAS in the upstream catchment. The following list is not complete: Settlements such as villages, small or large cities, sewage treatment plants in operation, or absence of those, agricultural areas, pastures adjoining the water front, industries with biologically degradable output (that may end up in the water course). Eutrophication may follow through atmospheric nitrogen deposition from industrial areas, large cities with heavy traffic or from fossil fuel plants. Water-tight areas like roads, buildings etc. may lead to higher surface runoff and transport of pollutants to the water courses. Forest drainage or peat extraction can leach eroded organic matter and dissolved humic substances.

One means to quantify the UAS derived GHG emissions is to compare the reservoir trophic state (oligotrophic, mesotrophic, eutrophic, hyper-eutrophic) with the trophic states of nearby lake systems. If the trophic state in the reservoir is significantly higher than in the nearby lakes them the quantity of UAS needs to be more accurately determined. In order to evaluate if the UAS are strong enough to explain the higher trophic state, the carbon and nutrient load should be calculated by means of measurements (direct approach) or using indices such as Population Equivalents, P.E. (indirect approach).

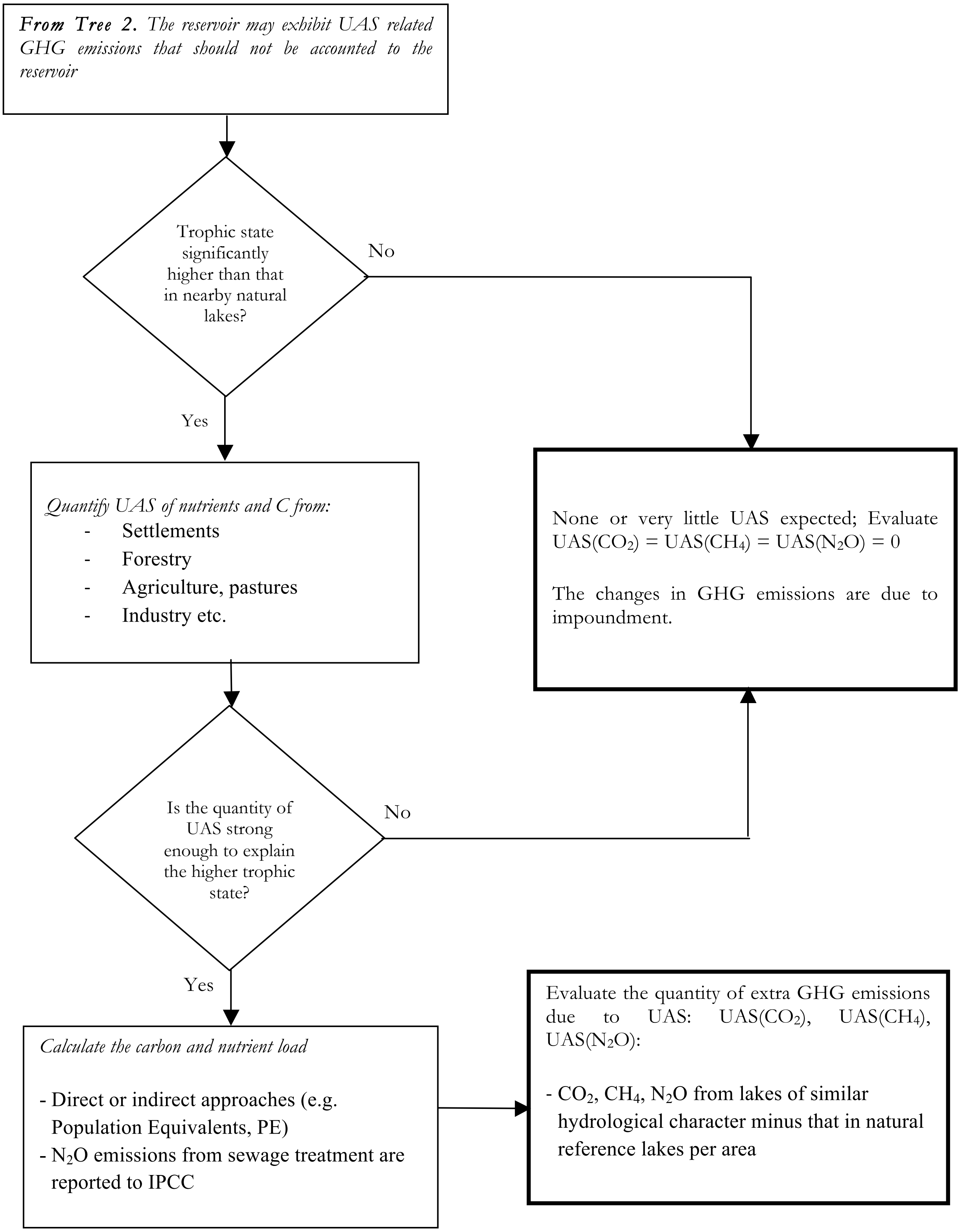


Figure 6 – Decision tree 3

2.4 Environmental and Technical Descriptors of Reservoirs

Context

The frequency and intensity of the processes that ultimately define the net GHG emissions from a reservoir depend on a number of characteristics of the inundation area, of the reservoir, of its upstream watershed, of the facilities which convey water downstream, and of the downstream reach where water is released. A set of environmental and technical variables were chosen to synthesize these characteristics and they should be searched and included, when available, in the net GHG emission evaluation report of a reservoir.

Environmental and technical variables have been chosen for each of the five components of the reservoir catchment:

- the inundation area,
- the reservoir,
- the upstream watershed,
- the reservoir facilities which convey water downstream, and
- the downstream reach where the water is released.

In addition these variables can be used to categorize reservoirs and hence compare measured GHG emissions against these variables.

Best Practice Guideline

A. A set of environmental and technical variables chosen to synthesize the characteristics of the system components should be searched and included, when available, in the net GHG emission evaluation report of a reservoir.

Commentary

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The frequency and intensity of the processes that ultimately define the net GHG emissions from a reservoir depend on a number of characteristics of the inundation area, of the reservoir, of its upstream watershed, of the facilities which convey water downstream, and of the downstream reach where water is released. The following set of environmental and technical variables where chosen to synthesize these characteristics and they should be searched and included, when available, in the net GHG emission evaluation report of a reservoir.

Inundation Area:

Land Cover: Land cover map for the time of the impoundment of the inundation area, and a table for each land use type containing its description, the areal percentage, and the best estimate of the carbon and nitrogen content.

Reservoir

Location: Latitude, longitude and elevation at the maximum normal operation level.

Age: Date of the beginning of reservoir operation.

Reservoir Topography: Topographic map of the reservoir area.

Reservoir Operation Levels: Maximum and minimum normal operation reservoir levels. Seasonal expected range of reservoir levels.

Hypsographic and Volumetric Curve: Water surface area x elevation and storage area x elevation relationships given by polynomials or tables built on topographic charts with scales not greater than 1:10.000 and with 5 meter equidistant contour lines.

Mean Depth: Calculated by the ratio between volume and water surface area. Obtain values for maximum and minimum normal operation levels.

Maximum Depth: Obtain value for maximum normal operation level

Percentage of Littoral Zone: Calculated at the maximum normal operation level using the hypsographic curve. Consider littoral the area with less than 4,572 m (15 feet) in depth.

Reservoir Size Ranges: Total inundated area, main channel length from downstream reservoir boundary to upstream reservoir boundary and external shoreline size, calculated at maximum and minimum normal operation levels.

Reservoir Shape: shoreline development index (SDI) given by the ratio between the external shoreline size (P) and the square root of 4π times total area (A), calculated at the maximum normal operation level.

$$\mathrm{SDI} = \frac{\mathrm{P}}{\sqrt{4\pi \times \mathrm{A}}} \qquad (31)$$

Global Retention Time of the Water: Assuming well-mixed water in the storage volume, a global retention time is calculated dividing the long term mean inflow by the long term mean storage in the reservoir. This information can be augmented with maps and graphs describing the spatial distribution of the residence time in the reservoir for different hydrological and meteorological conditions obtained by hydrodynamic studies.

Climate: Seasonal mean values of air temperature, daily maximum and minimum air temperature, daily sunshine hours, seasonal precipitation, seasonal evaporation, wind speed, relative humidity, and atmospheric pressure for the reservoir area locality.

Water Quality: Monthly total dissolved oxygen, water temperature, pH, nutrients and chlorophyll profiles at the forebay and at mid-reservoir, obtained from measurements or outputs from calibrated numerical models.

Upstream Watershed

Geomorphology: The following indexes are suggested to describe the upstream watershed geomorphology (Gallagher 1999):

- **Basin area**,
- **Basin length** - straight-line distance between the mouth and the drainage divide nearest the source of the main stream,
- **Basin relief** - difference between highest and lowest elevation in the basin,
- **Basin relief ratio** - ratio between basin relief and basin length,
- **Total stream length** - sum of all perennial streams lengths,
- **Drainage density** - ratio between the total stream length and drainage area,
- **Drainage shape** - ration between drainage area and square of total stream length,
- **Main channel slope** - ratio between the difference in elevations at the 85% length and at the 10% length of the main channel and three quarters of the main channel length,
- **Basin surface storage** – percentage of the basin covered in lentic and impounded water bodies, including wetland areas
- **Strahler Stream order of the watershed mouth**

Land Cover: A map showing the geographic distribution of the land cover types occurring and a table containing for each type occurrence, its description and its areal percentage.

Biome and Eco-Regions: Biome(s) and eco-region(s) within it the drainage basin is located. If more than one biome or eco-region, provide a map showing the geographic distribution of them in the watershed and the areal percentage of each.

Climate: Climate zone(s) in the Koeppen's classification system within it the upstream watershed is located. If more than one climate zone, provide a map showing the geographic distribution of them in the watershed and the areal percentage of each. Collect seasonal mean values of air temperature, daily maximum and minimum air temperature, daily sunshine hours, seasonal precipitation, annual snowfall, seasonal evaporation, wind speed and direction, relative humidity, and atmospheric pressure for weather stations in the drainage basin and calculated mean areal values of these parameters for the whole drainage basin, or for homogeneous compartments, providing a map showing the areal distribution of these parameters in the watershed. Alternatively, isohyetal maps of these parameters can be provided.

Hydrology: Expected monthly reservoir inflow (long term means) and its variability (standard deviations), annual daily flow duration curves and annual maximum daily flow (or peak flow) frequency curves.

Water Quality: Monthly or seasonal median and interquartile ranges of measurements in the reservoir inflow of temperature, dissolved oxygen, pH, alkalinity, hardness, total dissolved solids, and nutrients concentrations.

Sediment Transportation: Estimates of mean annual reservoir inflow sediment yield and its year-to-year variation (interquartile range or standard deviation).

Discharge Facilities

Outflow Capacity: List outflow capacity for the power station and each type of discharge facility. Seasonal mean outflow in normal operation for each discharge facility.

Intake Level: List intake levels for the power station and each type of discharge facility.

Downstream Reach

Operation Levels: Maximum and minimum tailrace levels for normal operation. Seasonal expected range of tailrace levels.

Hydrology: Expected monthly flows (long term means) and its variability (standard deviations), annual daily flow duration curves and annual maximum daily flow (or peak flow) frequency curves.

Water Quality: Monthly or seasonal median and interquartile ranges of measurements in the downstream reach of temperature, dissolved oxygen, pH, alkalinity, hardness, total dissolved solids, and nutrients concentrations.

3.0 Quantitative Analysis of Pre-Impoundment Emissions

3.1 Introduction

In order to calculate pre-impoundment emissions of reservoirs, two situations can be considered: reservoir is not in place or reservoir is already built.

a) If the reservoir is not in place, the measurement programs can be planned to asses the regime of GHG fluxes between surface and atmosphere and permanent carbon burial rates prevailing in the area which will be flooded.

b) If the reservoir is already built, the pre-impoundment regime of GHG fluxes between surface and atmosphere and permanent carbon burial rates should be estimated based on a baseline describing what would be the conditions if the reservoir were not in place.

Items 3.2 and 3.3 provide guidance on recommended methods for estimation of pre-impoundment emissions separately for each situation.

3.2 Pre-Impoundment Emissions Quantification for Planned Reservoirs

Context

Estimates of pre-impoundment emissions for planned reservoirs are more accurately calculated from i) measurements of fluxes between surface and atmosphere for the three considered greenhouse gases (CO_2, CH_4 and N_2O) made at spatially distributed sites at the inundation area and at the downstream reach and; ii) measurements of permanent carbon burial rates made at spatially distributed sites at the floodplain compartment and at the lakes sub-compartment.

Best Practice Guideline

A. Estimates of pre-impoundment emissions of planned reservoirs should be calculated based on a set of procedures.

B. Estimates of pre-impoundment emissions of planned reservoirs should consider multi-year variability

Commentary

A. Estimates of pre-impoundment emissions of planned reservoirs should be calculated based on a set of procedures.

For the estimation of pre-impoundment emissions of planned reservoirs, the following procedures should be adopted:

- The spatial distribution of measurement sites at the inundation area should take into account the sub-compartments division of the inundation area described in item 2.2. Each sub-compartment should be mapped and its area measured. A table with the areas for each sub-compartment should be prepared. The area of the downstream reach should be also measured.
- The spatial distributions of the measurements sites at each inundation area sub-compartment and at the downstream reach surface should be randomly defined.
- Different techniques can be used to measure GHG fluxes between surface and atmosphere and permanent carbon burial rates at the sampling sites. In the water bodies sub-compartments and in the downstream reach, diffusive water-air surface fluxes can be measured using floating chambers. At the upland sub-compartments, diffusive fluxes can be measured using soil incubation methods, chamber techniques, and eddy covariance towers. Descriptions of gas flux measurement techniques can be found in Tremblay et al. (2005), IHA (2010) and cited bibliographies. The measured values should be expressed in $mg.m^{-2}.d^{-1}$ and be accompanied with associated standard uncertainties and degrees of freedom.
- In general, continuous measurements are not feasible, and temporal sampling should be planned considering the local temporal fluctuations of light intensity, soil humidity and temperature of air, water and soil. The year can be divided in periods and measurement campaigns planned as close as possible for the middle of the periods. In some climatic zones the seasonality is strong and four clearly different seasons can be observed, while in tropics and sub-tropics the wet and dry seasons are more clearly distinguished. In the temperate and especially in the boreal zone the lakes are typically ice-covered almost half a year, and a spring flood follows snowmelt.
- Estimates of the flux of each gas at a sub-compartment (or at the downstream reach) can be obtained together with assessments of its uncertainties assuming that measured values deviate from the mean fluxes[13] by the sum of two independent random factors: spatial random variations inside the sub-compartment or downstream area and random measurement errors. A similar assumption can be made for the permanent carbon burial rates measurements at the flood plain and lake sites.

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[13] The mean flux is the total flux at the sub-compartment (or downstream reach) divided by the sub-compartment area (or downstream reach area).

- If ideal conditions were fulfilled during the field campaign (large number of sampled sites, GHG flux at the water-air interface or permanent carbon burial rate in the same sub-compartment (or in the downstream reach) fluctuating with fixed variance around a fixed value and without substantial spatial/temporal covariance structure, and also, measured values obtained at sampled sites with approximately uniform measuring accuracy) simple arithmetic mean could provide an adequate estimate of the mean GHG flux or mean permanent carbon burial rate. Otherwise, as in practical situation these conditions are hardly met; the median of the measured values is usually considered as a better estimate of the mean GHG flux or of the mean permanent carbon burial rate. The median is a robust estimation method, providing protection against occurrence of outliers and also against cases of different accuracies.
- If the arithmetic mean is used for estimation, standard uncertainties are calculated by the standard deviations of the measured values divided by the square root of the number of measurements. The associated degrees of freedom is the number of measurements minus one. If the median is used, bootstrap method (Efron & Tibshirani 1993) should provide the standard uncertainties and degrees of freedom associated with the estimates.
- Summing the estimates of mean fluxes for each sub-compartment multiplied by its area provides a estimate of the flux for the whole inundation area, estimates of permanent carbon burial rates are obtained by summing the estimates of mean permanent carbon burial rate at the floodplain and lakes multiplied by their respective areas, and estimates of fluxes at the downstream reach are obtained by multiplying the estimates of its mean fluxes by its area. All these estimates should be expressed in mg.d^{-1}.
- Evaluations of the uncertainties on GHG fluxes or permanent carbon burial rate should take into account uncertainties attached to the correspondent estimates. In these evaluations, the uncertainty propagation rule with first-order derivatives can be applied and all errors considered as uncorrelated (JCGM, 2008).
- GHG flux estimates for each period are averaged considering the period durations to obtain annual estimates in mg.d^{-1}.
- Permanent carbon burial rate are estimated in an annual basis and expressed in mg.d^{-1}.
- Uncertainty on annual estimates should be evaluated considering uncertainties in seasonal estimates and seasonal durations, what can be done assuming all errors uncorrelated and using the first-order derivatives for uncertainty propagation rule.

An example of the procedures is provided for a simple division of the inundation area into three compartments (upland, river and flood plain). In this case, CO_2 emissions for the total inundation area are estimated for each campaign, as follows:

$$\hat{F}_{CO2} = A(up)\hat{f}_{CO2}(up) + A(river)\hat{f}_{CO2}(river) + A(flood)\left(\hat{f}_{CO2}(flood) - (44/12)\hat{b}_C(flood)\right) \quad (32)$$

Where:

$\hat{F}_{CO2}$ is the estimate for the total CO_2 emissions at the inundation area,

$A(up)$ is the area which was classified as upland,

$A(river)$ is the area which was classified as river,

$A(flood)$ is the area which was classified as floodplain,

$\hat{f}_{CO2}(up)$ is the estimate of the mean CO_2 flux in the upland compartment,

$\hat{f}_{CO2}(river)$ is the estimate of the mean CO_2 flux in the river compartment,

$\hat{f}_{CO2}(flood)$ is the estimate of the mean CO_2 flux in the floodplain compartment and

$\hat{b}_C(flood)$ is the estimate of the mean permanent carbon burial rate in the floodplain compartment

For the case of a "dry season" lasting 4 months and a "wet season" of 8 months, estimates of CO_2 flux obtained in a dry and a wet campaigns in one year are combined to obtain the estimate of total annual CO_2 flux using:

$$\hat{F}_{CO2}(annual) = \frac{1}{3}\hat{F}_{CO2}(dry) + \frac{2}{3}\hat{F}_{CO2}(wet) \quad (33)$$

B. *Estimates of pre-impoundment emissions of planned reservoirs should consider multi-year variability*

In general, GHG emissions of any surface area vary according with weather conditions. Multi-year campaigns will provide information on inter-annual variability of fluxes and improved estimates of the long-term mean annual GHG pre-impoundment emissions. Statistically, three observations is a minimum for estimating variability. More years would provide better estimative of the inter-annual variability. If the campaigns provide estimates with approximately uniform accuracy, the mean of the annual estimates is the best estimate for the long-term annual value; otherwise, the annual estimates should be weighted proportional to the inverse of its squared standard uncertainty. Uncertainty evaluation of the long-term annual estimates can be done approximately considering uncorrelated annual estimates.

3.3 Pre-Impoundment Emissions Quantification for Existent Reservoirs

Context

If the reservoir is already in place and pre-impoundment measurements of GHG fluxes between surface and atmosphere and permanent carbon burial rates at the inundation area and at the downstream reach has been made as described in Item 3.2, estimates of long-term annual values of pre-impoundment emissions with associated uncertainties are available. If no pre-impoundment measurements have been made, estimates of pre-impoundment emissions can be obtained from a literature search or from measurements of GHG fluxes and permanent carbon burial rates made at sites near the inundated area, considering the environmental and biological characteristics.

Best Practice Guideline

A. Estimates of pre-impoundment emissions for existing reservoirs where pre-impoundment measurements have not been taken should be estimated based on a set of procedures.

B. Estimates of pre-impoundment emissions for existing reservoirs should consider multi-year variability.

Commentary

A. Estimates of pre-impoundment emissions for existing reservoirs where pre-impoundment measurements have not been taken should be estimated based on a set of procedures.

If no pre-impoundment measurements have been made, estimates of pre-impoundment emissions can be obtained from a literature search or from measurements of GHG fluxes between surface and atmosphere and permanent carbon burial rates made at sites near the inundated area, considering the environmental and biological characteristics. The following procedures should be adopted:

- A baseline should be established for the inundation area and downstream reach which would be in place if the reservoir wasn't built. The inundation area and downstream reach status at the time of the impoundment may be the most natural baseline, although the actual land-use pattern in surrounding areas can be used to build the baseline. A sub-compartment division as described in Item 2.2 should be developed for the adopted baseline. The area of each sub-compartment should be estimated and put in a table.
- Campaigns for measurement of fluxes between surface and atmosphere for the three considered gases (CO_2, CH_4 and N_2O) and permanent carbon burial rates should be planned and performed at chosen sites similar and nearby the inundated area which resemble the baseline inundation area

sub-compartments and downstream reach. Similarly as describe in Item 3.2, the year can be divided into “seasons”, and measurement campaigns planned as close as possible for the middle of the seasons.

- Best estimates of each greenhouse gas fluxes between surface and atmosphere and permanent carbon burial rate expressed in mg.d^{-1}, together with associated standard uncertainties and degrees of freedom for each sub-compartment, whole inundation area and downstream reach, can be obtained from the measurement results following the same procedures described in Item 3.2.
- Alternatively a literature search can provide estimates, with associated standard uncertainties and degrees of freedom, of mean annual fluxes between surface and atmosphere of each greenhouse gas for each sub-compartment and for the downstream reach and also, for permanent carbon burial rates at the floodplain and lake. All these estimates should be expressed in mg.m^{-2}.d^{-1}. This information can be used directly as substitutes of estimates of mean fluxes or mean permanent carbon burial rates obtained from measurements. Considerable care should be taken when transferring uncertainty information from literature search to values of standard uncertainty. The standard uncertainty is related to the interval centered in the best estimate with 67% of chances for containing the true value, while very often the literature provides range intervals which cover all estimates. Standard uncertainty can be assumed to lie between 1/3 to 1/4 of the range. Also, very often there is no information on the associated degree of freedom, and it must be assigned, based on evaluations of the proportional uncertainty in the standard uncertainty and equation (29).

B. *Estimates of pre-impoundment emissions for existing reservoirs should consider multi-year variability*

As described under similar circumstances in Item 3.2, multi-year campaigns at nearby sites will provide information on annual variability of fluxes and improved estimates of the long-term mean annual GHG emissions.

4.0 Quantitative Analysis of Post-Impoundment Emissions

4.1 Introduction

This chapter contains guidance for estimation of post-impoundment regimes of emissions. Only the situation where the reservoir is already in operation is considered here. Estimations for planned reservoirs are done with the aid of models, which will be covered on volume 2.

Estimates of gross emissions for existent reservoirs are more accurately calculated if measurements of GHG fluxes between surface and atmosphere for each emission path and of permanent carbon burial rates are made at the reservoir area and downstream reach. This chapter contains guidance on recommended estimation procedures separately for each emission path and permanent carbon burial rate.

4.2 Diffusive Fluxes

Context

Estimates of GHG diffusive fluxes both for the reservoir and for the downstream reach component should be calculated for all three greenhouse gases (CO_2, CH_4 and N_2O). These estimates should be obtained from measurements made at sets of sites spatially distributed in these two components.

Best Practice Guideline

A. ***Estimates of GHG diffusive fluxes between surface and atmosphere should be calculated both for the reservoir and for the downstream reach components for all three greenhouse gases (CO_2, CH_4 and N_2O) based on a set of procedures.***

Commentary

A. ***Estimates of GHG diffusive fluxes between surface and atmosphere should be calculated both for the reservoir and for the downstream reach components for all three greenhouse gases (CO_2, CH_4 and N_2O) based on a set of procedures.***

The following procedures should be adopted to obtain estimates of diffusive fluxes between surface and atmosphere:

- The estimates should be obtained from measurements made at sets of sites spatially distributed in the reservoir and in the downstream reach components;

- The spatial distribution of measurement sites at the reservoir should take into account a stratification of the reservoir surface. The most common stratification is to consider four strata: upstream, mid, coves and forebay;
- Each stratum should be mapped and its area measured. A table with the area for each stratum should be prepared;
- The spatial distribution of the measurements sites at the downstream reach surface and at each stratum of the reservoir surface should be randomly defined;
- The most common technique to measure GHG diffusive fluxes between surface and atmosphere at the samples sites is the use of floating chambers. Descriptions of this technique can be found in Annex B, FURNAS (2008), Tremblay et al (2005), IHA (2010) and cited bibliographies. The measured values should be expressed in $mg.m^{-2}.d^{-1}$ and be accompanied with associated standard uncertainties and degrees of freedom;
- In general, continuous measurements are not feasible and temporal sampling should be planned considering the local temporal fluctuations of light intensity, soil humidity and temperature of air, water and soil. The year can be divided in periods, and measurement campaigns planned as close as possible for the middle of the periods. The planning of periods should consider those periods with special situations. In cold climates, GHG emissions may have temporal maximum during the thermal overturn of the water body. When the reservoir is covered by ice during the winter, GHG's may accumulate in the water body especially in reservoirs with long retention time and organic rich sediment. Spring thaw and thermal overturn of the water may result especially in emissions of CO_2 (Kortelainen et al 2006; Demarty et al. 2011) and CH_4 (Juutinen et al. 2009) stored in the water. The ice-out CH_4 emissions may be high new reservoirs or small ones with lots of buried organic materials. Characteristically the ice-out emission period is very short and requires a special campaign. Another GHG maximum period may occur when the summer time thermocline is broken during the autumn overturn.
- Estimates of the flux of each gas through diffusive flux for each stratum of the reservoir surface and for the downstream reach can be obtained together with an assessment of its uncertainty assuming that measured values of diffusive flux deviate from mean diffusive flux as the result of spatial random variations and random measurement errors. The median of the measured values is usually considered as an adequate estimate of the mean diffusive emission, providing protection against occurrence of outliers and also against cases of different accuracies;
- If the median of the measured diffusive flux values is used, the associated standard uncertainties and degree of freedom are obtained by the bootstrap method. It the arithmetic mean is used, the standard uncertainties are calculated by the standard deviations of the measured diffusive flux

values divided by the square root of the number of measurements and the associated degree of freedom is the number of measurements minus one;

- Summing the estimates of mean diffusive fluxes for each stratum of the reservoir surface area multiplied by its area provides an estimate of the diffusive flux for the whole reservoir, which should be expressed in $mg.d^{-1}$. Also, estimates of the diffusive flux at the downstream reach are obtained by multiplying the estimate for the mean diffusive flux by the downstream reach area, which result should again be expressed in $mg.d^{-1}$;
- Uncertainties on whole reservoir and downstream reach diffusive flux estimates should be evaluated taking into account uncertainties in mean diffusion flux estimates. In the evaluations, the uncertainty propagation rule with first-order derivatives can be applied and all errors considered as uncorrelated (JCGM, 2008);
- GHG diffusive flux estimates for each period are averaged considering the period durations to obtain annual estimates;
- Uncertainties on annual whole reservoir and downstream reach diffusive flux estimates should be evaluated considering uncertainties in seasonal diffusive flux estimates and seasonal durations, which can be done assuming all errors uncorrelated and using the first-order derivatives for uncertainty propagation rule.

4.3 Ebullitive Emissions

Context

Estimates of reservoir GHG ebullitive emissions should be calculated for CO_2 and CH_4 and for the reservoir component. These estimates should be obtained from measurements made at sites spatially distributed in the region of the reservoir where bubbling can occur (ebullitive emission area), which can be considered as the region where depths are lesser than 20 m.

Best Practice Guideline

A. Estimates of reservoir GHG ebullitive emissions should be calculated for CO_2 and CH_4 and the reservoir component, in the region where bubbling can occur, based on a set of procedures.

Commentary

A. Estimates of reservoir GHG ebullitive emissions should be calculated for CO_2 and CH_4 and the reservoir component, in the region where bubbling can occur, based on a set of procedures.

Estimates of reservoir GHG ebullitive emissions should be calculated for CO_2 and CH_4 and for the reservoir component. These estimates should be obtained from measurements made at sites spatially distributed in the region of the reservoir where bubbling can occur (ebullitive emission area), which can be considered as the region where depths are lesser than 20 m. The following procedures should be adopted:

- An estimate of the ebullitive emission area of the reservoir should be mapped and its area measured.
- The spatial distribution of the measurements sites at the ebullitive emission area should be randomly defined.
- The most common technique to measure ebullitive emissions is the use of sets of inverted funnels. Descriptions of this technique can be found in Appendix B, IHA (2010) and cited bibliographies. The measured values should be expressed in $mg.m^{-2}.d^{-1}$ and be accompanied with associated standard uncertainties and degrees of freedom.
- Continuous time measurements are not feasible and temporal sampling should be planned considering the local temporal fluctuations of light intensity, soil humidity and temperature of air, water and soil. The year can be divided in "seasons", and measurement campaigns planned as close as possible for the middle of the seasons.
- Estimates of ebullitive emissions can be obtained together with an assessment of its uncertainty assuming that measured values deviate from mean emissions as the result of spatial random variations and random measurement errors. The median of the measured values is usually considered as an adequate estimate of the mean ebullitive emissions;
- If the median of the measured ebullitive values is used, the associated standard uncertainties and degree of freedom are obtained by the bootstrap method. It the arithmetic mean is used, the standard uncertainties are calculated by the standard deviations of the measured ebullitive values divided by the square root of the number of measurements and the associated degree of freedom is the number of measurements minus one.
- The estimate of mean ebullitive emissions multiplied by the area of the ebullitive emission area of the reservoir provides an estimate of the flux for the whole reservoir which should be expressed in $mg.d^{-1}$.
- Uncertainties on ebullitive emission estimates should be evaluated taking into account uncertainties in mean ebullitive emission estimates. In the evaluations, the uncertainty propagation rule with first-order derivatives can be applied and all errors considered as uncorrelated (JCGM, 2008).
- Ebullitive emission estimates for each period are averaged considering the period durations to obtain annual estimates.

- Uncertainties on annual ebullitive emission estimates should be evaluated considering uncertainties in seasonal ebullitive emission estimates and seasonal durations, what can be done assuming all errors uncorrelated and using the first-order derivatives for uncertainty propagation rule.

4.4 Degassing

Context

Estimates of reservoir GHG degassing emissions should be calculated for all three greenhouse gases (CO_2, CH_4 and N_2O). These estimates should be obtained from differences of gas concentration measurements made in water samples collected at the entrance of outflow structures and at the downstream reach as close as possible the outflow structure multiplied by the outflow discharge.

Best Practice Guideline

A. Estimates of reservoir GHG degassing emissions should be calculated, for all three greenhouse gases (CO_2, CH_4 and N_2O), based on a set of procedures.

Commentary

A. Estimates of reservoir GHG degassing emissions should be calculated, for all three greenhouse gases (CO_2, CH_4 and N_2O), based on a set of procedures.

Estimates of reservoir GHG degassing emissions should be calculated for all three greenhouse gases (CO_2, CH_4 and N_2O). These estimates should be obtained from differences of gas concentration measurements made in water samples collected at the entrance of outflow structures and at the downstream reach as close as possible the outflow structure multiplied by the outflow discharge. The following procedures should be adopted:

- Measurements of GHG degassing emissions for the three considered gases (CO_2, CH_4 and N_2O) should be performed at all outflow structures where degassing is suppose to occur. In the case of hydropower reservoir, the collection of upstream samples should be made inside the power house.
- Description of the technique can be found in FURNAS (2008) and cited bibliographies. The measured values should be expressed in $mg.d^{-1}$ and be accompanied with associated standard uncertainties and degrees of freedom.
- In general real time measurements are not feasible, and temporal sampling should be planned considering the local temporal fluctuations of light intensity, soil humidity and temperature of air,

water and soil. The year can be divided in "seasons", and measurement campaigns planned as close as possible for the middle of the seasons.

- Estimates of the emission of each gas through degassing can be obtained together with an assessment of its uncertainty assuming that measured values of degassing emissions in each outflow structure deviate from the correspondent true degassing emissions as the result of random measurement errors. Summing the estimates of degassing emissions from each outflow structure provides the best estimate of the degassing emission for the whole reservoir in mg.d^{-1}.
- Uncertainties on whole reservoir degassing emission estimates should be evaluated taking into account uncertainties in degassing emission estimates for each outflow structure, what can be done by applying the uncertainty propagation rule with first-order derivatives and all errors considered as uncorrelated (JCGM, 2008).
- GHG degassing emission estimates for each period are averaged considering the period durations to obtain annual estimates.
- Uncertainties on annual reservoir degassing emission estimates should be evaluated considering uncertainties in seasonal degassing emission estimates and seasonal durations, which can be done assuming all errors uncorrelated and using the first-order derivatives for uncertainty propagation rule.

4.5 Permanent Carbon Burial Rates

Context

Estimates of post-impoundment permanent carbon burial rates should be obtained from measurements at sites spatially distributed in the sedimentation zone of the reservoir.

Best Practice Guideline

A. Estimates of post-impoundment permanent carbon burial rates should be obtained from measurements at sites spatially distributed in the sedimentation zone of the reservoir, based on a set of procedures.

Commentary

A. Estimates of post-impoundment permanent carbon burial rates should be obtained from measurements at sites spatially distributed in the sedimentation zone of the reservoir, based on a set of procedures.

Estimates of post-impoundment permanent carbon burial rates should be obtained from measurements at sites spatially distributed in the sedimentation zone of the reservoir. The following procedures should be adopted:

- An estimate of the sedimentation zone of the reservoir should be mapped and its area measured. The standard uncertainty and degrees of freedom of the estimated area for the sedimentation zone of the reservoir should be evaluated.
- The spatial distribution of the measurements sites at the sedimentation zone of the reservoir should be randomly defined. The most common technique to measure permanent carbon burial rates is to perform ^{210}Pb concentrations measurements on sediment cores. Nevertheless, this technique can be appropriated for measuring accumulation during decades, and alternatives methods should be developed for estimating carbon burial rates in daily intervals. Appendix B describes a technique for obtaining permanent carbon sedimentation rate using silicon (Si) as a tracer. Failure in obtaining estimates of carbon burial rates can occur due to disturbance by surface sediment lateral advection or dredging. In case of difficulties in estimating permanent carbon burial rates, the null rate can be adopted. The measured values should be expressed in $mg.m^{-2}.d^{-1}$ and be accompanied with associated standard uncertainties and degrees of freedom.
- Estimates of permanent carbon burial rates in the reservoir can be obtained together with an assessment of its uncertainty assuming that measured values deviate from mean permanent carbon burial rate as the result of spatial random variations and random measurement errors. The median of the measured values is usually considered as an adequate estimate of the mean ebullitive emissions.
- If the median of the measured values is used, the associated standard uncertainties and degree of freedom are obtained by the bootstrap method. It the arithmetic mean is used, the standard uncertainties are calculated by the standard deviations of the measured values divided by the square root of the number of measurements and the associated degree of freedom is the number of measurements minus one.
- Estimates of mean permanent carbon burial rate multiplied by the sedimentation zone of the reservoir provide an estimate of the permanent carbon burial rate for the whole reservoir.
- Uncertainties on permanent carbon burial rate estimates can be evaluated taking into account uncertainties in mean permanent carbon burial rate estimates and in the area of the sedimentation zone of the reservoir. In the evaluations, the uncertainty propagation rule with first-order derivatives can be applied and all errors considered as uncorrelated (JCGM, 2008).

4.6 GHG emissions from unrelated anthropogenic sources

Context

According with the general procedures described in item 2.3, estimates of emissions of a specific gas that can be attributed to anthropogenic sources unrelated with the reservoir should be taken out in the balance of fluxes for the estimate of post-impoundment emissions for that gas.

Several human activities in the upstream watershed may contribute to GHG emissions in the reservoir. As examples, we can list: settlements (villages and cities); sewage treatment plants (or absence of those); agricultural and pastures adjoining the reservoir shoreline and the upstream watercourses; and industries which contaminates water courses with biologically degradable output. Reservoir eutrophication may follow from nitrogen deposition from industrial areas, large cities with heavy traffic or from fossil fuel plants. Watertight areas like roads, buildings etc. may lead to higher surface runoff and transport of pollutants to the water courses. Forest drainage or peat extraction can supply water courses with eroded organic matter and dissolved humic substances. The inventory of such activities in the upstream watershed gives means to identify the related load of carbon and nutrients affecting the GHG fluxes regime in the reservoir. If only a small amount for such load is found, then UAS is insignificant for the reservoir GHG emissions and can be ignored.

Best Practice Guideline

A. ***Quantitative attributions which define with precision the amount of GHG emissions attributable with a specific anthropogenic source is only possible with the aid of simulation models.***

Commentary

A. ***Quantitative attributions which define with precision the amount of GHG emissions attributable with a specific anthropogenic source is only possible with the aid of simulation models.***

A quantitative attribution which defines with precision the amount of the emissions of a certain gas attributable with a specific anthropogenic source is only possible with the aid of a controlled experiment with two identical reservoirs, with only one of them suffering the influence of the analyzed anthropogenic source. In practice, this situation is unlikely to be available, and computer simulation model should be used to obtain the emission amount which can be attributed by demonstrating that measured emissions in the reservoir are consistent with the emissions calculated in the model simulations with the action of the anthropogenic source, and inconsistent with the emissions calculated in the model simulations without the anthropogenic source. Volume 2 contains recommendations for this goal.

4.7 Multi-Year Variability

Context

In general, GHG emissions from reservoir areas vary according to weather conditions. For reservoirs more than 20 years old it can be considered that the steady state has been achieved and multi-year campaigns can provide information on annual variability of fluxes and improved estimates of the long-term mean annual GHG gross emissions.

Best Practice Guideline

A. Estimates of reservoir GHG gross emissions from reservoir areas should consider multi-year variability

Commentary

A. Estimates of reservoir GHG gross emissions from reservoir areas should consider multi-year variability

If multi-year campaigns provide estimates with approximately uniform accuracy, the mean of the annual estimates is the best estimate for the long-term annual value; otherwise, the annual estimates should be weighted proportional to the inverse of its squared standard uncertainty. For new reservoirs, reservoir age is another important factor, and the steady state cannot be considered to be achieved. In this case, the mean of the annual estimates does not have any significance. On the other hand, the annual variations in the GHG gross emissions are of relevance.

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APPENDIX A: Process Governing GHG fluxes and Permanent Carbon Burial Rates in Surface Areas

Introduction

Three different classes of processes govern GHG fluxes and permanent carbon burial rates of any surface area: biological, physical and chemical. Basic biogeochemical processes of concern in carbon balances are the ones resulting in net exchange of CO_2 in photosynthesis and respiration of autotrophic organism like plants and cyanobacteria, and decomposition of dead organic matter by heterotrophic organisms such as animals, fungi, bacteria and archae releasing CO_2 and CH_4. For nitrogen balance the biological processes are biofixation, ammonification, nitrification, and denitrification, and the last two can result in a release of N_2O. Physical processes of concern are organic matter advection and dispersion, whereas the main chemical process of concern is combustion.

Several local environmental characteristics control the intensity and frequency of the functioning of the basic process governing carbon and nitrogen transport and storage in natural or man-disturbed environments. As a consequence, prevailing regimes of GHG emissions and permanent carbon burial rates reflects the distribution of these characteristics. In the following, the description of the governing process is discussed in relation with soil organic matter and soil water content characteristics of the environment.

CO_2 and N_2O cycles

While atmospheric CO_2 is bound by autotrophic plants and microorganisms (algae and cyanophyta) in photosynthesis, much of it is soon released back in maintenance respiration of those organisms.

In the photosynthesis processes the CO_2 present in the atmosphere is fixed to produce organic matter using solar energy:

$$H_2O + CO_2 + \text{Energy} \rightarrow (CH_2O)n + O_2$$

Through the aerobic respiration of organisms the organic matter is consumed and the $CO2$, produced:

$$(CH2O)n + O2 \rightarrow H2O + CO2 + \text{Energy.}$$

Nitrogen is fixed from the atmosphere in biofixation, but is also taken, through assimilation by plant roots as ammonium (NH_4+) and nitrate (NO_3-). The assimilation products created in primary production are used for the production of organic compounds for growth and reproduction. Bacteria activities complete the nitrogen cycle transforming ammonium to nitrate (nitrification) and nitrate to N_2 (denitrification).

Soil Organic Matter and Soil Water Content

About half of the dry organic matter formed consists of carbon. While perennial plants can store organic matter in their biomass for several years, a forest may serve as carbon storage over decades. Litter is formed in the annual cycle of plants that renew their aboveground and belowground parts and constitutes a significant part of the ecosystem carbon flow.

Soil organic matter is the substrate for heterotrophic organisms such as fungi and bacteria. Most of the litter produced is thereby used as energy source of those microbes and much of the carbon is released to soil as CO_2 and as dissolved organic carbon (DOC). When the soil organic matter decomposes in oxic conditions, limited amount of organic matter can be stored in soil over long periods of time. However, if the soil is inundated at least part of the year, the heterotrophs rapidly consume the available oxygen, and the soil conditions may turn hypoxic or completely anoxic. In those conditions the efficient aerobic decomposition is retarded, and the rate of breakdown of organic matter is lowered. Decomposition can still continue at much lower rates due to anaerobic processes. Methanogenic archae are obligatory anaerobes that use CO_2 and H+ or acetic acid from the organic decomposition chain as substrates, and produce CH_4. Some of the methane can be consumed by methanotrophic bacteria in more oxic conditions in the topsoil, and turned to CO_2. The net CH_4 emission thus depends on the degree of water saturation in soil. The methanotrophs in dry soils may consume the atmospheric methane, which can be detected when CH_4 concentration in soil pore space is lower than that in the atmosphere (1.8 ppm). In those cases upland soils may serve as a sink for methane. The wetter the soil conditions, and the more there is organic matter, the higher the net CH4 emissions can be. The processes that occur in water saturated upland soils also occur in permanently saturated peatlands and lake sediments. Ultimately, on areal basis the catchment's CO_2 and CH_4 balance depends on the distribution of organic matter and hydrologic conditions in the catchment.

Release of N_2O to the atmosphere is typically connected to the availability of ammonium or nitrates in the pore water. N_2O can be released by microorganisms either in nitrification or denitrification (Maag & Vinthe 1996). Nitrification is the dominant process in N_2O release from fertilizers. As nitrate is often a restrictive nutrient for plant growth, and plants can take up most of the available NO3- with their roots, release of N_2O by denitrification may occur episodically when the substrate is available. In boreal catchments these releases may occur during spring thaw. Denitrification also occurs in hypoxic conditions that mostly prevail in peatlands, riparian, or littoral ecosystems. A prerequisite for N_2O release is the availability of both nitrogen in a suitable form and carbon as an energy source.

Complete Waterlogging

With increasing inundation or complete waterlogging[14], the organic deposits become thicker and may be preserved over millennia. Wet organic rich soils such as peat and muck are called histosols. Wetlands are typically formed in topographically lower parts of the catchments with soils of low infiltration rate. Peat is the ultimate histosol with a very low mineral content. Peatlands can be formed either by primary paludification where the organic layer accumulates on top of mineral soil due to constant or frequent waterlogging, terrestrialization[15], or by secondary paludification of a forest. Peat is often formed of the remains of sedges and mosses adapted to wetland conditions, but tropical peats can be formed from dead woody biomass. A special case of peat formation are blanket bogs that are formed on hilltops in maritime climates with less evapotranspiration than precipitation.

In wetlands, saturation with water is the dominant factor controlling soil development and the species of plants and animals that occur. Bacteria in the moist and anoxic wetland soil produce CH_4 as they decompose dead plant material, making wetlands an important CH_4 source. The opposite is true for N_2O. Although bacteria found in wetlands do produce N_2O, flooded conditions tend to support bacteria that consume N_2O and produce nitrogen gas (N_2). Therefore, wetlands are believed to be a negligible source of N_2O and might act as a minor sink (EPA 2010). In general, emissions of CH_4 and N_2O from wetlands to the atmosphere are a small residual of the much larger amounts of these gases produced and consumed in wetland soils. The different types of bacteria in wetlands that produce and consume these gases are affected differently by environmental factors (e.g., temperature, water level, and organic matter supply and characteristics). Therefore, a relatively small environmental change can result in a large change in flux by changing the balance between production and consumption (Itoh et al. 2007).

The mosaic of ecosystems and land use together with the distribution of annual climatic patterns determine the catchment GHG balance over a year. Precipitation and drought modulate the oxic/anoxic conditions in soils, and temperature controls the rates of plant growth and the microbial processes in decomposition. Land use changes may alter the conditions as well. For all these reasons the catchment's GHG balance is a subject for large interannual variation due to natural and anthropogenic factors.

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[14] Waterlogging refers to the saturation of soil with water.

[15] Terrestralization refers to overgrowth of a pond by aquatic vegetation

Impoundment

Building a reservoir alters the hydrological conditions in the flooded area, and also in the surroundings by raising the water table. The inundation will flood organic matter in soil and vegetation, nutrients and organic matter from the upper catchment will start to accumulate in the reservoir (Rosa et al., 2004). Very important controls of the GHG exchange balance are the availability of organic matter, nutrients and especially oxygen. Enrichment of the reservoir by nutrients and organic matter may lead to an increase in primary productivity and sedimentation rate. Organic sediment almost certainly will tend to provide anoxic conditions suitable for methanogenesis, and the net release of CH_4 then will depend on the balance of methanogenic and methanotrophic activity controlled by oxygen at the sediment-water interface and in the water body (Rosa et al. 2004; Iwata 2010; Morishita & Hatano 1999). Temporal anoxia in the water would accentuate the diffusive CH_4 emissions, but the strong methanogenesis in the sediment could lead to strong episodic ebullition as well. There are methanogens adapted to low and high temperature regimes, and high productivity is possible in both climatic conditions. Furthermore, the CH_4 emission to the atmosphere depends on the depth of the water column. If the release of CH_4 from the sediment to the water occurs on a deep area of the reservoir, most of the produced methane can be transformed to CO_2 at the water column. However, if the CH_4 is produced in shallow areas, an increased release of methane to the atmosphere can be expected.

A terrestrial plant cannot grow with their roots in permanently anoxic sediment. Aquatic plants are adapted to in those conditions by ventilating their roots with aerenchyme, a type of tissue with continuous air spaces between the cells from stoma to root tips. While oxygen enters the roots and rhizophere outside the fine roots through aerenchyme, the gases formed in the sediment close to roots can also ventilate to the atmosphere using the same pathway. Typical plants capable of such ventilation are reeds, sedges and alike. The aerenchymatous pathway provides an "escape route" for CH_4 from the sediment instead of slow diffusion passing methanotrophic bacteria that could otherwise consume much of the methane at the oxic sediment surface layer. Thereby the littoral vegetation of lakes and rivers has the greatest importance in lake's overall CH_4 emission (Juutinen et al 2003). Similarly, formation of large littoral vegetation in a reservoir may cause an increase in landscape CH_4 release.

The specific process of GHG emission in reservoir, especially dam lake, compared to natural lake and pond, is the degassing process through outflow structure. The dissolved GHG, mainly CO_2 and CH_4, concentrations are high in deeper layer behind dam under higher pressure of water column. The discharge through outflow structure such as discharged water after rotating turbine or intake facility in irrigation dam reduces water pressure, consequently being followed by GHG emissions by exposing discharged water to lower GHG pressure in atmosphere (Morishita & Hatano 1999).

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APPENDIX B: Measurement Techniques

by Marco Aurelio dos Santos, COPPE/UFRJ, Brazil

This appendix presents a description of techniques for measurement of GHG fluxes between surface and atmosphere and permanent carbon burial rates. More detailed information on measurements techniques and analytical methods can also be found in Tremblay et al. (2005), IHA (2010) and cited bibliographies.

1- MEASURING GHG EBULLITION FLUXES WITH FUNNELS

1.1- Sampling Bubbles

Quantifying ebullitive releases requires the capture of bubbles that are released spontaneously. To do so, anchored inverted funnels are used, suspended from buoys close to the water surface, with the top of the funnel some 30 cm below the surface.

Each funnel covers an area of 0.75 m^2, with its vertex linked to a collection flask that is filled previously with water from the reservoir.

The water in the flask is gradually forced out by the rising bubbles that are captured, resulting in an accumulation in the flask of gas released during the sampling period (typically 24 hours) after which the total volume is measured and a portion is taken for chromatographic analysis in the laboratory. (Figure B1 and Figure B2)

Figure B1 – Details of the Bubble Collection Funnels Configuration

Figure B2 – Funnel Installation in Hydroelectric Power Dam Area

1.3- Sampling Bubble Emission Rates in Rivers

In to sample the ebullition flux in rivers, it must be borne in mind that the entire river area does not emit bubbles. Characteristically, due to the river current, there is not enough sediment accumulates to form bubbles. Instead, these bubbles are found in calm areas close to banks with far slower currents than along the central area, allowing some build-up of fine sediments that can generate bubbles. Steered by this criterion, the funnels must be placed in areas close to the bank in calm areas (Figure B3).

Figure B3 - Funnels installed close to the bank

The funnels must be placed no more than two meters from the bank.

Based on the maximum distance between the funnels and the bank, a bank buffer must be prepared, corresponding to the maximum funnel placement distance. The calculations of the areas must be based on the following data:

*Actual river area along with the segment under consideration, in km^2
*Bank buffer area (area emitting bubbles) in km^2
*Area not emitting bubbles in km^2

2- MEASUREMENTS OF DIFFUSIVE FLUXES OF GHG WITH CHAMBERS IN AQUATIC AND TERRESTRIAL ENVIRONMENTS

2.1- Measurements of Diffusive Fluxes in Water

The diffusive release or emanation of CO_2, as well as CH_4 or N_2O, is the dissolved gas flux that escapes into the atmosphere at the water – air interface or vice-versa. This is measured through diffusion chambers.

The functioning of these chambers may be compared to an inverted glass that holds a known volume of air on the water surface, receiving gases that emanate from the water and are trapped in this volume.

If the initial concentration of methane, for example, is known in the trapped air and if a new concentration is established after a few minutes of exchange, the mass will be determined crossing the area covered by the glass during the sampling period, typically in a few minutes. (Figure B4 and Figure B5).

However, there is a saturation effect, meaning that the emanation rate is not uniform throughout the entire sampling period, even if brief (~16 minutes), because emanated gases dissolve back into the water.

Figure B4 – Details of the Floating Diffusion Chamber (1,000 mL)

Figure B5 – Installation of the Floating Diffusion Chamber (1,000 mL)

The concentrations of these gases in the samples are measured by Gas Chromatography (GC) on the same days as the sampling campaigns. The CH_4 and CO_2 concentrations are determined through the use of Porapack-Q columns and FID and TCD detectors respectively. The N_2O concentrations are determined with a Varian brand GC with a Porapack-Q column and an ECD detector.

With the chromatographic analysis findings, a linear adjustment is made to the concentrations in order to obtain the rate of increase (positive flux) or decrease (negative flux) of the gas concentrations in the chamber. In some cases, the non-linear approach is more appropriate, e.g. for small static chambers. The linear approximation is the standard procedure for estimating GHG flux from static chambers in UNESCO/IHA measurement specification guidance. Figure B6 presents a sampling example using a one liter chamber with an area of $0.049 m^2$ at the following times: 0, 2, 4 and 8 minutes.

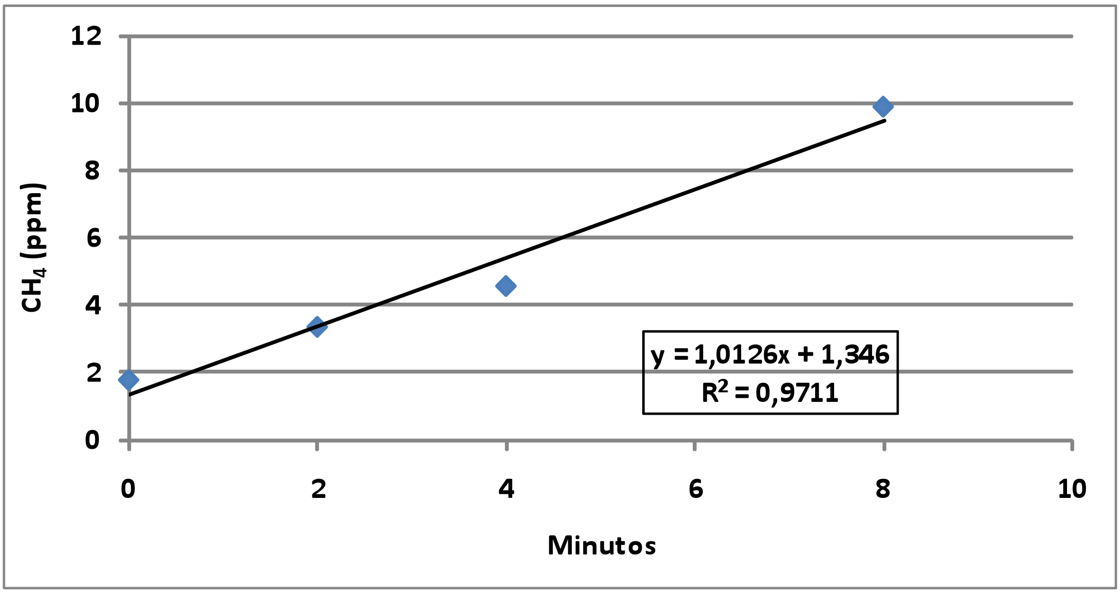

Figure B6 – Example of Diffusion Chamber Data Adjustment

With the findings to hand, the next procedure is the acceptance or rejection of the measurement.

The flows are accepted when the determination coefficient (R^2) of the linear regression adjustment function of the partial pressure versus the time is higher than 0.85 and $p<0.002$, as set forth in the recommendations in the *UNESCO/IHA Measurement Specification Guidance for Evaluating the GHG Status of Man-Made Freshwater Reservoirs* (2009)[16]. The R^2 measure has been criticized as it tends to refuse measurements of low fluxes. In order to overcome this drawback one can accept fits with $R^2<0.85$ provided the residual standard error divided by the mean concentration is lower than a critical value and experts evaluation is used.

Another flux rejection factor is when the sample is contaminated by CH_4 rich bubbles enter the chamber headspace after rising from the bottom. Should this occur during the final measurement, as is the case with the sample mentioned above, this point is discarded and the adjustment is made with the first three points. Should contamination take place before the last sample, the measurement at this point will be rejected.

If some problem occurs during the chromatographic analysis, resulting in the loss of the sample, it will be discarded and the flux will be calculated with the three remaining samples.

After acceptance by the filters, the gas flux calculation continues through the use of the straight line slant linear adjustment, as shown in the following formula:

$$\mathrm{FLUX} = \frac{\mathrm{Rate} \times \mathrm{P} \times \mathrm{F1} \times \mathrm{F2} \times \mathrm{V}}{\mathrm{SP} \times \mathrm{R} \times \mathrm{T} \times \mathrm{A}}$$

where:

Rate – rate equals gas concentration increase rate overtime (ppm.s $_{-1}$), given by the straight line slant;

P – Atmospheric pressure in the laboratory at the time of the analysis (kPa);

F1 – Molecular weight of the gas (44 for CO_2 and N_2O and 16 for CH_4);

F2 – Conversion factor for seconds into days (86,400 s);

V – Air volume in the chamber (m^3);

SP – Standard pressure at average sea level (101.33 kPa);

R – Universal constant for gases (0.08207 L. atm. Mol $^{-1}$. K $^{-1}$)

A – Chamber area in contact with the water (m^2);

T – Air temperature in the laboratory at the time of the analysis (K);

FLUX – in mg meter $^{-2}$ d $^{-1}$.

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[16] Goldenfum, Joel A. (2009). "Determination of the fluxes and acceptance/rejection procedure". In: *UNESCO/IHA Greenhouse Gas (GHG) Research Project: the UNESCO/IHA Measurement Specification Guidance for Evaluating the GHG Status of Man-made Freshwater Reservoirs.* [IHP/GHG-WG/5]. p 39. Available at UNESDOC: http://unesdoc.unesco.org/images/0018/001831/183167e.pdf.

2.2 – Measurements of Diffusive Fluxes in Soil

In general, the CO_2 emitted by the soil is generated by the respiration of soil-dwelling organisms, mainly bacteria, micro-fungi and roots.

This respiration rate rises with higher soil temperatures, but may be limited if the soil has a moisture content of less than around 10%.

The CH_4 is generated by anaerobic bacteria living in swampy soils, while other bacteria absorb CH_4 with normal moisture content; this process may also be curtailed in very dry soils.

The N_2O, is also generated by nitrogen cycling biochemical processes, emitted with appreciable fluxes by recently wetted or moist soils. The sampling points must be selected to represent environments with the main types of plant cover, riverbank forests, grazing lands and pastures and plantations.

The gas fluxes from the soil can be measured through the static chamber method (Maddock & dos Santos 1997; Livingston & Hutchinson 1995). The chamber consists of a PVC ring with a diameter of 30 cm and a height of 14 cm, whose lid is fitted with a capillary respirator and a septum for sampling with a syringe. (Figures B7 and B8)

The chamber is inserted in the soil at depths of between 2 to 20 mm, in order to ensure it is airtight, after which 30 mL samples of air are taken from the chamber with a 60 ml polypropylene syringe or pre-evacuated glass vials.

The samples are taken at intervals of 5, 10, 15 and 20 minutes for CH_4 and CO_2[17], and 10, 20, 30 and 40 minutes for N_2O.

The concentrations of these gases in the samples are measured through Gas Chromatography (GC) on the same days as the sampling campaigns. The CH_4 and CO_2 concentrations are determined through the use of Porapack-Q columns and FID and TCD detectors, respectively. The N_2O concentrations are determined through a GC, with Porapack-Q column and ECD detector. For each gas, appropriated GC equipment and protocols should be used.

Next, the fluxes are calculated according to the variations in the gas concentrations in the chambers and the corresponding sampling times, using the procedure mentioned above.

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[17] For CO2 flux, IRGA analyzer can be used to obtain automatically a time series of CO2 concentrations measurements with short time intervals (seconds) saving measurement time and enhancing the accuracy.

Figure B7 – Placement of the Chamber in the Soil

Figure B8 – Greenhouse Gas Collection by Chambers in the Soil

3- MEASUREMENTS OF GHG EMISSIONS BY DEGASSING

3.1- Collection of Samples

For the degassing calculation, water samples must be collected before (Pre-Turbine) and after (Post-Turbine) at each power generation unit in operation during the period of each campaign.

The samples must be collected at the power house suction pipe, taken directly from the spiral casing (pre-turbine), through the spiral casing outflow pipe. These water samples accurately represent the water sucked in by the turbines (Figure B9). Two water samples a day must be taken at each of the machines.

Figure B9 – Degassing Water Collection site

The post-turbine measurements must be taken with the assistance of a boat, some ten meters away from the dam wall, or at a place as close as possible to the water outflow point from the machines, where the water wells back up to the water surface, using water collectors and ropes. A sample must be collected in front of each water outlet leading from the machines (Figure B10).

For the spillways, water samples must be collected at the reservoir area near the inlet structure (at a safe distance) in different depths until the crest level. Downstream water samples must collected after the turbulence region in front of the outlet structure.

The samples must be poisoned with mercury chloride (HgCl) in order to inhibit biological activities after collection. The samples must be taken immediately to the laboratory, where the concentrations of CO_2 and CH_4 dissolved in the water are measured through the headspace technique.

Figure B10 – Collecting Water Sample Downstream From the Dam Wall for Headspace Analysis

3.2 – Extraction of Gases Dissolved in Water – Headspace Techniques

The syringe containing the water collected from the turbines must be partially emptied to half its volume. This volume is then filled with an inert gas, depending on the type of chemical to be determined. Nitrogen or helium is generally used.

After the formation of the headspace, the syringe is shaken vigorously for two minutes, in order to establish a balance between the gases dissolved in the water and the headspace air.

Immediately afterwards, the gas sample from the headspace is transferred to a smaller syringe, which is in turn analyzed in the laboratory through gas chromatography. With the gas concentrations known, the dissolved gas mass may be calculated, using the following formula:

$C = Q \text{ x } P$

where,

$P = p \text{ x}10 – 9 Z / 760$ (atm), partial pressure in atm of the gas under analysis;

$Q = v / (VRT) + 54.85 \exp (A+B/T+C \ln T +DT + \text{and } T2)$ (mol per liter per atmosphere) is the extraction coefficient.

The meanings of the variables and constants are the following:

v	– volume of the headspace (Liters)
V	– volume of the water sample (Liters)
R	– 0.082 [L atm K^{-1} mol^{-1}]
T	– temperature in K of the water and in the laboratory

p – partial pressure expressed in ppm of gas extracted from the headspace

Z – ambient pressure in the laboratory, in mm Hg

The Sandler empirical constants are shown in Table B1.

Table B1 – Sandler Empirical Constants

	CO_2	CH_4
A	– 4957.82	– 416.159289
B	105288.4	15557.5631
C	933.17	65.2552591
D	– 2.85489	– 0.061697573
E	$1.480857E^{-3}$	0

3.3 – Degassing Calculation

For the degassing calculation, the average of the samples taken at each turbine is used (pre-turbine) compared with the values found in the samples taken downstream from the dam wall (post-turbine), as shown in the diagram presented in Figure B11.

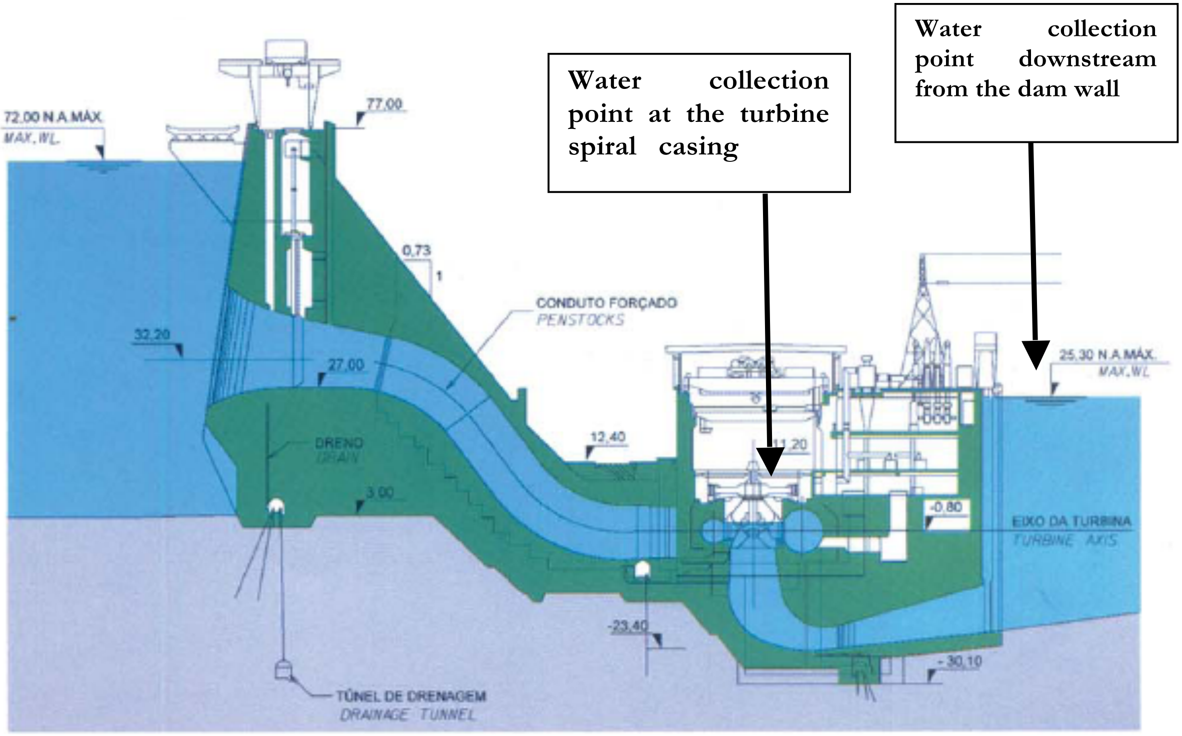

Figure B11 – Schematic Figure Showing Degassing Water Collection Locations

For the degassing calculation, the gas concentration in the pre-turbine must be subtracted from the concentration found in the post-turbine water, multiplying the result by the turbine flow rate.

$$\text{Degas sin g} = \left([\text{gas}]_{\text{pre-turbine}} - [\text{gas}]_{\text{post-turbine}}\right) \text{x flow}$$

The degassing calculation must be based on the water flowing into the turbines and the water flowing out after running through the turbines using the average CH_4 concentrations for the set of machines (pre-turbine) and the average downstream concentration (post-turbine).

Nevertheless, degassing takes place in the power house, prompted by the abrupt relief of hydrostatic pressure and the phenomenon of cavitation on the turbine blades, although the gas returns to equilibrium after running through the turbines, in some cases, reaching a nil degassing level.

4- PERMANENT CARBON SEDIMENTATION RATES

Three measurements are needed to obtain the permanent carbon (C) sedimentation rate, expressed in mg C meter^{-2} d^{-1}, using silicon (Si) as a tracer, as follows: Si (mg Si meter^{-2} d^{-1}), SI concentration [Si], SI sedimentation rate (% Si), and the C concentration [C] in the sediment profile (% C). Once the SI sedimentation rate T is determined through the use of Si sediment traps and the ratio R between C and Si is established in the permanent sediment layer, then the permanent carbon sedimentation rate is $P = T \times R$.

Although not strictly necessary, another measurement is the 'fresh C' (C_f) daily sedimentation rate, defined as carbon that sinks through the water column at around 1m of sediment, which is the critical zone where its final destination of either decomposition or fossilization is finally determined. Requiring the use of traps, this measurement can check the consistency of the Si tracer method, as the permanent C daily sedimentation rate must be less than the C_f daily sedimentation rate.

4.1- Silicon Sedimentation Rate

The sedimentation traps consists of polyvinyl chloride (PVC) pipes that are 40 cm long (l), with a diameter of 7.1 cm (d), with closed bottoms. The 5.6 ratio of the (l / d) aspect must be used to minimize the interference of the trap in the measurements (Rosa, 1994).

When placed in the water, a deadweight mooring buoy is connected to the lower part of the trap by a short (~ 0.5 meter) cord. The top of the trap is tied to a suspension cord. A picture of the maquette of this array is presented in Figure B12. At the other end of the suspension cord, a polyethylene terephthalate buoy (e.g. a PET bottle) is tied two or three meters above the trap mouth. The deadweight mooring buoy is sufficiently heavy to sink the float, which remains submersed, positioned vertically in the trap. Just above this float is a marker buoy, held in position by a length of cord whose lower end is tied to the submerged suspension cord. This marker buoy indicates the trap location, for easier removal. Traps are placed at locations where the water column is at least ten meters deep. The configuration of the trap placed in the water column is: the deadweight mooring buoy is placed on the bottom, the trap is suspended by the submerged float, and the trap mouth is approximately one meter above the bottom.

The trap is filled to the brim with iced water, free from particles in suspension, while still in the boat before being placed in the water, and is then submerged down to the dam bottom. Ice water prevents initial convection and the possible loading of the trap with undesired particles. Thus, the temperature of the water that initially fills the trap cannot exceed 14°C. Dam bottom temperatures typically vary between 20°C and 27°C.

Between one and three Si sedimentation traps are placed at each site, where they remain for approximately 24 hours. Also mentioned in the literature (Leite *et al.,* 2000; Leite 2002), this length of time is preferred because practice has shown that the materials collected in a single day are sufficient for analysis. During this period, the particles that are dropping towards the dam bottom enter the trap and remain there. At the end of this period, the trap is hoisted up and its contents are placed in a flask, taking care to resuspend any deposits that might have built up on the trap bottom.

In the laboratory, the trapped water is filtered through a paper filter with a pore size of 0.45 µM. More than one paper filter is used when the filtering speed is very slow due to clogging. The filters trap all the silicon particles that enter the trap mouth. The filter papers and the filtrates are then submitted to alkaline fusion (Jackson 1958), in order to solubilize the silicon as sodium silicate, through the following procedure: the folded filter papers (still wet, or dried at room temperature) are cut up with scissors in order to fit into a nickel crucible with a volume of 65 mL. Then 20 mL of 1 mol L^{-1} NaOH are added and the mixture is digested and dried for 30 minutes on a hot-top with a diameter of 12 cm and 600 Watts voltage. The crucible is then heated in a kiln reaching 800°C – 900°C in 40 – 60 minutes. An additional 10 – 15 min allows the completion of fusion. The methods used to dissolve and analyze the alkalized smelted residue, in order to produce a silicate solution (similar to the S solution are described below) in the treatment for sediment samples.

4.2 – Obtaining Sediment Cores

The cores must be taken from the reservoir bottom with a Niederreiter corer (made by UWITEC), consisting of a drill pipe fitted with a locking device at its lower end. Pre-damming sediment cores are rejected when they contain dryland matter such as roots and branches, for example, as they may constitute outliers in the set of carbon concentrations measured.

The cores must be cut in horizontal slices with a thickness of 1 – 3 cm, depending on the sediment texture, and are then stored in plastic bags until reaching the laboratory, where the carbon and silicon concentrations in the slices are determined through a Shimadzu Brand Carbon Analyzer, SSM model – 5000A.

4.3 – Alkaline Fusion and Silicon Analysis in the Sediment

The following procedure is a variation on the methods described in Jackson (1958) and Mackereth *et al.* (1978): Based on a sediment sample (previously dried at 110°C for one hour, and ground) a portion of 50 mg is accurately measured in a platinum crucible (Pt) with a volume of 35 mL, and mixed with Na_2CO_3 at four times its mass. The platinum crucible is then placed in a triangle with an aluminum rim on a tripod and heated with a blowtorch until it glows bright red (800°C – 900°C), which takes less than one minute. After cooling, 100 mL of distilled water is used to dissolve the smelted alkaline residue and wash the crucible. The solution and the washing water are placed together in a plastic cup, filtered through a paper filter, neutralized at pH 7 with a solution 1 mol L^{-1} of HCl, and topped up with distilled water to 150 mL. The resulting silicate solution is called S.

Next, the silicon content is determined through the yellow silicomolybdic method: 20 mL of the S solution is transferred to a polyethylene cup, to which 2 mL of freshly prepared solution of 0.1 mol L^{-1} of ammonium molybdate is added and shaken. After resting for 15 minutes, 5 mL of H_2SO_4 1:1 solution is added, then left to rest for 10 – 15 min.

The absorbance is then determined against a blank, with a □ wave length = 410 nm (absorbance A is the logarithm for the 10 base of the ratio between the blank transmittance and the sample transmittance, which is the definition commonly used for absorbance in spectrophotometric analysis), and then compared with the absorbance of a standard silicon solution. Alternatively, a calibration curve may be established. For the analysis conditions described above, using an optic path of one centimeter, the following linear relation between absorbance A and the silicon concentration SC in the analyzed solution S:

$$\mathrm{SC}\ [g\ Si\ L^{-1}] = 0.000534 + 0.1347\ \mathrm{A} \qquad (4.1)$$

For absorbances of up to A = 0.15, the estimated error was less than 5%. Figure B12 shows the position of the sedimentation trap in the water.

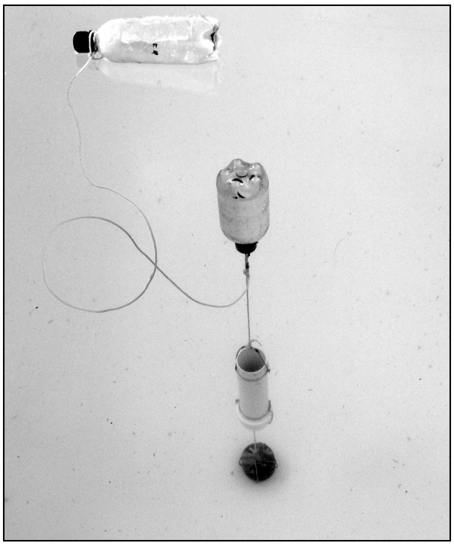

Figure B12: Sedimentation Trap

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