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

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Volume 2 – Modeling

November 2015

IEA
Hydropower
Agreement:

Annex XII

FINLAND JAPAN NORWAY BRAZIL USA FRANCE CHINA AUSTRALIA

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 organizations.

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 modernization 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 as an environmentally desirable energy technology to the worldwide debate.
- 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 2 – Modeling

Member Countries:

AUSTRALIA, BRAZIL, CHINA, FINLAND, FRANCE, JAPAN, NORWAY and USA

November 2015

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Volume 2 – Modeling

ABSTRACT

The present state of knowledge regarding hydropower reservoir GHG emissions contains a large degree of uncertainty and many diverging positions. 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 analyses of net GHG emissions from man-made reservoirs, including 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* and *Volume 2- Modeling* (this document). Volume 2 comprises an executive summary, four chapters and an appendix.

The first chapter gives an introduction and, overview while outlining the need, objectives and scope of this work. A roadmap is offered for use by the hydropower industry and acceptance by the broader community is outlined. The second chapter is devoted to screening the importance of emissions, covering the first-phase of the decision-making process, the development of a predictive screening tool to enable an understanding of the likelihood of high risk of net GHG emissions from reservoirs system. Importantly, for those reservoirs where high net GHG emissions are not expected, additional investigations, monitoring, and studies would not be necessary. The third chapter focuses on modeling activities, bringing the description of general recommended approaches for formulating, calibrating, validating and using models to obtain predictions of net GHG emissions from reservoirs. These cover reservoirs which a screening procedure has clearly shown that high net GHG emissions are expected, or where the risk is unknown or unclear. Chapter 4 on reporting Net GHG emission, covers the way to report the outcomes of the screening and any modeling process, through comprehensive documentation of the data inputs, methodologies and results. The appendix covers the invitation to users of the Guideline to submit examples of their work to the IEA Hydro website. This will provide a collection of ideas on how modelers have approached the determination of estimated GHG emissions and the challenges that may have been faced and overcome.

While these Guidelines are written for hydropower reservoirs, or reservoirs that include hydropower as one of their multipurpose services, the processes that have been documented can, in general, be applied to any reservoir and can affect policy for both water and energy services

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

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EXECUTIVE SUMMARY

This state-of-the-art document, Guidelines for Quantitative Analysis of Net GHG Emissions from Reservoirs (Guidelines), defines procedures and best practices for the modeling of Greenhouse Gas (GHG) Emissions from Freshwater Reservoirs. It provides users with a reference framework for performing quantitative analysis of net GHG emissions and changes in carbon stock. From this reference a sufficient analysis and study to understand the process of GHG emissions from an existing or planned reservoir can be completed.

The Guidelines contain a set of suggested requirements for models and modeling approaches, sourced from the experience of engineers, scientists and academics, and experts from the hydropower industry. This work also provides a roadmap for communicating the science of modeling outcomes in terms that are both appropriate for use by the hydropower industry and acceptable by the broader scientific and engineering community.

One of the prime objectives of the Guidelines is to enable a “big picture” view in the selection of an appropriate GHG modeling approach for a reservoir or series of reservoirs. There are many types of man-made reservoirs globally, though only a small percentage have been developed for or include hydropower facilities. Hydropower reservoirs come in a wide variety of sizes, displaying orders of magnitude differences in surface area, depth, and age. They can vary from huge bodies of water with multiple years of storage capacity to small head ponds for run-of-river projects. Some reservoirs may exhibit high GHG emissions compared with those from the pre-inundation landscape area, particularly in their early years of operation. Other hydropower reservoirs have been measured with emissions on par with natural reservoirs or even as a net carbon sink. The Guidelines roadmap identifies the modeling approach relevant to each type of hydropower reservoir, clarifying that a blanket application of a single emission factor to all reservoirs is not correct as their characteristics can result in vastly different GHG emissions risk profiles. Importantly, for those reservoirs where the potential risk of net GHG emissions is shown to be low, additional investigations, monitoring, and studies may not be necessary. For this reason, the initial data screening approach employs a process to predict emissions that is straightforward but scientifically credible.

The present state of knowledge regarding hydropower reservoir GHG emissions contains a large degree of uncertainty and many diverging positions. To meet this challenge, the IEA Hydropower Implementing Agreement on Hydropower Technologies and Programs (IEA Hydro) initiated a new Annex on “Managing the Carbon Balance in Freshwater Reservoirs”. The objectives of the Annex, executed through a comprehensive work program, are to increase knowledge on processes associated with reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs, and standardize GHG flux evaluation methods.

These guidelines embody a best practice that will assist the reader in measurement, data analysis, and model development of net GHG emissions from hydropower reservoirs. Volume 1, completed in 2012, addressed measurement programs and data analysis, whereas Volume 2 addresses the quantitative analysis of net GHG emissions from reservoirs through modeling.

While these Guidelines are written for hydropower reservoirs, or reservoirs that include hydropower as one of their multipurpose services, the processes that have been documented can, in general, be applied to any reservoir and can affect policy for both water and energy services

1.0 INTRODUCTION TO GUIDELINES

1.1 OVERVIEW

The present state of knowledge regarding hydropower reservoir GHG emissions contains a large degree of uncertainty and many diverging positions. 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”. The objectives of the Annex are to increase knowledge on processes connected to reservoir GHG emissions, establish best practice guidelines for planning studies on the carbon balance in reservoirs, and standardize GHG flux evaluation methods.

The Guidelines provide best practices to assist the reader in performing measurements, analyzing data, and modeling net GHG emissions from multipurpose reservoirs. They have been prepared in two volumes:

Volume 1 – Measurement Programs and Data Analysis, contains advice and procedural recommendations for performing measurement campaigns and data analysis, and for obtaining estimates and quantifying uncertainties of net GHG emissions (IEA Hydro 2012).

Volume 2 – Modeling, provides users with a reference framework for performing quantitative analysis and modeling of net GHG emissions and changes in carbon stock. From this framework readers can undertake sufficient analysis and study to understand the process of GHG emissions from an existing or planned reservoir correspondent to long-term horizons.

It should be noted that a general introduction to the subject of reservoir emissions is contained in Volume 1 of these Guidelines. It is further noted that, as GHG emissions from reservoirs is not limited to those supporting hydropower development, but cover the full range of services that a reservoir can provide, the following text will cover reservoirs in a generic sense.

1.2 GUIDELINE OBJECTIVES AND SCOPE

The purpose of these Guidelines is the development of a state-of-the-art methodology for a quantitative estimation of net GHG emissions from man-made reservoirs. This will provide users with a reference framework for performing quantitative analysis of net GHG emissions, from which they can undertake sufficient analysis and study to understand the process of greenhouse gas cycles at existing or planned reservoirs. The primary objectives are to:

- Provide a reference framework for performing quantitative analysis of net GHG emissions from reservoirs, based on best practices;
- Provide a roadmap to enable the selection of the appropriate GHG modeling process for each reservoir or series of reservoirs. This holistic approach offers guidance from the data screening stage through project planning optimization, where potential impacts and outcomes of the modeling process are used to inform design modifications, operational strategies, or management practices for new or existing reservoir projects;
- Guide the scientific community on modeling processes to address issues associated with reservoir GHG emissions;
- Recommend a set of requirements that models and modeling approaches should follow in order to capture the relevant processes of GHG emissions with adequate accuracy;
- Provide guidance to ensure modeling process outcomes are aligned with the requirements of the end user;
- Facilitate communication of model outcomes in a way that ensures broad uptake and acceptance of the modeling processes.

These objectives will be established and communicated through the application of these *Guidelines* to 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.

The *Guidelines* objectives were created through a comprehensive and collaborative approach that incorporated:

1. Literature Reviews of previous work on reservoir GHG emission modeling;

2. Reviews of the extensive research and modeling carried out in Brazil, as well as in Australia, Canada, China, Finland, France, Japan, Norway, the USA, and through IHA/ UNESCO as appropriate;

3. Workshops with Annex members and contributing parties in Rio de Janeiro, Brazil, Knoxville, USA Rovaniemi, Finland and London, UK, to discuss and draft the guidelines;

4. Identification of and communication with numerous scientists and academics with extensive subject knowledge and engineers well versed in industry practices

5. The collected knowledge of the authors and other contributors;

6 Peer review from an external group of experts.

While these Guidelines are written for hydropower reservoirs, or reservoirs that include hydropower as one of their multipurpose services, the processes that have been documented can, in general, be applied to any reservoir and can affect policy for both water and energy services

1.3 FORMAT AND USE OF GUIDE

The framework for identifying best practices for performing modeling of net GHG emissions from reservoirs is set out in this volume, with a format as follows:

Chapter 1: Introduction and Overview - explains the needs, concepts, objectives and scope of this volume. In addition, a roadmap or pathway for use by the hydropower industry and acceptance by the broader community will be outlined. This chapter will provide the user with an understanding of what these Guidelines on modeling contains and where it will be applicable to the user's needs.

Chapter 2: Screening for the Importance of Emissions– covers the first phase of the decision-making process, the development of a predictive screening tool to enable an understanding of the likelihood of a moderate to high risk of net GHG emissions or removals from a reservoir system. Importantly, for those reservoirs where the potential risk of net GHG emissions is shown to be low, additional investigations, monitoring, and studies may not be necessary.

Chapter 3: Modeling of Net GHG Emissions and Removals from Reservoirs – covers the description of general recommended approaches for formulating, calibrating, validating and using models to obtain predictions of net GHG emissions from reservoirs. Modeling approaches are relevant when a reservoir screening procedure has clearly shown a potential risk of moderate to high net GHG emissions, or where the potential risk is unknown or unclear.

Chapter 4: Net GHG Emission Reporting – covers the way to report the outcomes of the screening and modeling processes through comprehensive documentation of the data inputs, methodologies and results.

Appendix 1: Examples of Models Supporting the Net GHG Approach – covers the invitation to users of these *Guidelines* to submit examples of their work to the IEA Hydro website. This will provide a collection of ideas on how modelers have approached the determination of estimated GHG emissions and the challenges that may have been faced and overcome.

1.4 ROADMAP FOR ASSESSING RESERVOIR NET GHG EMISSIONS

These Guidelines can assist the user to efficiently and effectively identify best practices for modeling net GHG emissions from reservoirs. Furthermore, guidance is provided to enable a “big picture” view and help in the selection of the appropriate GHG modeling process for each reservoir or series of reservoirs. Some reservoirs may exhibit high GHG emissions compared with those from the pre-inundation landscape area, particularly in their early years of operation. The roadmap process will identify the modeling approach that is relevant to each case. Some reservoirs will also have low or insignificant GHG emissions, and some may even be carbon/GHG sinks. For this reason, the modeling approach will start with a screening tool (see Chapter 2). The user should, therefore, consider the relevance of each section of these Guidelines to their particular circumstance and how the guidance applies to their project.

While GHG emissions are seen as low or insignificant at a majority of man-made reservoir sites globally, the means of recognizing the projects where GHG emissions may actually play a significant role should be simple and based on credible science. This includes the processes for data collection and an efficient means to distinguish risk factors (or the absence thereof). Such screening is possible, but can be costly using expert services site by site. The intent is to be able to apply a commonly accepted “GHG screening procedure” that fulfills the required qualities in terms of both science and usability.

The procedure for assessing the net GHG risk in a planned or existing reservoir is illustrated in Figure 1.1. The method is relevant for both the planning of a new project and for assessing the unknown GHG balance of an existing reservoir. The goal of the GHG assessment path, as described in Figure 1.1, is to provide adequate information for an Environmental Impact Assessment (EIA) or a similar administrative purpose (e.g. continuous licensing). The level of risk may be obtained either directly through a credible screening process, if no high GHG emissions are expected, or through a more comprehensive pathway, including comprehensive monitoring, measurement and modeling activities. Ideally, the screening process allows for modification of plans or management of the reservoir, and adaptations for changed conditions.

Since the net GHG impact assessment follows the IEA/Hydro Guidelines Vol. 1 (IEA/Hydro 2012), collection of certain information is essential. The net GHG emission calculation is determined using GHG balances under pre-impoundment and post-impoundment conditions and the estimated impact of unrelated anthropogenic sources (UAS). The latter is actually a part of the post-impoundment, but as noted by the IPCC (SRREN, 2011), the impact of UAS on reservoir GHG emissions should be eliminated. Chapter 3.4 gives guidance on modeling of the UAS impact.

The information required for estimating UAS can be obtained either in the case of planning a new reservoir project or managing an existing one. Most of the information required concerns the land cover, land use activities, population, and industry in the watershed. In the former case the land cover and land use of upstream watershed areas can be determined using modern remote sensing techniques. This would cover the upstream watershed, land cover of the inundation area prior to the impoundment, and human activities that may cause release of nutrients and organic matter to the watercourses from the upstream catchment. In the latter case such information would likely have been obtained for technical planning reasons.

The GHG assessment procedure, or roadmap to decisions thereupon, is described in more detail in Figure 1.1 with numbers referring to respective points in the text.

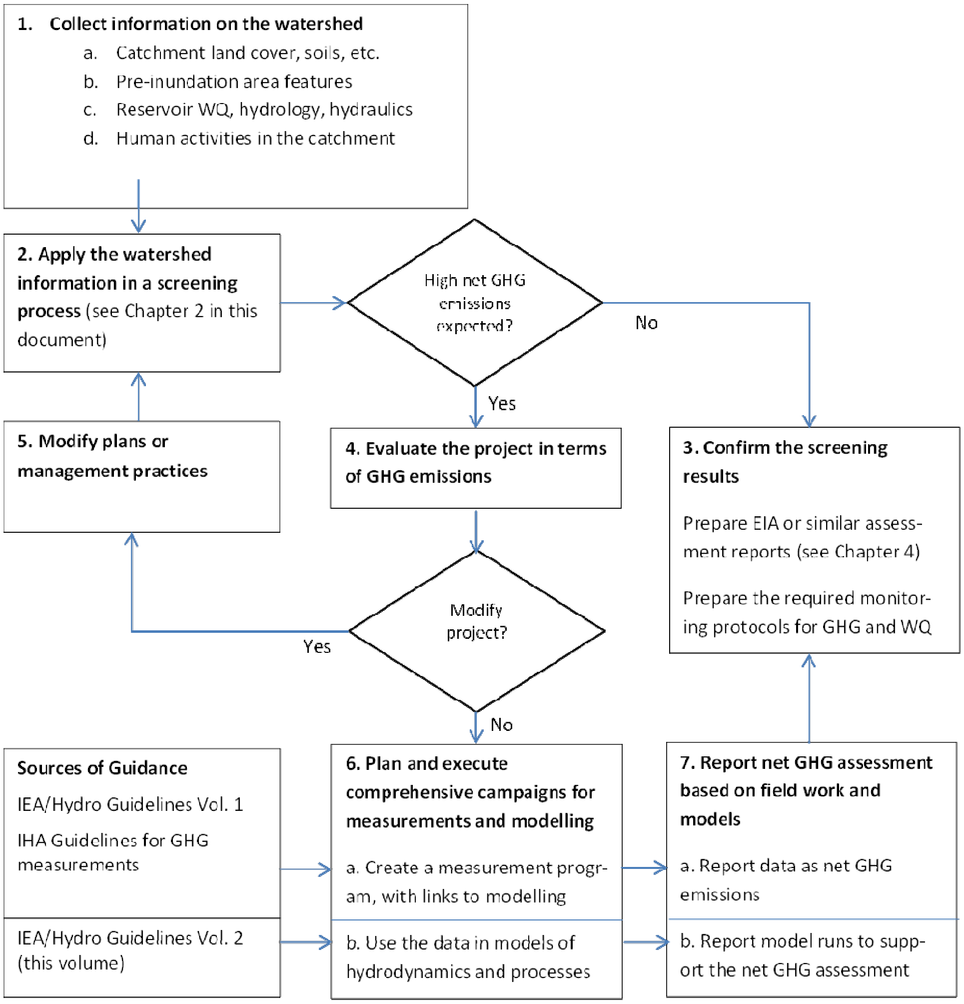

Figure 1.1. A general description of the course of actions in preparing a net GHG emission assessment for EIA or similar purpose. (Numbers in boxes refer to respective points of explanation in text).

1. **Collect information for the screening process and the GHG impact assessment**
    a. *Catchment features*. The factors that have an impact on reservoir GHG balance are those charging the reservoir with nutrients and organic matter, including land cover (forests, grasslands/shrublands, wetlands, open areas etc.), land use (croplands, pastures, settlements, built-up land, mining activities, especially when releasing nutrients or organic matter), and soil types. The catchment physiography and other related information should be well known either in the planning process or for an existing reservoir.
    b. *Pre-inundation area features*. Land cover, area of water bodies (rivers and lakes) and soil types in the area to be inundated, or the area that was inundated when the

reservoir was dammed, should be determined or recovered from historical documents including maps, or old aerial or satellite images. In absence of such data, land cover and land use that very likely occupied the area should be applied. When characterizing the future reservoir, properties such as mean depth, residence time and shape should be estimated.

   c. *Sewage loads from human activities in the watershed*. Diffuse and point source sewage load from population and industry that affect the watercourse nutrient should be estimated.

2. **Apply the information to a screening process (see Chapter 2 of this document)**
   a. Use an appropriate threshold or performance criteria for the determination of high net GHG emission.
   b. If the screening process clearly indicates a minimal risk for high net GHG emission from the new project or an existing reservoir, proceed to use the information collected in 1a, b, c, and the results obtained from the screening process (2), in preparation of an EIA or a similar document and possibly also for planning a monitoring program of GHG emissions and/or WQ (3).
   c. If the screening process indicates a risk for high net GHG emissions to occur, go to (4).
3. **Confirm the screening results**

   Prepare EIA and monitoring protocols as required. The IEA Hydro Guidelines Volume 1 provides a description of net GHG emission assessment. Use that and the information collected for a new project, the results from the screening process, possibly the measured data and model runs, and the framework set by legal bodies, to formulate an appropriate assessment of net GHG emissions. Chapter 4 of this Volume gives guidance on transparent reporting.

4. **Evaluate the new project or existing reservoir in terms of GHG emissions**

   Use the screening results to make decision on whether the net GHG emission risk is high enough to merit modifications to the planning process or reservoir operation. If these modifications are effective, run the screening process again with updated data (5). If eligible modifications are not available, including withdrawal from the project, proceed to formulate a GHG measurement and modeling program, commensurate with the expected GHG emissions (6).

5. **Modify plans of new or management practices for new or existing reservoirs**

   Provide data describing the modified conditions in the features of the catchment, inundation area, and human activities. This can also include modifications to the design and operation of project features. Run the screening process again (2).
6. **Measure and model the GHG fluxes**
   a. The IEA Hydro Guidelines Volume 1 provides guidance for the development of a comprehensive measurement program that supports the net GHG calculation procedure, and the IHA Manual (IHA 2009) provides comprehensive details on GHG measurement techniques and processes.
   b. The IEA Hydro Guidelines Volume 2 provides guidance for the development of new, or modifications to existing hydrodynamics and biogeochemistry models, for use in the prediction of net GHG emissions from planned or existing reservoirs.
7. **Apply the net GHG emission assessment results for new and existing reservoirs**
   a. Report the results of the comprehensive GHG measurement program for the preparation of an EIA or for similar purposes (3).
   b. Use the measured data in 1D, 2D or 3D models, as described in the present document. Report the results of GHG model run for the preparation of EIA or for similar purposes (3).

1.5 DEFINITIONS AND ASSUMPTIONS

Term	**Definition**	**Explanation and Assumptions**
Application of modeling	All reservoirs, existing, under construction and planned	The application covers all reservoirs, including, but not limited to, hydropower.
Flux	Flow of matter, e.g. a GHG species, passing a boundary such as from water to the atmosphere, per unit time and area.	Called efflux or influx depending on the direction of flux. The flux rate may vary daily or seasonally. Relevant unit times from seconds to years in association with processes of interest.
Gas types under	CO_2, CH_4, N_2O	Volume 1 of this Guideline determines the

consideration		relevant GHG's for net emissions and removals calculation.
Gross emissions	Total GHG emissions from a reservoir.	These emissions are measured, calculated or postulated from conditions in the reservoir, also referred to as post-impoundment emissions.
Hydropower	A renewable source of power derived from the energy of falling water	Hydropower can be classified as Run-of-river, Storage hydropower and Pumped storage.
Modeling output	Net GHG emissions expressed as CO_2eq g/m^2/year.	This is considered the most useful way of comparisons between reservoirs and against threshold/performance criteria.
Net emissions	Modification of GHG emissions due to the creation of the reservoir	The contribution of GHG that a reservoir makes to the environment, being the difference between post-impoundment balances of gross GHG emissions and carbon removals, excluding the gross GHG emissions from UAS, and pre-impoundment balances of gross GHG emissions and carbon removals.
Pre-impoundment emissions	GHG emissions prior to the creation of the reservoir.	These emissions are measured, calculated or postulated from conditions in the natural pre-inundated river basin.
Reservoir	A natural or artificial man-made lake, storage pond, or impoundment from behind a dam which is used to store or divert water	Reservoirs may use their storage and diversion capacity and capability to provide multiple services (multi-purpose reservoirs)
Spatial Coverage	The reservoir footprint, the upstream catchment and the river downstream that is influenced.	The screening process will cover just the reservoir footprint.
Stock	Storage of matter within a	Carbon stock in sediment or forest trees and

	body of interest, e.g. sediment, mass per volume.	soil may be important for fluxes after impoundment-
Time frame for GHG fluxes and changes in Carbon budget	100 years, with the assumption of no change in natural and anthropogenic impacts.	This assumption is not likely in reality, but allows for a comparison considered suitable for the pre- and post-impoundment situation as well as with and without UAS.
Unrelated Anthropogenic Source (UAS)	GHG emissions due to inflow of nutrients and carbon from sources unrelated to the reservoir, e.g. sewage, agricultural run-off, forestry waste etc.	It is important to distinguish between natural background and anthropogenic emissions.

2.0 SCREENING FOR THE IMPORTANCE OF EMISSIONS

2.1 INTRODUCTION

There are many types of reservoirs globally, though only a small percentage have been developed for or include hydropower facilities. Hydropower reservoirs come in a wide variety of sizes and can vary from huge bodies of water with multiple years of storage capacity to small head ponds for small run-of-river projects. Each can also have very different geomorphological features in terms of shape and depth. The reservoir shoreline and inundated areas can range from solid bedrock through original forest to swamp and the catchment area can have varied uses, some with significant existing development and others which will be radically affected by the building of the reservoir.

Reservoirs pose a potential risk in terms of net GHG emissions, but there is an extremely wide range of conditions that can affect this potential. In addition to the physical parameters, there is also the influence of extreme events such as floods which, if significant, can carry large amounts of sediment and organic debris into the reservoir. Emissions can also be variable in different climatic zones, different parts of the reservoir, and in different seasons of the year. Emissions can also be affected by UAS such as agricultural waste, industrial effluent and sewage.

Importantly, for those reservoirs where the potential risk of net GHG emissions can be shown to be low, additional investigations, monitoring, and studies would not be considered necessary. For this reason, the approach to predicting emissions starts with data screening using a process that is simple but scientifically credible.

It is extremely important that any screening process includes an understanding of the variables in each particular situation and its inherent limitations (including the use of screening tools). Screening should be based on an assessment of all important variable parameters and on good engineering and scientific judgment.

2.2 SCREENING PROCESS AND CRITERIA

Context

All reservoirs pose some risk of GHG emissions, though in many cases, e.g. projects with a low retention time, this risk is considered to be low to extremely low. Where there is a requirement or desire to evaluate a project in terms of its net GHG emission risk, it is prudent to separate out those projects which do not have a high risk.). Importantly, for those reservoirs where the risk of net GHG emissions can be shown to be low, additional investigations, monitoring, and studies would not be considered necessary.

For this reason, the use of a screening process can be very useful in providing an appropriate approach for the determination of those projects not having high risk exposure for net GHG emissions. The decision-making process is shown in Figure 1.1. The fundamental requirement of a screening process is to enable decision-making on the likelihood of a high risk of net GHG emissions from a reservoir system. This in itself will provide regulatory agencies, financing groups and developers with confidence on the way forward and will help guide sustainability practices.

Best Practice Guidelines:

A. ***The screening of reservoirs should determine the risk of net GHG emissions***
B. ***Screening of reservoirs should be based on a risk assessment process.***
C. ***The screening process should be appropriate for assessment of both existing reservoirs and the development of new schemes.***
D. ***Screening outcomes should include criteria to classify net GHG emission risk levels.***
E. ***Where the screening of a reservoir indicates a high risk of net GHG emissions, further evaluation and analysis should be undertaken.***
F. ***The screening process should be acceptable to reservoir owners, regulators and stakeholders.***

Commentary

A. The screening of reservoirs should determine the risk of net GHG emissions

The primary purpose of screening is to determine the risk of GHG emissions and whether the level of risk warrants more detailed investigation and analysis. Other purposes include:

- The need to better understand the net balance of GHG emissions.
- An appraisal of the level of emissions from new and existing reservoirs, as an initial step.
- The ability to undertake a rapid assessment of the GHG emissions from reservoirs
- For multipurpose dams, providing a balanced way of allocating net emissions from the reservoir system to the range of energy and water services that the reservoir provides.

B. Screening of reservoirs should be based on a risk assessment process.

The screening process should be based on a risk assessment approach. This will include the pre-conditions that signal environmental issues which could lead to moderate to high GHG emissions, and the methodologies that would lead to their determination. It should also highlight and identify factors which may increases GHG risks for reservoirs. This process will enable assessments to be made against criteria of moderate/high or low potential of GHG emissions.

Screening methodology should be developed that meets the requirements of the screening process, based on a risk assessment process. The risk criteria for this development and use should include:

- A simple methodology for determining net emissions of GHG associated with a reservoir system based on parameters that do not require fieldwork.
- Simple and easy to use processes, requiring low levels of onsite measurement of potential contributory factors.
- Robust and independently verifiable results for reservoirs across all geographic regions.
- A net result consisting of an assessment of post-impoundment minus pre-impoundment emissions minus an estimate of UAS.
- Datasets of catchment and reservoir properties.
- A threshold or performance criteria for GHG emission risk.
- Identification of reservoir systems which are at risk of high GHG emissions and will therefore require further detailed modeling, monitoring or mitigation.

Net GHG emissions cannot be observed or measured directly, they need to be estimated using a risk based approach as the basis of the screening process and include the following components:

- *Pre-impoundment emissions* - based on the source of emissions from the reservoir basin before the reservoir was in place and including consideration of the land-use patterns, existing water bodies and other relevant activities.
- *Post-impoundment emissions* - based on the emissions due to reservoir impoundment, which may be referred to as ‘gross emissions’ and cover the reservoir and downstream reaches.
- *Unrelated anthropogenic sources* - based on the component of the overall emissions caused by processes beyond the control of the reservoir/basin, including activities which increase the nutrient loading of the upstream water course and hence reservoir emissions.

Consideration should also be given to the allocation or apportionment of the net emissions from the reservoir systems to the energy and water services that the reservoir supplies. These services could include hydropower, irrigation, flood control, water supply, navigation, recreation, etc.

C. The screening process should be appropriate for both assessment of existing reservoirs and the development of new hydropower or multi-purpose schemes.

The screening process needs to be flexible enough to enable decisions on the likelihood of a potential risk of net GHG emissions from either an existing reservoir system or a proposed development of a new reservoir system. This will provide regulatory agencies, financing groups and developers with confidence on the way forward. For existing schemes, this is especially pertinent at the time of hydropower re-licensing, and for the development of new schemes, will allow appropriate design input.

The screening process should also cover reservoirs that provide multipurpose services. The process is shown on Figure 1.1.

D. Screening outcomes should include criteria to classify net GHG emission risk levels

The screening process should provide clear guidance in terms of the net GHG emissions risk levels, based on classification criteria. These criteria should be based on units of CO_2eq g/m^2/year and CO_2eq tons/year from the inundated area.

The screening process and criteria should be developed to a level of confidence sufficient to enable decision-making in terms of separating between two categories:

1. Projects that clearly have minimal risk for high net GHG emissions, and
2. Projects where there is a risk of high net GHG emissions, or where the risk is unknown or unclear.

For Projects in Category 2, and where eligible modifications to the reservoir design or operation are not feasible, including withdrawal from the project, a program of further study should be initiated. This could include the formulation of a GHG measurement, monitoring and modeling program, commensurate with the expected net GHG emissions. This is covered in Chapter 3 of these Guidelines.

E. Where the screening of a reservoir indicates a high risk of net GHG emissions, further evaluation and analysis should be undertaken

The outcome of the screening process will be sub-divided into three categories:

1. *Reservoirs that clearly have minimal risk for high net GHG emissions.* These reservoirs will not require any further analysis for GHG emissions.
2. *Reservoirs that clearly have a risk of high net GHG emissions.* This category will cover projects where high risk of net GHG emissions has been already confirmed or is strongly anticipated. For these reservoirs, a comprehensive research program with data collection and monitoring should be established, followed by modeling of hydrodynamics and biogeochemistry of the reservoir. The screening process should also identify, wherever possible, the conditions and characteristics that lead to high risks.
3. *Reservoirs where the potential risk is unknown or unclear.* This category will cover projects with insufficient data to run the screening process. In these cases a limited program of data collection will be required in order to determine the risk level.

The screening process is indicated in Figure 1.1. The scale of the research program will depend on the following parameters:

- The net GHG emissions estimated and risk factors indicated by the screening process;
- The size and complexity of the reservoir, including bathymetry and shoreline morphology;
- The expected influence of floods and extreme events;
- Water quality focusing on concentrations of nutrients and organic matter in reservoir inflows (these parameters can fuel the anoxic methane engine); and
- Comparison with data sets for other reservoirs in the region.

The data thus obtained will be used as input to models implemented to address the hydrodynamics and biogeochemistry of the reservoir. To ensure consistency and transparency in the functionality of the screening process, the basis and methodology of its use should be contained in an easily accessible and readable User Manual. This manual should be comprehensive, transparent in terms of source of information, unambiguous, structured and adapted for targeted end-users.

F. The screening process should be acceptable to reservoir owners, regulators and stakeholders

The screening process should be based on the risk potential of net GHG emissions and provide a straightforward approach for estimating the risk of net GHG emissions from a reservoir system. This will allow the identification of reservoir systems which are at risk of high net GHG emissions that will require further detailed measurements, study, modeling, monitoring and mitigation. By using the latest research and data available, it should be possible to improve the quality of data when updating the screening process and incorporating relevant variables.

3.0 MODELING OF NET GHG EMISSIONS AND REMOVALS FROM RESERVOIRS

3.1 CONCEPTIONS FOR GHG MODELING

3.1.1 Introduction

Reservoirs planned for the development of water resources in a river basin are not built at the same time. Anytime a reservoir is built and filled, part of the valley terrain environment is replaced by an inundated area, and a new regime of GHG fluxes is established, including those between the reservoir surface and the atmosphere and those due to permanent carbon burial rates. The new regime can include: the diffusive and ebullitive GHG fluxes across the new air-water interface corresponding to the reservoir area; the new regime of permanent carbon burial rate established at the reservoir sedimentation zone; the GHG emissions from water discharged downstream through outflows structures due to abrupt changes in the hydrostatic pressure ("degassing"); and the modified GHG fluxes across the air-water interface in the downstream reach due to changes in concentrations of dissolved gases in the downstream water releases.

The new GHG emissions and permanent sedimentation rates regime which appears after the filling of a specific reservoir is influenced by the decomposition of flooded biomass and organic matter stored at the inundated area at the time of the reservoir filling and this influence persist until the decomposition of this material is still significant. The new regime will also depend on process occurring in the reservoir upstream watershed. In the upstream watershed, carbon- and nitrogen-containing compounds collected by the drainage network are conveyed through the river system to the new reservoir where microbial activity eventually converts them to GHG. In general, any upstream anthropogenic activity which contributes to the concentrations of carbon- and nitrogen-containing compounds in reservoir inflows will determine GHG emissions to a certain extent[1].

In order to improve predictive capability on the changes in GHG fluxes and in permanent sedimentation rates induced by reservoir construction inside river basins, the complexity of physical, chemical and biological processes before and after the impoundments are represented in simpler manners by models where only relevant phenomenon features and processes are included. This chapter covers the description of general recommended approaches for formulating, calibrating, validating and using models to obtain predictions of net GHG emissions from reservoirs.

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[1] Upstream anthropogenic activities not related to the reservoir which induces GHG emissions at the reservoir has been defined in Volume 1 as Unrelated Anthropogenic Sources.

3.1.2 General Procedures for Modeling

Context

Modeling is not a straightforward activity. The approach to be adopted in any situation will depend strongly on the objectives of the analysis and available data, among other factors. On the other hand, there are general procedures that should be adopted when choosing the most appropriate modeling approach for assessing the GHG status of man-made reservoirs.

Best Practice Guidelines:

A. The adopted modeling approach should be appropriate to the type of analysis.

B. Predictions of post-impoundment emissions can be obtained with simulations of mechanistic models whereas predictions of pre-impoundment emissions can be obtained using emission factors.

Commentary

A. The adopted modeling approach should be appropriate to the type of analysis.

Building reservoirs in a river basin introduces a new regime of transformations, transport and storage of chemical species, including carbon- and nitrogen-containing compounds, at the different portions of the valley from that prevailing before the impoundments. These modifications yield a new regime of GHG fluxes between surface and atmosphere and of permanent carbon burial rates all over the basin. In the pre-impoundment period, before reservoirs existed in the river basin, upland vegetation comprised a net CO_2 sink or source, depending on the stage of vegetation succession. The surface soil/peat layer cover could temporally and spatially make them net CO_2 sinks; the flood plains acting as sources of CH_4 with permanent carbon burial. In the lakes, substantial permanent carbon burial could occur. The river reaches and streams, transporting water and sediments, were constantly producing GHG's as a result of microbial community activity.

Reservoir managers may already use hydrodynamics models that are adapted to their specific conditions and technologies. In addition to water management procedures, some of those models may address most important water quality measures such as oxygen saturation and nutrient concentration in the water body. On the other hand, some very simple models cannot be coupled to modules simulating biogeochemical processes.

For detecting a situation with potential for high GHG emissions, even the simplest correlation models should be able to indicate at least emergence of hypoxic conditions in the reservoir. Methane is considered as the most important GHG species emitted from reservoirs and is formed under strictly anoxic conditions (e.g. Bastviken 2009). There may be a positive relationship between methane emission and total P or N concentration in water (Huttunen et al. 2003). Similarly, DOC content and super-saturation of CO_2 in water and net CO_2 emission (net heterotrophy) may be related (Huttunen et al. 2002, Kortelainen et al. 2006). Long retention time in certain parts of the reservoir may be associated to development of local oxygen deficiency and potential CH_4 release.

A zero or one-dimensional model of key biogeochemical processes leading to significant GHG emissions can be useful as a primary screening tool. Such a model can be run with varying sets of parameters in order to identify the sets of conditions when oxygen deficiency may appear and launch GHG emissions. A screening model may also be based on a priori collected database of observed GHG fluxes, environmental conditions, geographical location, and other relevant properties of reservoirs. A 2D model can be configured to follow either for depth – longitudinal (2DV) approach, or lateral – longitudinal (2DH) approach.

The observed or expected stratification of the reservoir may encompass the selection of the approach. Reservoirs with thermal stratification may require 2DV models. Models of different complexity can be used to solve different tasks. While simple deterministic models work in static conditions, increasing dimensionality adds model´s capability to adapt to varying conditions. Although modern technologies allow for running complicated 3D models such as general circulation models, e.g. those used in weather and climate predictions, models should be selected according to the scale of the problem to be solved. Basic reservoir GHG emission modeling may not need the most complex models.

More complex models may detect developing eutrophication. Oxygen can be consumed via chemical and biological pathways. Some chemical conditions such as the presence of sulfate as an alternative electron acceptor may suppress methanogenesis (see Thauer 2011). Eutrophication may lead to increased occurrence of hypoxia and CH_4 emissions (Huttunen et al. 2003, Juutinen et al. 2009, Martinez and Anderson 2013). However, H_2S and CH_4 have been observed to co-exist in anoxic bottom waters of reservoirs (Ruane 1993). Maintenance of eutrophic conditions initially requires that both organic carbon and nutrients are available in excess. Ultimately when eutrophication proceeds beyond a certain point, an internal nutrient cycle may be established (e.g. Numburg and

Peters 1984, Correll 1998). In those conditions, active heterotrophic consumption of oxygen leads to hypoxia, and the phosphorus sedimented in dead organic matter dissolves under anoxia and gets released as PO_4. Consequently, algal blooms may occur (Smith 2003) leading ultimately to further sedimentation of organic matter and oxygen deficiency (Anderson & Garrison 1997).

B. Predictions of post-impoundment emissions can be obtained with simulations of mechanistic models whereas predictions of pre-impoundment emissions can be obtained using emission factors.

Applications of mathematical mechanistic models can provide reliable predictions of post-impoundment fluxes if proper modeling procedures are adopted. General model building procedures are given in the following items of this chapter; whereas Chapter 3.3 provides more detailed guidance on recommended procedures for this type of models.

While there are some reported experiences on extending mechanistic hydrodynamic/water quality models with process to simulate exchanges of GHG with the atmosphere, no attempt has been reported of including landscape-atmosphere GHG exchanges in existent state-of-art physically-based watershed simulation models. The standard procedure for obtaining estimations of post-impoundment emissions is to use indirect estimations based on mapping the use of the soil before impoundment and the appliance of emission factors. Chapter 3.3 provides detailed guidance on recommended procedures for obtaining post-impoundment emissions estimations.

3.1.3 Conceptual Model for Net GHG Emissions and Removals

Context

Volume 1 of these guidelines has defined net GHG emissions for man-made reservoirs 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”. In order to make quantitative analysis considering this definition, a conceptual model of a reservoir has been developed which is a starting point for building models to predict reservoir GHG status.

Best Practice Guidelines:

A. The conceptual “net” model should be used as the basis for building models to aid in man-made reservoir GHG status assessments.

Commentary

A. The conceptual “net” model should be used as the basis for building models to aid in man-made reservoir GHG status assessments.

The conceptual model presented in Volume 1 focuses on the modifications occurring in the reservoir area and its vicinity[2] by taking into account the following GHG flux pathways both before reservoir construction and during reservoir operation:

- GHG emissions and removals occurring in the reservoir area;
- Simulate the role of chemicals involved in the process;
- Permanent carbon burial rate occurring in the reservoir area;
- Degassing during the passage of water through outlets[3]; and
- GHG emissions in the river downstream of the dam (tail-water) for some considerable distance.

In general, Volume 1 lists fluxes of CO_2, CH_4 or N_2O between surface and atmosphere and permanent carbon burial rates occurring in different components of the system (see Figures 1 to 3 in Volume 1). These fluxes and rates were assembled as parcels in equations to assist obtaining reservoir net GHG emissions estimates. The set of equations represents the balance of GHG emissions and removals. The equations cover both pre-impoundment and post-impoundment conditions, including the post-impoundment emissions attributed to anthropogenic sources unrelated with the reservoir, which should be discounted. Modeling efforts should consider the parcels of the equations in Volume 1.

3.1.4 Prediction Uncertainty Analysis

Context

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[2] The concept model can be extended to assess also modifications inside broader areas in the whole river basin which can be appropriated for assessing GHG status of sets of cascaded reservoirs.

[3] Degassing only occurs during reservoir operation.

Models can be built to provide long-run values of GHG fluxes between surface and atmosphere and permanent carbon burial rates in a valley considering the situations with and without a reservoir so that predictions of the reservoir net GHG emissions can be obtained. Uncertainty inherited in most model´s prediction efforts derives from unpredictable natural forcing functions (e.g., wind, rain, temperature) to which the system will be submitted over the long term. It also includes assumptions and approximations adopted for the mathematical description of physical and biogeochemical processes involved, parameter setting uncertainties, imprecise boundary conditions descriptions and numerical errors in the solution algorithm. Moreover, prediction uncertainty analysis is also fruitful during the model development stage in identifying key factors most influential for model predictions and of the associated efforts that should be made to pursue accurate predictions. Prediction uncertainty analysis should include its communication.

Best Practice Guidelines:

A. Modeling studies for prediction of GHG emissions of multipurpose reservoirs should also include an analysis of the prediction uncertainties.

B. Reports of modeling predictions of GHG emissions of multipurpose reservoir should include two-sided 95% confidence interval.

C. Uncertainties associated with the predictions of net emissions resulting from the application of the models must take into account the uncertainties in the predictions of post-impoundment and of pre-impoundment emissions.

Commentary

A. Modeling studies for prediction of GHG emissions of multipurpose reservoirs should also include an analysis of the prediction uncertainties.

Results obtained through the application of predictive models exhibit varying degrees of uncertainty. Part of the uncertainty reflects the imprecision of data used in model calibration/validation, as well as the validity of model assumptions and simplifications, especially beyond the conditions on which the model was calibrated and validated. Even if calibration/validation data fulfill precision requirements and include a broad range of conditions, uncertainty in model predictions may come from random terms explicitly included in the model to represent non-modeled factors, as it is the case in empirical regression models. In mathematical mechanistic model applications, uncertainty is also present in the natural forcing functions (ex: inflows and wind) used as input data when calibrating models for the prediction period. These natural forcing functions usually contain substantial amount of randomness, inducing uncertainty in model outputs. To have a proper assessments of the status of GHG emissions from multipurpose reservoirs, modeling studies should include an analysis of the prediction uncertainties (Beck, 1987).

B. Reports of modeling predictions of GHG emissions of multipurpose reservoir should include two-sided 95% confidence interval.

Predicted values of GHG emissions of multipurpose reservoirs are better appraised if their report is done together with a measure of its uncertainty. The best practice is to add to each individual prediction a two-sided confidence interval, bracketing the predicted value between a lower bound and an upper bound range among which the true GHG emission is likely to lie with great confidence. The choice of the confidence interval should reflect a high likelihood that the true GHG emission will indeed lie between the upper and lower bounds. These guidelines recommend choosing 95% as the confidence level.

Two-sided 95% confidence intervals can be reported simply using (LB, UB), where LB is the lower bound and UB is the upper bound. Symmetrical two-sided 95% confidence interval can be reported as:

$$\hat{x} \pm 1.96\, u(\hat{x}) \qquad (1)$$

Where:

$\hat{x}$ is the prediction of the true emission value x, and

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

Estimates of confidence intervals for statistical model predictions can be obtained from appropriate procedures based on deviations between model predictions and data. These deviations should be used to check assumptions and evaluate model properties.

Estimates of confidence intervals for mechanistic model predictions are typically obtained by varying forcing inputs and/or parameters multiple model runs. A sensitivity analysis will identify the most influential factors or combination of factors which should be used to set the upper and lower bounds of modeled emission rates.

C. Uncertainties associated with the prediction of net emissions resulting from the application of the models must take into account the uncertainties in the predictions of post-impoundment and of pre-impoundment emissions.

By definition, net emissions are the difference between post-impoundment emissions and pre-impoundment emissions. Calculation of prediction uncertainty must take into account the uncertainties in predictions of post-impoundment and of pre-impoundment emissions. Predictions for post- and pre-impoundment emissions can be considered approximately uncorrelated so that standard uncertainties can be combined with:

$$u(\widehat{NET}) = \sqrt{u(\widehat{POS})^2 + u(\widehat{PRE})^2} \qquad (2)$$

Where:

$u(\widehat{NET})$ is the standard uncertainty of the net emissions prediction,

$u(\widehat{POS})$ is the standard uncertainty of the post-impoundment emissions prediction, and

$u(\widehat{PRE})$ is the standard uncertainty of the pre-impoundment emissions prediction.

3.2 ESTIMATING AND MODELING PRE-IMPOUNDMENT EMMISIONS

3.2.1 Introduction

One of the main impacts of the creation of a reservoir is the inundation of land containing natural ecosystems such as lakes, rivers, forest, grasslands, marshes, and land managed for agriculture, settlements or other use. In order to calculate a net greenhouse gas emission following the creation of a reservoir, and to model it properly, the sum of GHG fluxes (source and sinks) from natural ecosystems must be calculated or estimated. Pre-impoundment emissions may be measured or derived from literature. In this chapter we give guidance on how to model or estimate emissions prior to impoundment of the reservoir.

At the global scale, land surfaces may represent a mosaic of carbon sink and carbon source, and the inundation of land to create a reservoir may modify those carbon dynamics. In many cases it is difficult to calculate or estimate the pre-impoundment GHG exchanges, especially in existing reservoirs where no pre-impoundment mapping, analysis or relevant measurements were done. It may also be very challenging to estimate the changes in carbon storage. Generally, building a dam on a river would reduce water velocities and increase sedimentation rates, including the sedimentation of organic matter and carbon. The net emission of GHG requires an estimation of the sources of carbon and to keep track of the displacement of emissions. In many catchments the sources of carbon will come from upstream forests. Prior to inundation, GHG emissions resulting from upstream carbon sources would occur in the downstream river, while the same emission may occur from the reservoir when inundated. This displacement of emissions must be correctly accounted through the net emissions concept.

Another reason to address and model the landscape elements in the inundated area is that the post-impoundment GHG emissions and removals depend on the situation in aboveground biomass and the carbon stock in the soil of the area to be inundated, as the inundation would also mobilize carbon, GHG and nutrients in the soil. Organic matter that was stored on land over decades and centuries may lead to the release of nutrients and GHG after inundation. This *trophic upsurge* caused by flooded biomass and soil is known as a "GHG boost" in the early years of a new reservoir (Tremblay et al. 2005). Less degradable biomass such as large tree trunks will probably degrade over a century or even longer (Guyette et al. 2008, Arsenault et al, 2012). As in the case of natural lakes, reservoirs reduce water flows and increase particle and carbon sedimentation, which should be taken into account (Teodoru et al. 2012).

This guidance complements the pre-impoundment assessment as outlined in the IEA Guidelines Volume 1, and expands the commentary on modeling of the relevant GHG fluxes, carbon stock changes and nutrient loads. The purpose is to cover the aspects necessary to collect information for the modeling of the net GHG emissions and calculation of the net impact of creating a reservoir.

3.2.2 Systems Boundaries and GHG Fluxes in the Pre-Impounded System

Context

In order to assess the net greenhouse gas emissions from a reservoir, we first need to estimate the sum of all GHG fluxes of the different natural terrestrial and aquatic ecosystems and managed land that were or will be affected by the inundation of the reservoir. The net change in the catchment's GHG balance is calculated by subtracting the pre-impoundment emissions and the emissions caused by unrelated anthropogenic sources from the post-impoundment emissions. For this purpose, the status of the downstream reaches prior to inundation should also be known. In the mass balance calculation, emissions from the ecosystem to the atmosphere (e.g. decay of organic matter as CO_2 or CH_4 have positive signs and removals from the atmosphere (e.g. sequestration of atmospheric CO_2 by photosynthesis) are negative. The gases to consider are CO_2, CH_4 and N_2O as previously described in these *Guidelines*. Therefore, the main concern should be on processes affecting carbon and nitrogen transport and storage. GHG can be emitted through three pathways: diffusion, ebullition and degassing. In natural ecosystems, generally the first two are present; degassing may be occurring in some specific aquatic systems.

Best Practice Guidelines:

A. The landscape should be divided into three distinct areas; the area upstream of the reservoir, the area to be inundated and the area downstream affected by the reservoir.

B. The net balance of emissions and removals of GHG in terrestrial and aquatic systems of the area to be inundated should be determined.

Commentary

A. Landscape should be divided into three distinct areas.

1. Area Upstream of the Reservoir

The upstream area consists of the catchment feeding to the existing or planned reservoir. The upstream area of the catchment (part 1 of Figure 3.1) excluding the maximum impoundment area within the catchment), should exhibit a negligible change in carbon dynamics due to impoundment. However, sources of carbon or nutrients entering the impoundment or downstream reaches from upstream could change the net GHG emissions of the reservoir or the downstream reaches. This aspect will be discussed in Sub-chapter 3.4 of this Volume. It is assumed here that the GHG exchange between the terrestrial and aquatic components of the upstream catchment, including those related to human activities, remain the same prior to and after impoundment of the reservoir. Therefore, the balance of the upstream catchment is regarded as zero in the pre-impoundment GHG calculations, while the GHG balances of the area to be inundated are addressed more accurately.

2. Area to be inundated

For the purpose of assessing net GHG emissions, the inundation area can be schematically divided in three compartments: Water bodies, floodplain, and higher uplands. The water body compartment includes all aquatic ecosystems that remain aquatic systems throughout the year, such as river reaches, streams and lakes. The floodplain compartment corresponds to the inundated area where the soil is either flooded or saturated only during high flow periods, and the upland compartment covers the terrestrial part of the inundated area (IEA Guidelines Volume 1, 2012). It may prove convenient to further subdivide any of the above three compartments in order to better represent its heterogeneity in the inundated 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.

3. Area downstream of the impoundment affected by the reservoir

Downstream reaches denote the part of the river where the reservoir, either existing or planned, affects the carbon dynamics. IEA Guidelines (Volume 1, Ch. 4) gives guidance on the variables to be measured for the downstream reaches.

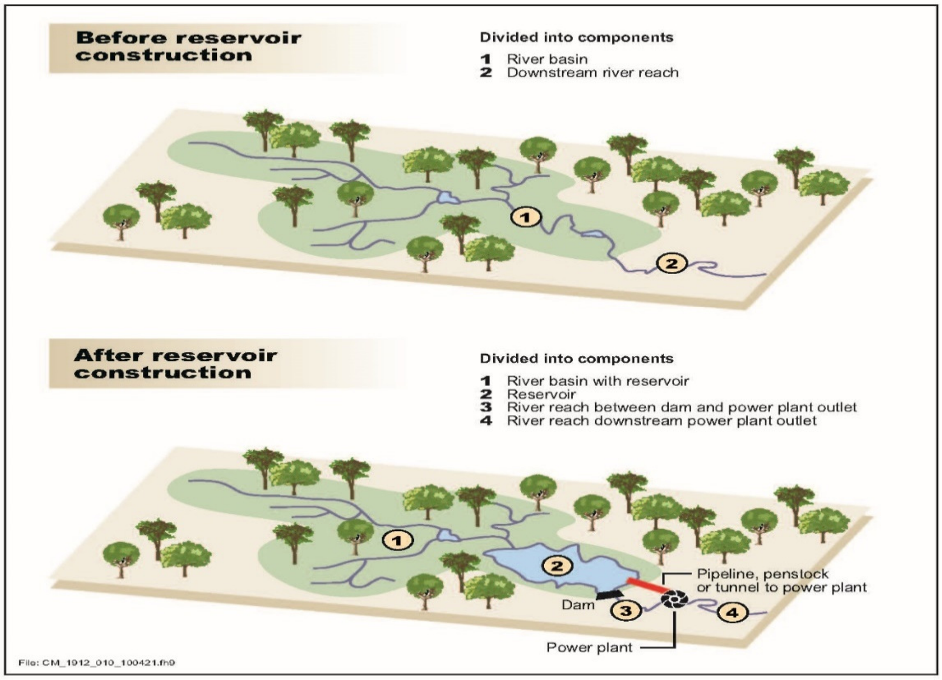

Figure 3.1. Conceptual image of the catchment before and after the reservoir construction.

B. The net balance of emissions and removals of GHG in terrestrial and aquatics systems of the area to be inundated should be determined.

Terrestrial components

Terrestrial areas are composed of forest, grasslands, temporary or permanent wetlands such as peatlands, bare areas, rural or urban settlements or agricultural areas such as croplands and pastures. Soil types may range widely from mineral or organic, and wetlands may be pristine or drained for exploitation in agriculture, forestry or other land use.

The main source of carbon in the GHG balance of terrestrial ecosystems is atmospheric CO_2 that is fixed by plants during photosynthesis for primary production of organic matter. GHG emissions in terrestrial environments are dominated by CO_2, CH_4 and N_2O. A large proportion of CO_2, annually sequestered in photosynthesis, is released by means of respiration of the autotrophic organisms, and aerobic or anaerobic decomposition of dead organic matter.

Fluxes of CO_2 are expressed as the net ecosystem exchange (NEE), which represents the balance between CO_2 uptake through photosynthesis and release through total ecosystem respiration at a given moment in time. Net ecosystem productivity (NEP) represents the annual carbon stock change for a specific location, and should include losses of carbon in CH_4 fluxes, from forest fires and insect outbreaks, as well as dissolved organic carbon (DOC) export. In the following, the special features of the most important terrestrial compartments are outlined.

Forest

Forest component is typically a significant sink of carbon. A net increase in forest biomass means removal of carbon from the atmosphere. As plants die or renew their belowground parts, some of the carbon ends as soil organic carbon stock, maintaining the forest carbon removal rate in the long-term. Mineral forest soils do not emit CH_4, they rather constitute a small methane sink. Carbon accumulation in mineral forest soil is a slow process. For studies covering only a few decades or time spans comparable to the forest regeneration cycle, the mineral soil carbon stocks may be assumed static in the calculation of pre-impoundment GHG balance.

Organic forest soil carbon stocks may also be disturbed by land use. Organic rich soils such as peatlands are typically formed in moist conditions, accumulating the necromass of plants adapted to grow in wet, oxygen-poor conditions. Disturbance of organic soils by drainage may change the GHG balance from net removal to net emission by exposing the soil to oxic decay, but strong CH_4 oxidation may also occur in dry organic soils. Peatlands have been drained for improving the forest growth. Drainage or organic soils may in some cases create a source of N_2O. Drainage also causes increased oxidation of soil organic matter and increases CO_2 emissions, and CH_4 emissions may occur from drainage ditches (see IPCC 2013). Similarly, above ground biomass and its GHG fluxes should be estimated. National or regional forest inventories could be used to assess this component.

Peatland

Undrained peatlands may be a significant source of CH_4, where also permanent carbon burial may occur at a significant rate. Those fluxes may be important in the pre-impoundment GHG balance of the inundation area. Ponds within peatlands could also be sources of both CO_2 and CH_4, either through diffusion or ebullition and should also be accounted for. Un-drained or drained peatlands have very high organic carbon stocks belowground that may be important in shaping the post-impoundment GHG emissions. Peatlands have been drained mostly for reclaiming area for forestry or agriculture. Peat has been extracted in many parts of the world for production of energy or growing media. Drainage of peat extracting areas causes a permanent release of CO_2 and CH_4. A review of published data and emission factors concerning carbon accumulation and CH_4 emission in natural un-drained, re-wetted or drained peatlands are available in the IPCC 2013 Wetland Supplement (IPCC 2013).

Cropland

Due to fertilizer use, croplands may be significant sources of N_2O and play a significant role in the export of carbon and nutrients to the downstream catchment. Organic soils may have been drained for crop production similar to forestry. Drained organic soils in agriculture are known to emit large amounts of CO_2 and N_2O. Emission factors for organic rich croplands can be found from the IPCC 2013 Wetland Supplement (IPCC 2013).

Pasture

Natural grasslands or shrublands may be used as pastures in dairy production. Ruminants emit CH_4 by enteric fermentation or from dung, forming a part of the net GHG balance in the pre-impoundment landscape. While the grassland soil GHG balance may be close to zero, enteric fermentation of ruminants and anaerobic decay of dung cause CH_4 emissions. Emission factors per head of different ruminant species of methane can be found from the IPCC 2006 Guidelines Chapter 10 (IPCC 2006).

Aquatic components

Although streams may represent a small surface area at catchment scales, they contribute to a large proportion of the ecosystem emissions and should be assessed adequately (Teodoru et al. 2009, Cole et al. 2007). Lakes have longer water residence time than rivers, favoring particle and carbon sedimentation and nutrients retention, which should be accounted for (e.g. Ferland et al. 2011, Teodoru et al., 2011). These aquatic systems can be a source of CO_2 relative to the atmosphere, emit CH_4, or act as a sink of carbon to the sediments according to the water residence time, productivity of the system and other parameters. There are published data on CO_2 and CH_4 emissions from natural lakes (e.g. Bastviken et al. 2004; Sobek et al. 2007, Therrien et al. 2005), and from rivers and streams (e.g. Campeau et al. 2014, Weyhenmeyer et al. 2012, Bouillon et al. 2012; Teodoru et al. 2009, Guérin et al., 2006; Richey et al., 1988, 2002). They should be included as aquatic components in the calculation of net GHG balance of the inundated area.

3.2.3 Estimation of the Pre-Impoundment GHG Exchange

Context

Sources of information on terrestrial ecosystem GHG exchange include direct measurements or in absence of measurements, representative literature data, national forest inventory statistics, global emission factors for managed land cover in different climatic zones (IPCC 2006, 2013). High resolution maps and satellite images could be combined to estimate surface areas of all relevant land cover and land use types. Models computing GHG emissions from cropland systems or forests have been developed (Colomb, Bernoux, et al. 2012), but none of the models cover all land cover or land use categories alone. Modeling of the landscape GHG exchange has to employ multiple tools, with a potentially large number of parameters and combined uncertainties. Because of the complexity in modeling the landscape GHG fluxes, a simplified approach using annualized emission factors is recommended for the basic purpose.

Together with the terrestrial landscape elements, the annual contribution of the aquatic components in the GHG exchange within the inundated area should be estimated. Complex models should include transport of carbon, nutrients and dissolved GHG species in the aquatic components. For the basic net exchange GHG calculations, the flux rates of rivers, streams and lakes can be derived from direct measurements or from sources in the literature (e.g. Bastviken et al. 2004; Sobek et al. 2007, Therrien et al. 2005, Campeau et al. 2014, Weyhenmeyer et al. 2012, Bouillon et al. 2012). A simple regression equation model can be used to estimate CH_4 emissions (Bastviken et al. 2004). Current advancements in modeling point out the complexity in biogeochemistry in freshwater lakes or reservoirs, including transport of carbon (Hanson et al. 2011). While there has been advances in understanding and modeling of the processes behind the lake energy balance and GHG exchange (Subin et al., 2012), major work is still going on, aiming to integrate all landscape elements, their management and their combined impact on the GHG exchange. The international flux tower network FLUXNET (fluxnet.ornl.gov) provides a useful source of data in large spatial scales.

Best Practice Guidelines:

A. Loading of carbon and nutrients released naturally or by human activities from upstream and entering area to be inundated should be evaluated.

B. The impact of reservoir on the downstream watercourse should be evaluated.

Commentary

A. Loading of carbon and nutrients, released naturally or by human activities and entering the impoundment area from upstream should be evaluated.

Land cover and land use in the upstream catchment are relevant for estimating the pre-impoundment loads and GHG emissions from the aquatic part of the pre-impoundment area. A large portion of the organic matter, released by decomposition in the upstream catchment will naturally pass through the freshwater systems, as water transports the degradable carbon from the forest soil to the ocean. On the way to the ocean, about 40 per cent of the carbon will be emitted to the atmosphere as CO_2 (Cole et al 2007). Some carbon will also be stored in the sediments of rivers, lakes, reservoirs and wetlands, while the rest are transported to the ocean. These processes contribute to the natural background GHG emissions, but depending on the properties of the reservoir, may also affect the GHG emissions released due to the impoundment. It is good practice to evaluate the loads entering the impoundment from upstream.

Carbon and nitrogen containing compounds that are leaching from the upstream catchment drainage network are conveyed through the river system to the reservoir (or future reservoir), where microbial activity may convert them to GHG. Measurements of these fluxes or estimation through literature review are important for the understanding, model calibration and prediction of the pre-impoundment regime of GHG fluxes between surface and atmosphere. High resolution maps revealing the land cover and land use, statistics on population living in the catchment, and monitoring of water quality may give important information on the natural and human affected nutrient or organic matter inputs to the impoundment area. It is good practice to map all land cover types in the upstream catchment in order to build a complete image of the potential sources of nutrients and organic matter, including those related to human activities.

B. The impact of reservoir on the downstream watercourse should be evaluated.

In the pre-impoundment phase, it is important to establish *baseline* data on transport of dissolved GHG, carbon, and nutrients, as well as water-atmosphere fluxes of GHG in the river downstream of the future reservoir. An important portion of GHG emissions from a river is due to carbon loading from upstream catchments (see above and Cole et al. 2007). This may be changed after the introduction of a reservoir, and pre-impoundment data are needed to assess the difference. As one does not know how far downstream the reservoir impacts from the creation of the reservoir will work, it is important to establish baseline data from a sufficient long section of the river downstream. Baseline data for transport and emissions of GHG from the downstream river may be derived from direct measurements or literature data. Modeling of the changes in GHG emissions in the downstream river due to impoundment may make advantage of those variables. The results should be viewed against the pre-impoundment status of the river. Impacts of the terrestrial components, land cover and land use, as well as unrelated anthropogenic sources of nutrients and carbon the upstream catchment at the pre-impoundment situation determine the river GHG emission.

3.3 MODELING POST-IMPOUNDMENT EMISSIONS

3.3.1 Introduction

Emissions in the non-flooded area should not differ from pre-impoundment GHG emissions. The methodology for estimating pre and post GHG emissions in this area is described above. In case of changes in the catchment area land use, the impacts of a modification of river loads can be simulated by the reservoir model. Chapter 3.3 focuses only on the modified aquatic ecosystems: the reservoir and the impacted downstream river(s).

As already described, the objectives of the model will constrain the choice of the model in terms of complexity (number of substances, of processes, of dimensions, etc.).

For aquatic models (reservoirs and rivers), the specific criteria of choice is the **expected spatial (vertical and lateral) heterogeneities in the reservoir and in the reservoir construction design** (withdrawn structures). If stratification or lateral heterogeneity is expected, then 3D models would probably be more definitive than 1D or 2D. Otherwise, a horizontal 1D (river) or 2D (reservoir) model may be sufficient. It should be noted that 3D models can be computationally expensive and users may have to compromise between computation time and spatial resolution. For this reason use of 1D or preferably 2D models with higher resolution could be more efficient and accurate. In simulations of temperature profiles, the vertical direction mostly needs to be represented in high resolution. All other generic criteria (knowledge of the system and of the processes, availability of the input data, time, money, expertise, etc.) also apply for the choice of the post-impoundment model(s).

3.3.2 Hydrodynamic modeling

Context

In reservoirs and rivers, the hydrodynamics is a key driver of water biochemistry, and thus GHG emissions. Since the 1970s hundreds of ecological water quality models have been developed (Jørgensen et al., 1996) but the physical processes of transport and mixing within the water body are generally oversimplified (Hamilton and Schladow, 1997). Correct modeling requires proper inclusion of hydrodynamic parameters such as thermal structure, current velocities, local residence time, or the vertical mixing due to density stratification (Hamilton et al., 1997; Martin and McCutcheon, 1999).**The first stage of the GHG modeling work is the correct simulation of these parameters**.

Best Practice Guidelines:

A. The hydrodynamics of the system (reservoir or river) should be thoroughly simulated and results should be carefully analyzed.

Commentary

A. The hydrodynamics of the system (reservoir or river) should be thoroughly simulated and results should be carefully analyzed.

Hydrodynamic models can give important information on the behavior of the system (reservoir or river) and the consequences of hydro operations, and may be used to identify likely significant hotspot(s) for GHG emissions (high residence time, high temperature, strong thermal stratification, etc.). The outputs of the hydrodynamics models do not give direct results on the potential GHG production and emissions from the modeled systems. However, once correctly developed, calibrated and validated, the outputs of the hydrodynamic model are used as input data for the water quality and GHG model.

3.3.3 Coupling with the WQ/GHG model

Context

Once the hydrodynamics are properly simulated, results are available for WQ / GHG modeling. According to the model characteristics, this coupling can be done on or off line. The coupling must be adequate to ensure the closure of the mass balances.

Best Practice Guidelines:

A. ***The coupling between the hydrodynamic and the GHG models should be reliable and straightforward.***

Commentary

A. ***The coupling between the hydrodynamic and the GHG models should be reliable and straightforward.***

The outputs of the hydrodynamic model are to be used for the WQ/GHG model. The coupling between the models should be reliable to avoid two drawbacks:

- Avoid the information “loss” and the risk to not respect the mass balances;
- Avoid numerical issues.

The processes described by the hydrodynamic and biogeochemical models may have crucial differences e.g. in time steps, which would lead to problems in numerics. To answer these two points, it would be better to have the same code or the same developers for the two models.

The coupling could be done on-line (advantage: sure to have the same model and no problem of mass balance or code “communication”, drawback: longer calculation time) or off-line. In this case, the use of models from a same developer is preferable to avoid numerical issues between two codes with different conception.

3.3.4 Water quality and GHG

Context

GHG (CO_2, CH_4 and N_2O) production in a reservoir involves numerous and complex bio-geochemical processes in the sediment and in the water column. The simulation of GHG cannot be done without modeling the main WQ processes and parameters (oxygen, nutrients, etc.). As well, GHG model results cannot be analyzed and discussed without a good understanding of the main WQ processes in the systems.

Best Practice Guidelines:

A. A WQ model, without GHGs, could be used as a first estimation tool to assess the potential GHG production and emissions.

B. GHGs, namely CO_2, CH_4 and N_2O, should be considered as additional water quality parameters and the model should not only simulate GHG production and emissions but also the other relevant WQ parameters (e.g. oxygen, pH, nutrients, various species of C, N and P).

C. More advanced models should also simulate phytoplankton dynamics (chlorophyll, sink of inorganic carbon and source of labile organic carbon), zooplankton and sediments.

Commentary

A. A WQ model, without GHGs, could be used as a first estimation tool to assess the potential GHG production and emissions.

The simulation of some “common” WQ parameters such as dissolved oxygen can give information on the risk of GHG production in the reservoir and in the river. If no oxygen is present (usually in bottom water) and the primary production and carbon load are high, GHG production will probably be significant. On the other hand, if the water column or river is still oxic the risk is low. A first approximation of GHG risk using a WQ model that does not include GHG modules can be used as an improved and reliable risk assessment tool.

B. GHGs, namely CO_2, CH_4 and N_2O, should be considered as additional water quality parameters and the model should not only simulate GHG production and emissions but also the other relevant WQ parameters (e.g. oxygen, pH, nutrients, various species of C, N and P).

Processes responsible for the production and emission of GHGs are complex and depend upon many chemical parameters (Stumm and Morgan, 1996; Hamilton and Schladow, 1997; Jorgensen, 1999; Smits and van Beek, 2013). This interrelationship implies that GHGs cannot be modeled alone but rather as an additional chemical parameter.

C. More advanced models should also simulate phytoplankton dynamics (chlorophyll, sink of inorganic carbon and source of labile organic carbon), zooplankton and sediments.

In natural aquatic systems (reservoir or river), the chemistry is partly driven by the biology, especially the phytoplankton. Moreover, the benthic processes (oxygen demand and nutrient diffusion, among others) also control the WQ in the water column. For systems where processes are expected to be of the first order, more sophisticated models should be used. These models are recommended to include phytoplankton and sediment if necessary (diagenesis). The zooplankton compartment may be also explicitly simulated in very advanced models.

Once again, the choice of the model relates to the main objective of the study.

3.3.5 GHG emissions and C burial rates

Context

The emission pathways to consider are: diffusion, bubbling, degassing, downstream export and carbon burial as explained in Volume 1.

Best Practice Guidelines:

A. The minimum requirement for a GHG emission model is to simulate diffusive and degassing flux as well as downstream export.

B. More advanced models should also consider ebullition and carbon burial (which implies a sediment model).

Commentary

A. The minimum requirement for a GHG emission model is to simulate diffusive and degassing flux as well as downstream export.

The WQ/GHG models described previously are used to establish the concentration in the water (reservoir and river). These concentrations can be then used to simulate GHG diffusion and downstream emissions from these aquatic systems:

- Diffusive fluxes in the reservoir (and in the downstream river). The simulation of this flux requires the calculation of GHG surface concentration associated with a transfer function. Such transfer functions are also used for re-oxygenation at the water-atmosphere interface.
- Downstream emissions (degassing, diffusion and export in the downstream river). Strictly speaking, degassing occurs generally immediately downstream the water release when natural (waterfalls…) or artificial (weirs…) structures are present while other downstream emission fluxes may occur within many kilometers in the downstream reach. To model degassing , diffusion and downstream export, simulation of GHG and carbon species concentrations in the reservoir releases is needed. To a first approximation, conservative estimates of fluxes can then be calculated by subtracting the concentration in the reservoir releases water (model) from the concentrations in the upstream river (measurements). This estimate does not take into account the fraction of CH_4 that is oxidized into CO_2.

B. More advanced models should also consider ebullition and carbon burial (which implies a sediment model).

For ebullitive fluxes and carbon burial rates, calculating dissolved GHG concentrations in the water are not sufficient. It needs the use of additional specific modules:

- Ebullitive fluxes. It requires the explicit simulation of the sediment compartment but it is complex to model and no fully reliable model exists to our knowledge. Fluxes can be estimated with literature data.
- Carbon burial rates. It requires the explicit simulation of the sediment compartment (diagenesis model) associated with planned schedule of dredging the bottom and sediment flushing in dam management.

3.3.6 Required input data

Context

The accuracy and reliability of the model rely greatly on the quality of the input data. The origin of the input data must be clearly identified and stated. Data collection may represent a significant part of the budget allocated to the modeling projects. Usually, this data collection is also used for the overall monitoring of the system (not only for modeling purpose).

Best Practice Guidelines:

A. Special care should be taken when collecting and validating input data, which is one of the most crucial stages.

Commentary

A. Special care should be taken when collecting and validating input data, which is one of the most crucial stages.

For hydrodynamic modeling of reservoirs, the required input data may include:

- Maps with the location of the inflows and outflows;
- Bathymetry (at least the volumetric curve for 1D models) or initial topography for new projects;
- Meteorological parameters;
- Discharges (in and out);
- Water temperature of inflow and outflow;
- Land cover (for roughness at the bottom of new reservoirs);
- Structure designs (discharge facilities, water intake, water release, spillway, gate type);
- Reservoir operations;
- Initial conditions.

For hydrodynamic modeling of rivers, the required input data are almost the same:

- Maps with the location of the inflows (tributaries);
- Bathymetry, usually only cross sections are available;
- Meteorological parameters;

- Discharges (in and out);
- Water temperature of inflow and outflow;
- Initial conditions.

For simple WQ / GHG models, only a few parameters may be needed such as dissolved oxygen, nutrients or carbon. For more complex models, the list of parameters may increase to include total suspended solid, iron, GHGs, chlorophyll-a, phyto- and zoo-plankton, etc. The physico-chemical dataset often suffers from low measurement frequency, the result of the need to strike a balance between natural variability (seasons, flood, etc.) and technical and economic feasibility. The location of the measurement stations must also be thoroughly assessed.

3.3.7 Calibration and validation

Context

The calibration is made by comparing simulation results and field measurements. The parameters on which the model must be calibrated are those included in the reservoir and river models.

For hydrodynamics in reservoirs, model calibration is usually carried out on water temperature profiles and water velocity (speed and direction). For rivers, calibration parameters typically include water temperature in several stations and water levels. The highest stream flow velocities will occur in the river section with river bed roughness having the greatest impact on water surface levels. Therefore, water levels can be used as a key calibration parameter.

For WQ/GHG, although the list of parameters depends on the choice of the model, the calibration must be done on some key model constituents including dissolved oxygen, nutrients and carbon species, including GHGs. In all the cases, the agreement between all the simulated parameters and the corresponding field measurements must be checked.

Best Practice Guidelines:

A. The calibration should be done on a sufficiently long period (at least one year) to be sure to cover seasonal variations.

B. The quality of the calibration should be obviously characterized using statistical tools such as root-mean-square-error, cost function, coefficient of correlation, Taylor diagram, etc.

C. Once calibrated, the model should be validated with a different dataset than that used for the calibration.

D. When data are not available, for a new reservoir as an example:

- ***the model should be chosen considering existing models on similar systems, i.e., the same model(s) should be used with the same default calibration set.***
- ***the calibration and validation processes should be replaced by a thorough and comprehensive sensitivity analysis.***

Commentary

A. The calibration should be done on a sufficiently long period (at least one year) to be sure to cover seasonal variations.

For hydrodynamics, the calibration is done on a couple of parameters: drag coefficient (that characterizes the influence of the wind at the free surface, or respectively the heat exchange due to evaporation, the sensible heat exchange, and the momentum exchange), and roughness (especially in the rivers), and sometimes on parameters of the turbulence closure models, such as Secchi depth (usually forcing data)

For WQ/GHG, depending on the model, the calibration is done on a number of parameters: process coefficients, constants, stoichiometric ratios, equilibrium concentrations. The calibration must be carried out in a step-wise and iterative manner, process by process, going from processes affecting independent state variables to processes affecting dependent state variables, starting from the coefficients for which the model appeared most sensitive.

B. The quality of the calibration should be obviously characterized using statistical tools such as root-mean-square-error, cost function, coefficient of correlation, Taylor diagram, etc.

Given the many interactions of substances/parameters and processes in a model, this procedure must be repeated until no further improvement is observed. To objectivize the agreement between simulations and measurements, statistical tools must be used. Among them, we can cite: the root-mean-square-error (RMSE), cost function, coefficient of correlation or Taylor diagrams. (e.g. OSPAR, 1998; Radach & Moll, 2006),.

Similar to forcing data (input data), the quality of the calibration relies on the quality of the field data. It should be noted that calibration of WQ models is more intricate than that for hydrodynamic models, due to the complexity of the chemical and biological processes. The input data for the monitoring program should be adapted to the model complexity. The minimum requirement for a reservoir is a vertical temperature profile per month in a station of the reservoir and a measurement in the river. The best solution is continuous measurements (vertical profile and rivers).

C. Once calibrated, the model should be validated with a different dataset than that used for the calibration.

Once calibrated, the model must be validated: the agreement between simulations and field measurements must be checked (statistically) for a relevant period (depending on the annual variability) without changing calibration parameters.

D. When data are not available, for a new reservoir as an example:

- ***the model should be chosen considering existing models on similar systems, i.e., the same model(s) should be used with the same default calibration set.***
- ***the calibration and validation processes should be replaced by a thorough and comprehensive sensitivity analysis.***

In case of a planned reservoir or future river modification, no calibration/validation data is available by definition. The calibration parameters can be adapted from a previous model developed for a similar aquatic system (climate, incoming loads) or from bibliographical data. In this case, a thorough sensitivity analysis must be done in order to test the robustness of the model (a small variation of a single calibration parameter may have huge effect on the result) and to see which parameters have the main impact on WQ and GHGs. Further analysis can then be done on the parameters (scientific research, expert opinion).

3.4 MODELING THE IMPACT OF UNRELATED ANTHROPOGENIC SOURCES

3.4.1 Introduction

Man-made reservoirs impounding water create conditions different from those prevailing in natural fluvial or limnic ecosystems. Changes in oxic status of organic deposits may alter the biogeochemical cycles and affect the GHG balance of the landscape. Leaching of nutrients and organic matter due to land use or land use changes, degradation of soil, or release of wastewater may add to the risk of

GHG emissions or affect the sedimentation rate removing carbon from the short-term cycle. Without those sources, the GHG emissions from man-made reservoirs could be lower.

The human-induced release of organic matter, nutrients and other material impacting directly or indirectly carbon cycling and GHG fluxes in the reservoir, but not directly due to the impoundment, were referred to as Unrelated Anthropogenic Sources (UAS) by the IPCC in the Special Report of Renewable Energy Sources (SRREN 2012) and in the Guidelines for Quantitative Analysis of Net GHG Emissions from Reservoirs, Volume 1 – Measurement Programs and Data (IEA Hydro 2012).

Excess of nutrients, in particular phosphorus (P) and nitrogen (N), when released to the reservoir, enrich the ecosystem and cause eutrophication. Visible signs of eutrophic waters include harmful algal blooms and fish kills as a result of anoxic conditions that may occur in waters suffering from increased production of biomass and eventually necromass. Examples of activities contributing to loads of nutrients and organic matter are agriculture, animal husbandry, release of inadequately purified wastewater from settlements or industry, mining of minerals or organic deposits, and efficient forest management using fertilizers, drainage or soil amendment. Some nutrients may enter the reservoir directly, e.g. from fish farming.

Direct measurements of UAS loadings are difficult if not impossible to obtain. Emissions of GHG's emerging from the water surface carry no signatures of their origins. Recognition of significant levels of UAS can therefore only be based on circumstantial evidence, such as loads of nutrients and organic matter from identifiable sources caused by human activities. However, in some reservoir catchments with naturally high nutrient background concentration, impoundment and reservoir formation might also create significant increases in primary production and natural eutrophication, removing carbon from the atmosphere. This change and contribution to the carbon sink might be related to the change in hydrodynamic condition which increases euphotic depth in the water column and provide suitable habitat for growth of phytoplankton.

For future management and mitigation of GHG emissions it is important to separate GHG emissions related to UAS from GHG emissions caused directly by the impoundment. Activities in the catchment that are already, or might in the future increase the GHG emissions from the reservoir and its downstream reaches are then identified. Management of those activities in ways that effectively suppress the UAS brings evident and mutual benefits to the interest groups using the services of the reservoir for their multiple purposes.

This chapter outlines the methodology useful for distinguishing the potential risk activities in the catchment and for evaluating the contribution of UAS to total GHG emissions from the impoundment, especially those occurring as CH_4.

3.4.2 Identifying and Modeling Unrelated Anthropogenic Sources

Context

Separating and evaluating the contribution of UAS to the emissions and removals profile helps to more accurately analyze the relevance of the components comprising net GHG emissions of man-made reservoirs. The impact of UAS should be determined both in the pre-impoundment and post-impoundment phases. The pre-impoundment UAS impact may affect the “background” emissions of GHG from water bodies within the inundation area and the downstream reaches. Identifying the effects of UAS during the pre-impoundment phase might indicate similar or increased post-impoundment impacts.

The change in GHG emission due to UAS eutrophication can be evaluated and accounted. Eutrophication in man-made reservoirs may have contributions from several sources. After reservoir impoundment, increases in hydraulic retention time, leaching of nutrients from soils and decomposition of terrestrial vegetation may lead to “trophic upsurge”, which indicates a boost of primary production in many young reservoirs. This phenomenon of “trophic upsurge” in reservoirs may diminish a number of years after impoundment. But some reservoirs with a high background level of nutrients and organic matter may continue in a eutrophic state even after the period of “trophic upsurge”. However, these phenomena occurring in especially young reservoirs, should not be attributed to UAS. Only the external loads of nutrients and organic matter from terrestrial ecosystem can be regarded as eutrophication due to UAS.

Direct measurement of the impact of the UAS with respect to the background GHG balance of the natural catchment or the impact due to impoundment may be very difficult to achieve, and modeling may provide the best means to assess this impact. This starts with assessing, via appropriate models, loads of key nutrients controlling the ecosystem productivity such as inorganic and organic phosphorus (P) and nitrogen (N) species. These can mimic primary production by phytoplankton and macrophytes, sedimentation, biological and chemical oxygen demand, and biogeochemistry of the watercourse. From this, the contribution of the additional loads to the occurrence of hypoxia, algal blooms, internal nutrient cycling and ultimately to the GHG balance may be revealed, most probably leading to increased methane emissions. The challenge is how to separate the natural sources from the UAS causing eutrophication. When the methodology applied in modeling allows, the upstream sources should be identified. Such information is useful in mitigation and reservoir management planning.

Best Practice Guidelines:

A. ***Identification of UAS should be based on observation of potentially significant human activities according to procedures outlined in Volume 1 of these Guidelines (IEA Hydro. 2012).***
B. ***If the loadings from UAS are deemed significant, the contribution of UAS to overall GHG emissions or removals should be estimated using modeling.***
C. ***Careful consideration needs to be given to special cases involving UAS.***

Commentary

A. ***Identification of UAS should be based on observation of potentially significant human activities according to procedures outlined in Volume 1 of these Guidelines (IEA Hydro. 2012).***

The impact of different UAS to overall net GHG emissions or removals in a man-made reservoir is likely to be shown as a complex cumulative response to the fluvial or limnic ecosystem. Separation of individual sources may require highly sophisticated scientific methods. However, the presence and activity of potential sources in the catchment should be used as an indicator of UAS. Observations showing the load may help to identify the quality and quantity of the source.

Water quality monitoring may give relevant information of particular areas in the catchment causing loading from diffusive sources such as land use, or point sources such as sewage outlets from settlements or industry. Information extracted from remote-sensed land cover, land-use analysis or regional statistics may be used to evaluate the role of different land-use related sources of UAS. Indirect indices such as population equivalent (PE) may serve in the estimation of community sewage loads.

In the absence of water quality monitoring data, literature values of similar man-made impoundments without obvious UAS effects should be employed for determining a reasonable reference level of organic or inorganic nutrient conditions, against which the conditions potentially affected by UAS can be compared. Similarly, natural fluvial or limnic systems may be used in defining a reference level for identifying the impact generated by both the reservoir and the possible UAS.

When no UAS can be identified, the comparison with natural systems may show the impact of the reservoir alone.

B. *If the loadings from UAS are deemed significant, the contribution of UAS to overall GHG emissions or removals should be estimated using modeling.*

Since UAS is a component in the calculation of the net GHG emissions and removals (IEA Hydro. 2012), a value equaling the respective GHG exchange rate (emissions or removals) should be assigned to each GHG species. The basis for such assignment could be the nutrient load entering the impoundment due to human activities in the catchment. Very low levels of activity may not be significantly different from the natural background. Modeling of the impact of UAS should therefore be able to distinguish the human impact from the natural background.

Where the presence or contribution of UAS are not shown to be important, it is best practice to assign a value of 0 (zero) to all GHG's (CO_2, CH_4, N_2O) respectively. Thus the impact of highly uncertain UAS is eliminated from the calculation of the net GHG balance. Modeling of the loads can still be employed, e.g., to estimate the sensitivity of the impoundment for additional loads, or when seeking improvements in the reservoir management options. In guidance for national greenhouse gas inventories (IPCC 2006) the IPCC considers that the N_2O emissions from reservoirs are due to only upstream sources such as agriculture or sewage treatment plants, and are reported in those categories, respectively. To avoid double counting N_2O emissions, reservoirs are considered to be zero. If the reservoir net GHG balances are used in national inventories, the IPCC approach should be followed. That would have the same impact on emissions from a reservoir, as when the UAS has been evaluated and subtracted. For reservoir scale and mitigation purposes, it would still be useful to identify the upstream sources of N_2O.

When the UAS potential is deemed significant enough that it may affect the GHG emissions or removals, the relative share of UAS compared to natural loads should be determined. Nutrient loads originating from the identified UAS activities, prominently those of P and N, or of organic carbon as DOC and POC, could be used as proxies for the UAS impact on the increased emissions of GHG from the reservoir. Eutrophication could eventually launch hypoxic or anoxic conditions in the reservoir, and thereby promote CH_4 emissions. While the linkage between reservoir nutrient concentration and occurrence of anoxia may be nonlinear, it is reasonable to assume that the probability of such occurrences increases with increasing trophic state in the water body. Since CH_4 is considered to be the most harmful GHG species emitted from reservoirs, efforts should be invested particularly in modeling of CH_4 emissions.

Because no direct protocol for measurement of the UAS impact on GHG emissions is available, modeling should be employed to distinguish the contribution of UAS from that of the impoundment. Hydrodynamics of the reservoir largely determine if and when the anoxic conditions may occur. The appropriate models should implement diffuse and localized nutrient loads and water borne transport mechanisms enriching the reservoir. The models should be parameterized according to the inventory of different land cover and land use types that can be identified in the catchment using e.g. remote sensing or high resolution maps.

A simple model employs nutrient loads from population and industry, and characteristics of the different land cover and land-use types. When released by UAS, nutrient and carbon loading into the reservoir comes from point and non-point sources in the catchment region. Point sources mainly refer to wastewater from sewage systems and effluents from wastewater treatment plants or industry. Nutrients or carbon loads from point sources could be estimated or calculated through the concentration of nutrients and carbon in the effluents and their flow rate. Non-point sources of nutrients or carbon loads include agricultural runoff, erosion of managed soil, and wastewaters from population or live stocks in rural areas. Information on community sewage loads or industrial loads may be available from monitoring statistics. Population equivalent loads can also be applied if the population density or actual number of inhabitants in the catchment is known.

Hydrological models of the catchment can be used to model the contribution of non-point sources of nutrients and carbon loads from terrestrial ecosystems into the reservoir. The assessment of relevant nutrient and organic matter sources in the model should be considered in two steps:

1. Modeling of nutrient loads from the catchment, and
2. Modeling the impact of these loads (including natural loads) to eutrophication, and including the reservoir hydrodynamics.

The impact of load should be evaluated using models implementing both the hydrodynamics and the response of the man-made reservoir to the load of nutrients and carbon, and they should be able to predict the GHG emissions and removals and carbon burial to the sediment. Models similar to those used for post-impoundment situations are applicable for estimating the impact of UAS to the man-made reservoir, but the models should also account for the effects on primary production, nutrient cycling, and sedimentation related to eutrophication.

The models should be parameterized using the input nutrient and organic carbon loads originating from the catchment. Best practices for modeling and simulation of post-impoundment are described in Chapter 3.3 of this document. Scenarios of different loads of nutrients and organic matter (see 3.3.2) should be used to evaluate the impacts on eutrophication and GHG emissions and removals.

C. Careful consideration needs to be given to special cases involving UAS.

For certain reservoirs and under unusual conditions, complex issues surrounding UAS need to be taken into account in the assessment of net GHG

Many existing and new reservoirs have multi-purpose features and provide a number of water-related services beyond hydropower, such as irrigated agriculture, water supply, navigation and recreational activities. These can trigger significant anthropogenic activity in the watershed, along the reservoir rim and downstream of the project and hence a significant increase in external loadings to the reservoir. This needs to be considered in project planning, development and operations. The critical question will be whether these external loadings are in some ways related to reservoir impoundment, or can be ascribed to UAS.

Levels of nutrient and organic loading from a reservoir catchment often increase dramatically during and following high precipitation events (i.e. as a component of surface run-off). In many catchments, high precipitation events can be the most significant contributor to GHG emissions from both natural sources and UAS. It is therefore very important to make a clear separation between these natural and UAS contributions. While the assessment of pre-impoundment conditions may be useful in identifying natural conditions, the methodologies used will likely have been different to UAS, and care should be taken in the analyses.

Some existing reservoirs may be in catchments where UAS loadings have changed dramatically since inundation and may be expected to continue to change. This can be either as overall increases or through extreme levels of variability. In these situations, UAS loadings should be carefully integrated over the expected life of the project.

4.0 NET GHG EMISSION REPORTING

4.1 INTRODUCTION

The purpose of modeling is to undertake a quantitative analysis of net GHG emissions and changes in carbon stock, and understand the process of GHG emissions from an existing or planned reservoir. The purpose of reporting is to provide appropriate input to the project Environmental Impact Assessment (EIA) or similar document, related to licensing of a new or re-licensing of an existing project. Modeling may also be used to assign an annual emission factor (tCO2-e/GWh) for reporting requirements in the case of hydropower reservoirs.

The net GHG emission approach allows comparison of emissions in the landscape prior to and after the impoundment, and a sound distinction of human activities that may contribute to the reservoirs GHG emissions. Transparent public reporting of robust modeling results also increases the understanding of where hydropower related emissions rank relative to other generation technologies. The document format depends on the specific context requirements and constraints of each project. Therefore the reporting format should be chosen according to the purpose of the work and the needs of reporting. It is important that the report follows the best practices of transparency and scientific clarity. When net GHG emissions and removals are reported, the complete chain, including the GHG balances at post-impoundment and pre-impoundment situations, and the identified UAS-related emissions, should be covered.

4.2 REPORTING REQUIREMENTS

Context

The *Guidelines* - Volume *2* describes a road map (Chapter 1.4) and suggests a screening process (Chapter 2) as the initial GHG assessment. Irrespective of the outcomes of the screening process, comprehensive reporting of the screening data inputs, methodology and results is essential. The screening outcome may indicate a low risk of significant GHG emissions based on the parameters applied. Another possible outcome is an indication of a raised risk of GHG emissions in an existing reservoir or a planned project. In this latter circumstance, further study would be warranted. A third outcome of the screening process is that results return a high uncertainty factor, most likely due to an absence of similar reference data. This would trigger the requirement for more input to the screening process or directly to further study.

The reason for high GHG emissions may be due to the function of the reservoir impoundment, or the impact of UAS in the catchment. For all screening outcomes, a well-prepared report is required. Where the emissions are deemed low and no large GHG research program is needed, the report should satisfy not only the reservoir stakeholders, but also the legal and regulatory requirements.

Best Practice Guidelines:

A. The Screening Report on net GHG emissions should describe all relevant parameters and methodology used in a transparent manner.
B. Conclusions and justifications covering the recommendations for the GHG and WQ measurement and monitoring program should be clearly reported.
C. Modeling assumptions and methodology should be documented in a transparent manner.
D. The Final Report should include the results and their uncertainty using the best scientific principles.

Commentary

A. ***The Screening Report on net GHG emissions should describe all relevant parameters and methodology used in in a transparent manner.***

The information and data to be collected for the catchment and inundation areas of an existing or planned reservoir should cover all relevant features affecting the project's net GHG balance. *Guidelines - Volume 1* (IEA Hydro. 2012) lists the variables that may contribute to the net GHG emissions or removals. The data needs are similar to what should typically be collected for the EIA or other documents related to licensing a new or re-licensing an existing reservoir. Screening methodology should be based on published scientific knowledge, transparently described. The assumptions applied in the screening process, and restrictions of the screening should be transparently and adequately described. Reporting of all relevant data and reservoir features should be transparent and appropriately satisfy the legal and regulatory requirements.

B. Conclusions and justifications covering the recommendations for the GHG and WQ measurement and monitoring program should be clearly reported.

If the screening results suggest that a low risk of significant GHG emissions exists within the current modeling framework, the report should clearly state the rationale for a low level monitoring program for the GHG emissions (or key driving force parameters) and WQ.

If the screening predicts adverse GHG emissions, the report should clearly state the need and outline a comprehensive research/monitoring program for the GHG emissions and WQ.

The reasons for the approach selected should be transparently explained, building on the principles applied in the screening process. The uncertainty involved in choosing the approach should be presented. The report should also outline where modeling is needed and set requirements for the modeling and monitoring program such that these needs are addressed in perpetuity.

C. Modeling assumptions and methodology should be documented in a transparent manner.

It is crucial to describe in the report the criteria used in the choice of the net GHG modeling approach. As described in Chapter 3.3 the questions to be addressed and some characteristics of the reservoir govern the kind of models to be used. Once the modeling approach is chosen, it is important to describe the assumptions used in the models, and how the models implement those assumptions. Because the net GHG approach consists of three separate entities, the pre-impoundment net GHG balance in the inundation area, the post-impoundment net GHG balance of the impoundment and the downstream reaches, and the possible impact of UAS in the catchment, it is best practice to describe how these entities are implemented in the model(s). The report should transparently explain how the net GHG emissions or removals are obtained by modeling or estimating of the GHG balances of the elements. If there is not enough information available and simple assumptions are not justified to describe the effects of pre-impoundment GHG balance or the effect of UAS, it is appropriate to set the GHG balance of one or more of these elements to zero in the overall net GHG calculation (see Chapter 3.1.3 in this Volume and Volume 1, IEA Hydro 2012). The zero value is also appropriate for UAS, if no such human activity is present. The reasons leading to those evaluations should be transparently explained.

The main criticisms of models are the lack of case studies or references justifying the relevancy of their methods. It is all the more true for recently or purposely developed models. In that case, a very thorough justification of the model components (e.g. concepts, numerical options, coding, drawbacks) must be described in the report. For widely and internationally used models, this stage is less crucial and can be replaced by a list of selected scientific papers.

D. The Final Report should include the results and their uncertainty using the best scientific principles.

The results of the model runs should be reported, including the simulation of the impacts of varying scenarios. These include the different management methods of the reservoir, different land use options in the catchment and other pertinent conditions. Scenarios based on the original assumptions and aims (Guideline C, Chapter 4.2) and how they affect the model outcomes should be transparently described.

4.3 EXAMPLES OF MODEL OUTPUTS

Context

This chapter provides some examples of model outputs having 1D, 2D, and 3D dimensions. It also serves as an introduction of concepts to enable examples to be posted on the IEA Hydropower Agreement website (www.ieahydro.org). Examples of more comprehensive net GHG modeling can be found on this site and the format of digitally available examples is described in Appendix 1.

Best Practice Guidelines:

- ***A. Model outputs should be focused on addressing the issues and reaching the target audience.***
- ***B. For medium or long term simulations (beyond 20 years), several simulations using a range of possible forcing data should be done to provide a reliable range of results.***

Commentary

A. Model outputs should be focused on addressing the issues and reaching the target audience.

Time-series – 1D

With deterministic models, all the simulated substances and fluxes (useful for GHGs) can be known at each time step and within each grid cell. A first way to export and use simulation results is the times series showing the evolution in concentration of a chemical species or a flux with time. This kind of output can be used for calibration purposes.

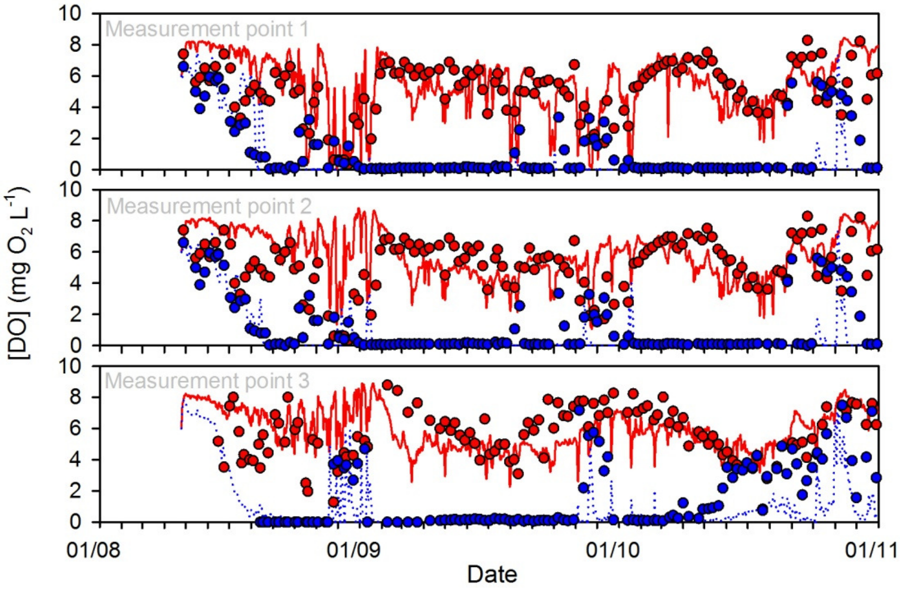

Figure 4.1 Example of time series showing the calibration of the parameter oxygen in a reservoir (lines: model, circles: measurements, red: surface concentrations, blue: bottom concentrations) (adapted from Chanudet et al., submitted)

Cross sections and Maps – 2D

In addition to the possibility of exporting data from a couple of single observation points, some models offer the possibility to integrate the results over the whole grid and therefore to calculate the average concentration or the total fluxes (for instance the diffusion GHG flux over the entire reservoir or river surface area). These outputs are essential to assess the impact of the entire system and calculate mass balances.

Cross sections can be used to assess the change of a substance concentration along a river or reservoir section. In this kind of graph, the lateral changes (e.g., along the river axis or the north-south axis for a reservoir) are usually plotted as a function of depth. This type of graph is suited for 2DV or 3D models.

Maps allow for a direct visualization of the geographical distribution of the simulated parameters. For 2DH models in which the substances are depth-averaged, this kind of representation gives a direct image of all the results and is very useful. For 3D models, a layer must be selected.

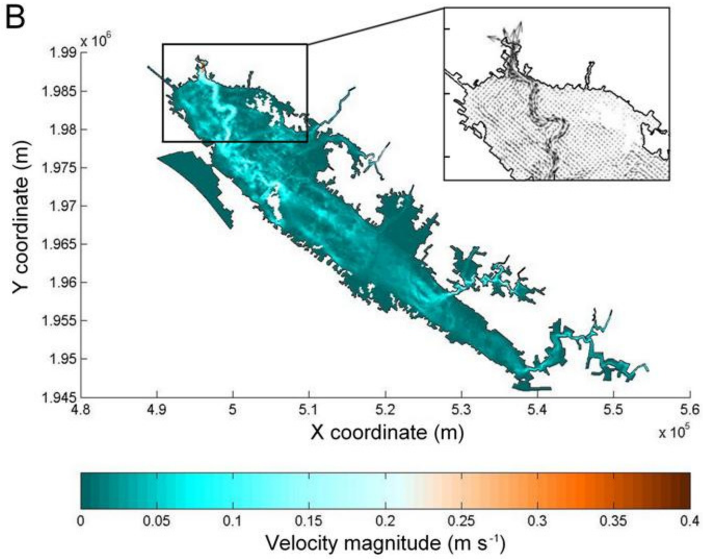

Figure 4.2. Map showing modelled water velocity in a reservoir (Chanudet et al., 2012)

These kinds of outputs are mainly used to provide an overview of the results or to identify and present local hot spots.

Video/animation – 3D

Videos can be used for communication to various audiences and may be valuable in explaining the net GHG emissions or removals concepts as part of the report auditions.

Predictions using simulations

Once calibrated and validated, models can be used for GHG emission prediction. The main uncertainties rely on the forcing input data. For instance, what will be the meteorological conditions in 10 or 20 years in the context of global climate change? General Circulation Model results applied by the IPCC can be used to provide a range of long term variation in the scenarios.

Once calibrated and validated models can be used to simulate various scenarios and to estimate the differences as compared to a "reference" ecosystem. Chapter 3.2 discusses the conditions important in the reference ecosystems. The interpretation of the scenario results must be made with caution. Indeed in the case of significant change, the structure of the ecosystem can be totally modified and some processes considered as not relevant, or of second order. This can result in calibration errors affecting scenario simulations.

B. *For medium or long-term simulations (above 20 years), several simulations using a range of possible forcing data should be done to provide a reliable range of results.*

Examples of long-term scenarios include:

- Effects of global climate change;
- Exceptional hydrological or meteorological events;
- Impact of a given project operation on the reservoir and/or the downstream river;
- Impacts of structural features of the project; and
- Changes in UAS during the scenario period.

Depending on the model concept selected (i.e., 1D, 2D or 3D), such long-term simulations can be computationally expensive in terms of time to complete. Users must be aware of this when planning simulations over long periods.

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APPENDIX 1

EXAMPLES OF MODELS SUPPORTING THE NET GHG APPROACH

Models developed with the concept of net reservoir GHG emissions and removals can potentially provide important information that could be used to support the management of existing reservoirs, the planning stages of new reservoirs, and the re-licensing of existing reservoirs. The IEA Hydropower Agreement website www.ieahydro.org maintains a collection of user exercises that illustrate how modeling has been used in the context of net GHG assessment following the IEA Guidelines (IEA 2012 and this Volume). Users of the Guidelines are invited to submit their work to the website. Modeling can support the net GHG assessment in multiple ways and levels. The intent of the website is to provide a collection of ideas, model approaches, and how model outputs have contributed to understanding the challenged inherent to net GHG estimation. The solutions need not be large scale ecosystem level models - solutions to specific challenges or questions are welcome.

We understand that companies may not necessarily want to publish their modeling tools. Therefore, the main focus is the description of the modeling chain: setting modeling goals, methods used to address those goals, model runs or results and interpretation of the results with respect to the goals. Users can choose which details of the work are uploaded to the site. The examples collection supports various levels of abstraction of modeling, from publishing open source code to more general introduction of ideas, links to results and publications produced. All these levels are useful for the reservoir modeling community in exchanging ideas and progressing towards working solutions of new questions. As the modeling expertise accumulates on the website, we hope it becomes an internationally useful toolbox for modelers with interests in reservoir hydrodynamics and biogeochemistry.

Description of modeling examples

The modeling example can be described using the following terms (supported by the web design):

Model name

Authors: affiliation, contact information

Abstract: Motivation for the modeling exercise, short description of methods used, main results and conclusions

Key words

Introduction to the exercise

Data and methods applied

Results obtained and their usefulness for the reservoir net GHG impact

Links to online publications and other materials, e.g. visualization of the results, websites describing the exercise