Emission and Measurement of Greenhouse Gases

Steve Folger

Emission and Measurement of Greenhouse Gases

Edited by **Steve Folger**

Callisto Reference

New York

Published by Callisto Reference,
106 Park Avenue, Suite 200,
New York, NY 10016, USA
www.callistoreference.com

Emission and Measurement of Greenhouse Gases
Edited by Steve Folger

International Standard Book Number: 978-1-63239-170-4 (Hardback)

Printed in the United States of America.

Emission and Measurement of Greenhouse Gases

Preface

Knowledge of greenhouse gas sources, emissions, measurements and management is crucial for the capture, usage, reduction and storage of greenhouse gases that play a significant role in matters like global warming and climate change. This book presents an overview of recently developed techniques, methods, and strategies regarding greenhouse gases. It includes an extensive investigation of greenhouse gases that are emitted from hydrocarbon reservoirs, vehicle transportation, agricultural landscapes, farms, etc. It also discusses the latest detection and measurement strategies. This book includes contributions from prominent experts with extensive experience in this field and will be helpful for interested readers.

The information shared in this book is based on empirical researches made by veterans in this field of study. The elaborative information provided in this book will help the readers further their scope of knowledge leading to advancements in this field.

Finally, I would like to thank my fellow researchers who gave constructive feedback and my family members who supported me at every step of my research.

Editor

Contents

Greenhouse Gases Emission and Measurement

1

Greenhouse Gas Emissions from Hydroelectric Reservoirs: What Knowledge Do We Have and What is Lacking?

Raquel Mendonça[1,2], Nathan Barros[1], Luciana O. Vidal[1], Felipe Pacheco[1], Sarian Kosten[2] and Fábio Roland[1]
[1]*Federal University of Juiz de Fora, Federal University of Rio de Janeiro*
[2]*Wageningen University*
[1]*Brazil*
[2]*The Netherlands*

1. Introduction

The question that motivated us to write this chapter was "How does hydroelectricity production contribute to the global emissions of greenhouse gases?". Here, we present an overview of (i) scientific advances on the topic and (ii) aspects of hydroelectric reservoir ecology in the context of greenhouse gas production, consumption and emission.

Electricity production is a challenging issue when it comes to mitigating greenhouse gases (GHG) emissions without risking development goals. Non-renewable energy sources, as fossil fuel burning, account for most of the global energy production (68% in 2007) and are responsible for most of the anthropogenic GHG emissions to the atmosphere (40%, International Panel on Climate Change - IPCC, 2007). Compared to fossil fuels, hydropower has been considered an attractive renewable energy source with the advantage of being less harmful in terms of GHG emissions (International Energy Agency - IEA, 2008). Hydropower currently provides about 16% of the world's electricity supply (IEA, 2008) with many countries depending on it for more than 90% of their supply. Indeed, hydropower is a proven, mature, predictable and typically price-competitive technology. Moreover, it has among the best conversion efficiencies of all known energy sources: 90% efficiency as opposed to up to 50% efficiency of e.g. fossil fuel burning. The historical perception of hydroelectricity as being GHG neutral (Hoffert et al., 1998), however, is now known to be flawed. The concern regarding the GHG emissions by hydroelectric reservoirs has steeply increased since the early 90's, even though it remains unclear what their actual emission is.

Although inland water systems naturally produce and emit carbon to the atmosphere (Cole et al., 2007) different characteristics of hydroelectric reservoirs cause that they often produce and emit more than natural systems, especially in the first twenty years after flooding (Barros et al., 2011). This is mainly due to the usually excessive availability of decomposable organic matter in hydroelectric reservoirs. Not only large amounts of soil and terrestrial vegetation are flooded by damming rivers, but terrestrial organic matter derived from land erosion is continuously flushed into reservoirs as well. The usually high water residence time in reservoirs as compared to rivers, combined with high inorganic nutrient inputs, favors organic matter decomposition and, thus, the production of two major GHGs - carbon dioxide (CO_2) and methane (CH_4). The amount of CO_2 and CH_4 emitted varies (a) among reservoirs (as function of drainage basin characteristics, reservoir morphology, climate, etc.); (b) within reservoirs (along longitudinal gradients from the tributaries to the dam, before and after the dam, etc.); and (c) over time (with reservoir aging, seasonally, daily, with changes in anthropogenic activities in the drainage basin, and with dam operation depending on energy needs and precipitation regime). Attempts to estimate the amounts of CO_2 and CH_4 emitted to the atmosphere should consider such variability which makes it a complex task.

Despite the complexity of the GHG issue, the effect of damming rivers on the atmospheric GHG concentrations cannot be disregarded. The concern about the impacts of hydroelectric reservoirs on the global GHG budgets has been increasing in the same pace as the construction of new dams. Nowadays, there are at least 45,000 large hydroelectric reservoirs in operation worldwide (World Commission on Dams -WCD, 2000). Moreover, recent inventories estimate the total surface area of world's hydroelectric reservoirs at about 350,000 km^2 (Barros et al., 2011). The substantial size of some hydroelectric projects and the extensive total surface area globally covered by reservoirs require that research determining the impacts of these systems be done at ever-increasing spatial and temporal scales.

This chapter focuses on the GHG emissions that are due to the landscape transformation (damming a river to form a reservoir) and to reservoir operation to produce electricity. First, the scientific advances towards understanding the role of hydroelectric reservoirs and their environmental effects as sources of GHG are delineated. Then, the metabolic processes involved in GHG production and consumption are described with focus on the two major interacting compartments: the water column and the sediment. Next, the external factors influencing the emission rates from reservoirs are discussed. Finally, an overlook of future perspectives in terms of GHG emissions from hydroelectric reservoirs is presented.

2. Important scientific advances

The ever increasing global energy demand and the concern about the changes in environment have lead to an urge to assess the hydropower 'footprint' in terms of GHG emissions to the atmosphere. Since the early 90's the role of hydroelectric reservoirs as sources or, as the opposite, sinks of GHG has rapidly become a global topic of investigation (**Figure 1**). At least 85 globally distributed hydroelectric reservoirs have so far been studied with focus on GHG fluxes (Barros et al., 2011). The first scientific papers focused on reservoirs located in Canada (e.g. Rudd et al., 1993; Duchemin et al., 1995), Brazil (e.g. Rosa & Schaeffer, 1994; Fearnside, 1995, 1997), Panama (Keller & Stallard, 1994) and French Guiana (e.g. Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Later, reservoirs in Finland (e.g. Huttunen et al., 2002), USA (e.g. Soumis et al., 2004), Sweden (e.g. Aberg et al., 2004; Bergstrom et al., 2004) and Switzerland (e.g. Diem et al., 2007) were studied. Only very recently, GHG emissions from reservoirs located in China, the country with the largest installed capacity in the world, became focus of investigation (e.g. Chen et al., 2009; Wang et al., 2011; Zheng et al., 2011) (**Figure 2**).

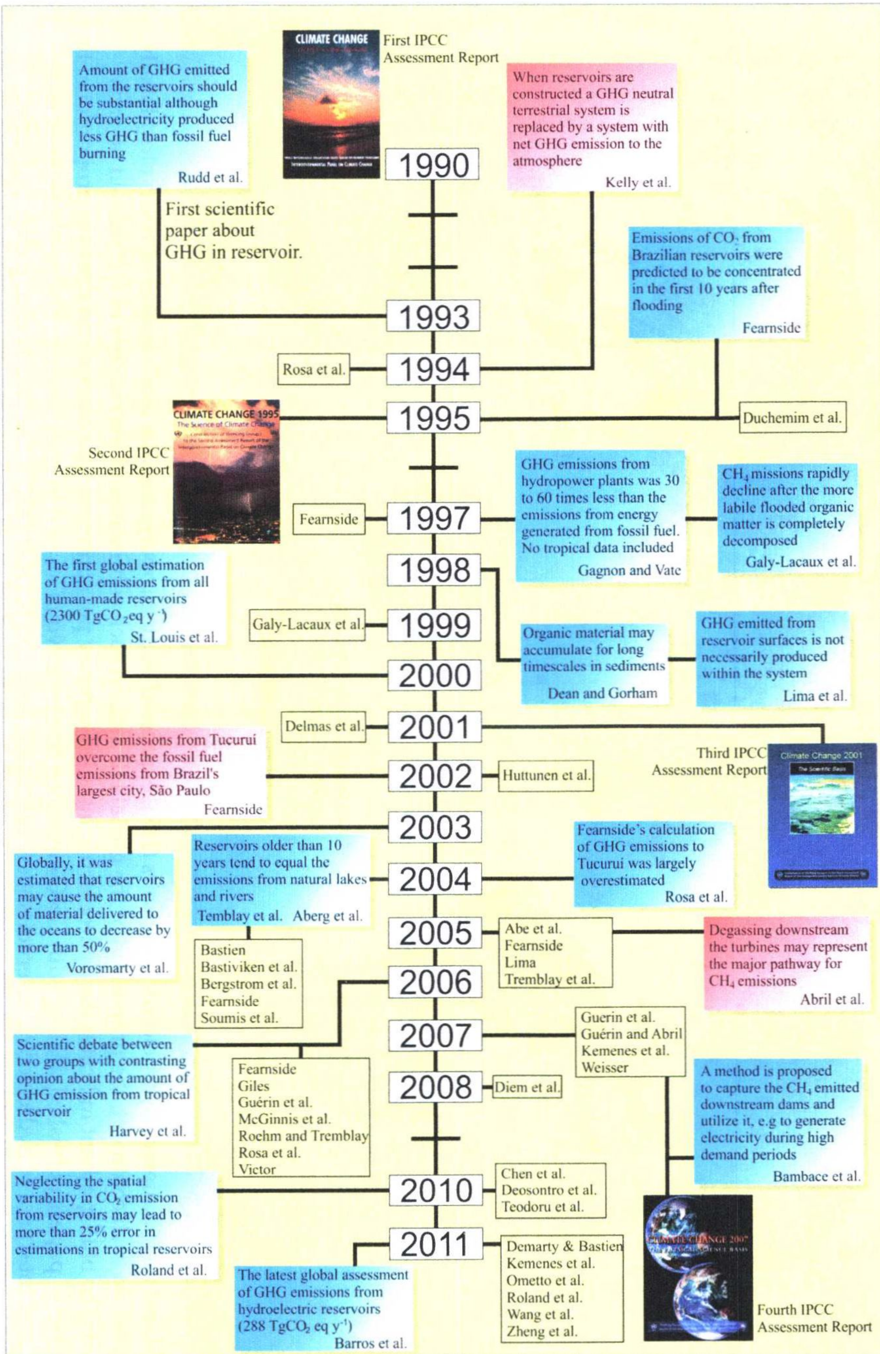

Fig. 1. Timeline of scientific advances regarding the role of hydroelectric reservoirs as sources of GHG to the atmosphere.

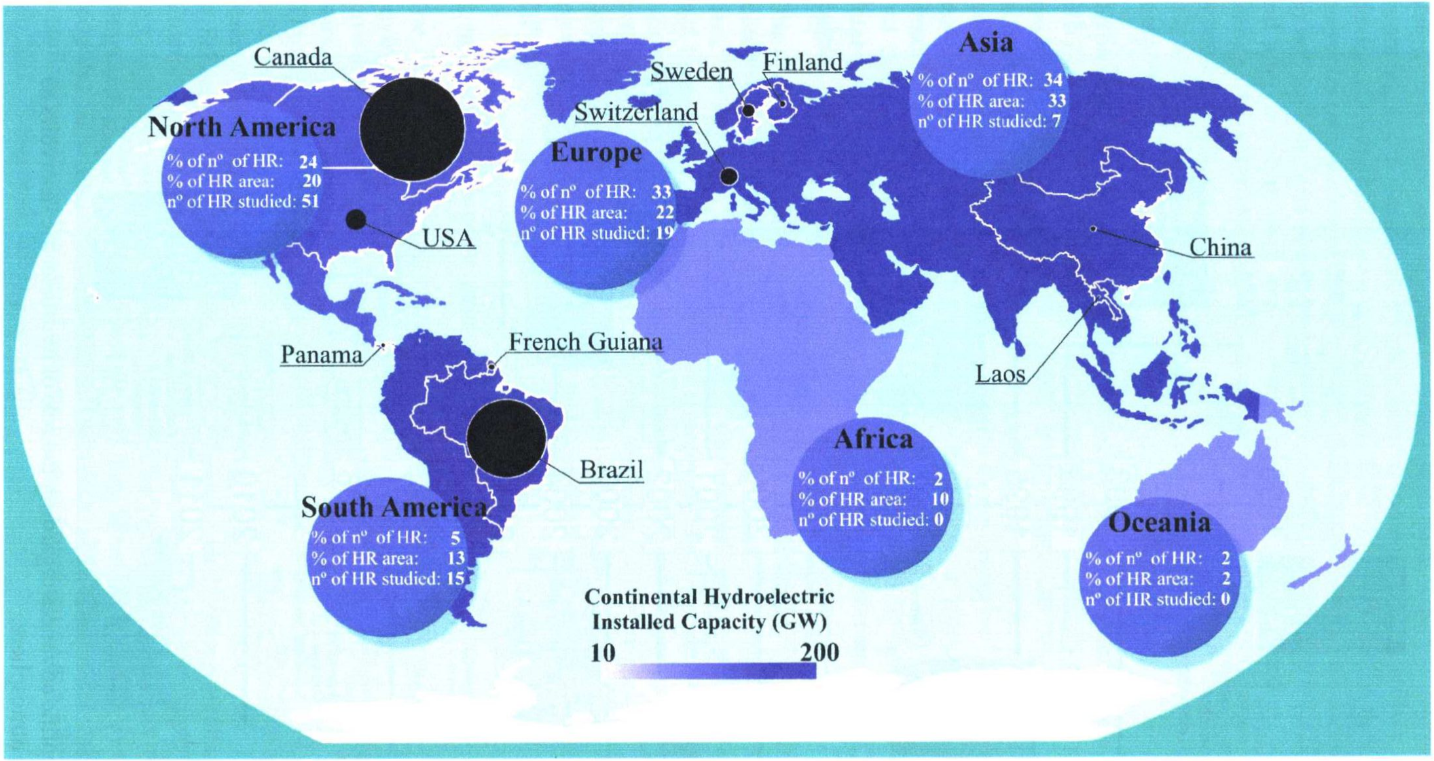

Fig. 2. Global distribution of hydroelectric reservoirs (HR), expressed as the proportion of the total number of reservoirs globally constructed on each continent, the proportion of the global HR area on each continent and the number of HR studied on each continent. The blue gradient indicates the hydroelectric installed capacity per continent. The black circle sizes are proportional to the number of papers published dealing with GHG emissions from reservoirs located in each country. The percentages of total number and total area of hydroelectric reservoirs were calculated based on ICOLD (2007). The numbers of papers published approaching GHG emissions from hydroelectric reservoirs were extracted from Barros et al., 2011, Chanudet et al., 2011, Wang et al., 2011, and Zheng et al., 2011.

2.1 GHG emissions – hydropower versus other electricity sources

Historically, the question to which extent hydropower is a GHG-friendly source of energy has been an important one. A first study focusing on reservoirs in northern Canada suggested that the amount of GHG emitted from reservoirs was substantial when compared to emissions from fossil fuel burning (Rudd et al., 1993). A subsequent assessment estimated that GHG emissions from hydropower plants (considering their full lifecycle) was 30 to 60 times less than the emissions from energy generated from fossil fuel (Gagnon & Van de Vate, 1997). This assessment, however, did not include data from hydroelectric reservoirs in tropical climates which were later found to have relatively high emissions. Yearly GHG emissions from a large reservoir located in the Brazilian Amazon (Tucuruí reservoir), for example, was argued to overcome the fossil fuel emissions from Brazil's largest city, São Paulo (Fearnside, 2002). Others criticized this finding and considered the reservoir GHG emissions to be largely overestimated (Rosa et al., 2004). This critic triggered a scientific debate between two groups with contrasting opinions (Fearnside, 2004; Rosa et al., 2004; Cullenward & Victor, 2006; Fearnside, 2006; Giles, 2006). Although the groups disagree on the amount of GHG emitted from hydropower in relation to other energy sources, they do agree that GHG emissions from tropical reservoirs are large. Emissions from the Brazilian Curuá-Una reservoir, for instance, were argued to overcome the emissions from oil generated electricity (Fearnside, 2005). Later, Brazilian hydroelectric reservoirs were shown to emit less carbon per energy production than thermonuclear power plants, with the exception of some cases of low power density, i.e. low energy production/flooded area ratio (Dos Santos et al., 2006). Finally, a recent inventory including several Brazilian reservoirs located both in the Amazon and in other biomes showed that the GHG emissions per energy produced (GHG/MWh) are lower in most reservoirs, regardless of their age (Ometto et al., submitted). This inventory showed that the highest GHG/MWh rates occur in large Amazonian reservoirs with low energy production rates.

Overall, hydropower may thus produce electricity with one of the lowest life-cycle GHG emissions (Weisser, 2007), especially in non-tropical regions (Barros et al., 2011). Nevertheless, the important role of hydroelectric reservoirs in the global GHG dynamics is unquestionable.

2.2 Organic matter and GHG

The high GHG emissions from hydroelectric reservoirs were originally argued to be due to the decomposition of flooded organic soil and vegetation (Rudd et al., 1993; Abril et al., 2005). This understanding of the role of reservoirs needs to take into account the balance between GHG emissions and consumption prior to and after the impoundment of a certain area (Teodoru et al., 2010). Net GHG emission was considered close to zero prior to impoundment, as emissions from rivers would be compensated by the sink of terrestrial photosynthesis. After flooding, the GHG neutral terrestrial system is replaced by a system with net GHG emissions to the atmosphere (Kelly et al., 1994).

This focus on the flooded organic matter further lead to the understanding that with reservoir aging, the amount of decomposable flooded organic matter would be gradually reduced and, thus, GHG emissions from reservoir surfaces would decline. Indeed, a long-term assessment of GHG emissions from the tropical Petit Saut reservoir showed that CO_2 and CH_4 emissions are high in the first two years after impoundment after which emissions rapidly decline when the more labile flooded organic matter is decomposed (Galy-Lacaux et al., 1997; Galy-Lacaux et al., 1999). Emissions of CO_2 from Brazilian reservoirs were predicted to be concentrated in the first 10 years after flooding (Fearnside, 1995, 1997). Later, evidence from Canadian systems showed a similar trend and suggested that CO_2 emissions from reservoirs older than 10 years tend to equal the emissions from natural lakes and rivers (Tremblay et al., 2004). Similar results were also reported for a Swedish reservoir which was compared with a natural lake (Aberg et al., 2004). Moreover, a significant negative relationship between age and GHG emissions was registered for temperate reservoirs (St Louis et al., 2000) and for reservoirs located all over the globe (Barros et al., 2011).

Nevertheless, other sources of carbon to reservoirs besides flooded organic matter should be taken into consideration. During their complete lifetime, organic matter and nutrients from the drainage basin are continuously flushed into the systems through tributary rivers (Fearnside, 1995; Roland et al., 2010) and aquatic primary production rates tend to increase (Bayne et al., 1983). Once in the reservoirs, organic matter derived from the drainage basin and from aquatic primary production mineralizes at different rates, the latest being usually more labile (Kritzberg et al., 2005; Vidal et al., 2011). Most of the organic matter mineralization and, thus, most of the GHG production in reservoirs occurs in the sediment (Aberg et al., 2004; Abe et al., 2005). Furthermore, it has become clear that GHG emitted from reservoir surfaces is not necessarily produced within the system, as tributary rivers may export large amounts of GHG to reservoirs (e.g. Lima et al., 1998).

2.3 Global emission estimates

From 2004 on, the studies were marked by a more holistic approach incorporating emissions from water passing through the turbines and downstream of dams, as has been done earlier in the tropical Petit Saut reservoir (Galy-Lacaux et al., 1997). Continuous measurements from Petit Saut reservoir lead to a 10-year assessment of GHG emissions which showed that degassing downstream the turbines may represent the major pathway for CH_4 emissions (Abril et al., 2005). High emissions downstream of dams were registered in other tropical (e.g. Guerin et al., 2006; Kemenes et al., 2007, 2011) and in temperate reservoirs as well (e.g. Soumis et al., 2004; Abril et al., 2005; Roehm & Tremblay, 2006). Motivated by the idea of mitigating CH_4 emissions from reservoirs, a method was proposed to capture the CH_4 emitted downstream dams and utilize it, for instance, to generate electricity during high demand periods (Bambace et al., 2007).

More recently, attention has turned to the spatial variability on GHG emissions within reservoirs. Measurements in tropical reservoirs suggested that neglecting the spatial variability in CO_2 emission from reservoirs may lead to more than 25% error in estimations (Roland et al., 2010). In the same year, spatial variability in CO_2 fluxes from temperate reservoirs was shown to decline with time after impounding (Teodoru et al., 2010). The importance of considering the spatial variability in CH_4 emissions was also addressed based on data from Chinese reservoirs (Zheng et al., 2011).

The first global estimation of GHG emissions from reservoirs was published in 2000 (St Louis et al., 2000). This assessment considered emissions from reservoirs of all uses, including irrigation, water supply, energy generation and others. Based on 21 systems located in temperate climate (i.e. Canada, United States, and Finland), the authors calculated average emissions of 1400 mg m^{-2} d^{-1} of CO_2 and 20 mg m^{-2} d^{-1} of CH_4. Their estimated emissions from tropical reservoirs (3500 mg m^{-2} d^{-1} of CO_2 and 300 mg m^{-2} d^{-1} of CH_4), though, were based on data from a very small number of systems (four) and might have been overestimated due to the inclusion of young reservoirs (1-2 year old) which have high emissions. After estimating the global area occupied by all reservoirs types, the authors calculated the global emissions of GHG to be 273 Tg of CO_2 and 48 Tg of CH_4 per year. Considering that CH_4 global warming potential is 25 times higher than that of CO_2 (IPCC, 2007), these emissions corresponded to 2,600 Tg of CO_2-equivalents per year.

After 2000, there was an important increase in the amount of data on GHG emissions from reservoirs located in both temperate (e.g. Huttunen et al., 2002; Aberg et al., 2004; Bergstrom et al., 2004; Soumis et al., 2004; Tremblay et al., 2004; Duchemin et al., 2006) and tropical regions (e.g. Delmas et al., 2001; Fearnside, 2002; Rosa et al., 2004; Abril et al., 2005; Guerin et al., 2006 ; Guerin et al., 2007). Comparisons between emissions in different regions were applied as tools to understand the factors controlling emissions from reservoirs. For example, CO_2 emissions from Swedish reservoirs were lower than those reported for other boreal regions, which was attributed to the fact that in Sweden often comparatively small areas with thin layers of organic soil are flooded for reservoir construction (Bergstrom et al., 2004). In 2011 a review of the achievements in 20 years of measurements of CH_4 emission from tropical and equatorial reservoirs came out (Demarty & Bastien, 2011). The document claims that GHG emissions might have been underestimated in the tropics due to the neglect of CH_4 emissions.

Finally, the latest global assessment of GHG emissions from hydroelectric reservoirs compiled data from 85 globally distributed systems which account for about 20% of the global area occupied by hydroelectric reservoirs (Barros et al., 2011). The authors estimated that hydroelectric reservoirs globally emit about 51 Tg of carbon per year (48 Tg per year as CO_2 and 3 Tg per year as CH_4 or 288 Tg of CO_2-equivalents per year) which is low compared to the first global estimation (321 Tg of carbon per year, St Louis et al., 2000). This difference is argued to be caused (i) by the greater amount of data currently available and (ii) by the smaller area occupied by hydroelectric reservoirs (350.000 km^2, Barros et al., 2011) when compared to the area occupied by all types of reservoirs (1.500.000 km^2, St Louis et al., 2000). Furthermore, this latest assessment showed that GHG emissions are correlated to reservoirs age and latitude, with the highest emission rates occurring in the Amazon region.

3. Environmental effects of hydroelectric reservoirs and the consequences for GHG emissions

By definition, hydropower is a renewable source of electricity in which power is derived from the energy of water moving from higher to lower elevations. The amount of energy generated depends both on the accumulated water volume and on the difference in height between the water inlet and the outflow. While dams perform an important function, their effect on landscapes is remarkable: a fragment of river and its adjacent terrestrial environment are transformed in a new freshwater system, the reservoir. According to recent global inventories, 10,800 km^3 of water were impounded in reservoirs (all kinds of reservoirs, e.g. irrigation, water supply, flood control, and aquaculture) in the last half century, causing the sea level to reduce by approximately 30 millimeters (Chao et al., 2008). The construction of reservoirs clearly represents, thus, one of the major human impacts on the hydrological cycle. The effects of such transformation, however, surpass the hydrological level. Impounded areas undergo a cascade of changes which influence, directly or indirectly, the local GHG fluxes (**Figure 3**).

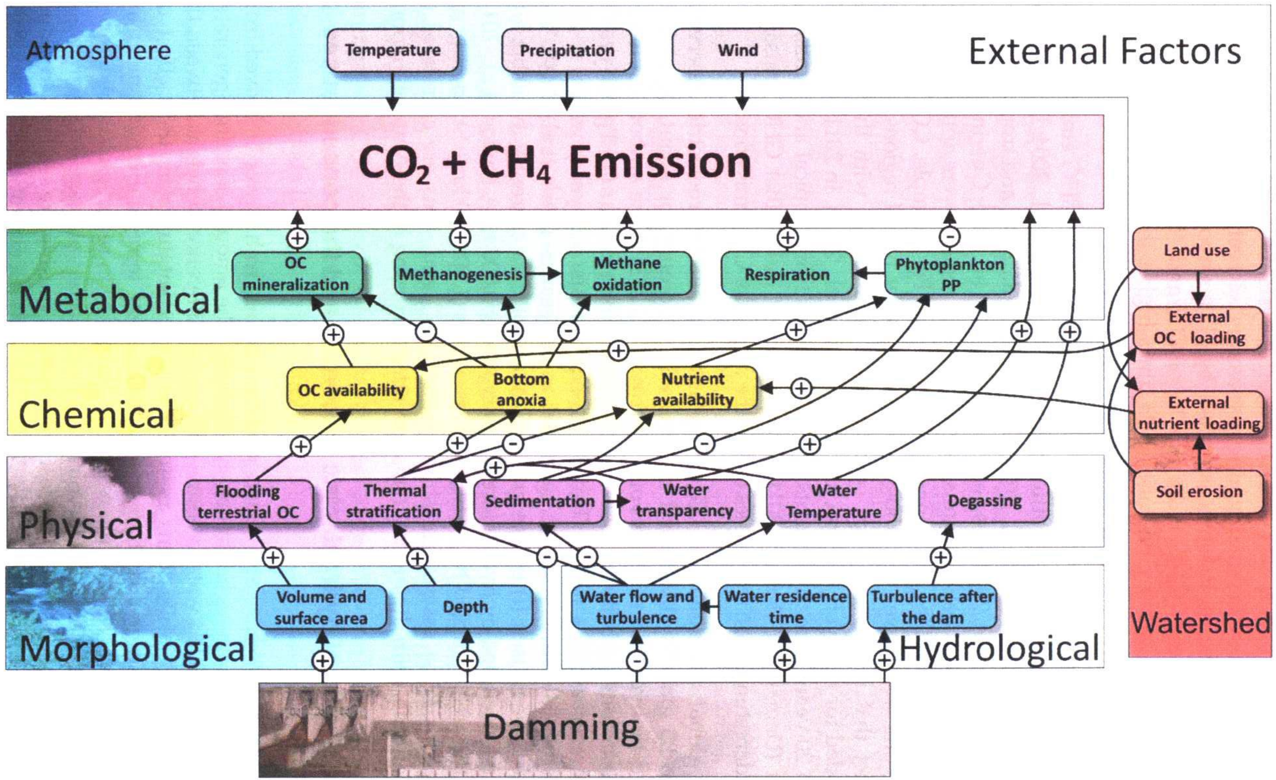

Fig. 3. Diagram illustrating some of the major impacts of damming rivers and their effects on GHG emissions. Direct hydrological impacts of damming rivers trigger a cascade of shifts in the physical and chemical environment, leading to indirect (through changes in metabolism) and direct changes in GHG fluxes. External factors affecting GHG emissions are mainly related to atmospheric conditions and drainage basin characteristics. OC = organic carbon; PP = primary production. Arrows with the (+) symbol represent positive effect; arrows with the (-) symbol represent negative effect.