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REPORT

Greenhouse gas status of hydro reservoirs

Atle Harby, SINTEF Energy Research, Norway
Frederick Guerin, IRD Toulouse, France
Julie Bastien and Maud Demarty, Environnement Illimité, Canada

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Preface

Since the early 1990's, hydropower reservoirs have been identified as a potentially significant source of carbon dioxide and methane for the atmosphere. There is still a lack of data and the complete understanding of all relevant processes involved. This report tries to explain the main processes and principles relevant to understand the greenhouse gas status of hydro reservoirs. The authors of the report are:

Atle Harby, SINTEF Energy Research, Norway
Frédéric Guérin, IRD Toulouse, France
Julie Bastien and Maud Demarty, Environnement Illimitée, Canada

All the authors are working for independent research and consulting institutes and have tried to present a non-biased overview of the important factors and findings, using key literature and their own knowledge.

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Atle Harby
Responsible author

Content

1 Executive summary

The atmosphere contains many gases and most of them have an effect of keeping the air temperature of the earth higher than it would have been without these gases. This is known as the greenhouse effect, and the most important so-called greenhouse gases are water vapour, ozone, carbon dioxide, nitrous oxide and methane. All these gases are found naturally in the atmosphere. C*arbon dioxide* (CO_2), *nitrous oxide* (N_2O) and *methane* (CH_4) are the three main *greenhouse gases* (GHG). Due to human activities, the concentration of these greenhouse gases in the atmosphere has increased the last 40 years. Increased concentrations of greenhouse gases have then increased the greenhouse effect, causing the temperature at the earth's surface to increase.

Hydro reservoirs are natural or artificial bodies of water used to store water and regulate flow for time scales varying from minutes to several years. Reservoirs are constructed for purposes like irrigation, water supply, navigation, flood control, drought protection and hydropower, and many reservoirs serve several of these usages, so-called multi-purpose reservoirs.

Since the early 1990's, hydropower reservoirs have been identified as a potentially significant source of carbon dioxide and methane for the atmosphere. Greenhouse gas emissions from reservoirs are still subject to large uncertainties, and very few studies document the net GHG emissions from creating a reservoir in a river system. The real perturbation of the carbon cycle and related emissions due to reservoir creation should take into account the carbon cycle and emissions from the whole catchment before the creation of the reservoir, and compare this to the situation after the reservoir has been built.

Key parameters that effect the GHG emissions are known to be concentrations of dissolved oxygen, water temperature, organic matter concentrations, supply of nutrients and biomass of plants, algae, bacteria and animals in the reservoir.

The *primary production* is the base of the food chain on earth. *Carbon dioxide* (CO_2) is used to produce *organic matter* and *oxygen (O_2)* by *photosynthesis* in the presence of light, water and nutrients.

All living organisms degrade organic matter to produce energy. This process is called *respiration*, and the first step is *aerobic respiration* with the use of O_2. This occurs therefore in oxygenated zones of environments (*oxic zones*). In O_2-depleted zones (*anoxic zones*), some specialized bacteria are able to perform *anaerobic respiration*. The very last step of organic matter degradation is *methanogenesis* or *methane (CH_4) production* which occurs strictly in anaerobic conditions (in anoxic zones), producing CO_2 and CH_4. Methanotrophic bacteria can transform part of the CH_4 into CO_2 by using O_2 if CH_4 is transported through an oxic zone. CH_4 which was not consumed in this process is either dissolved in water or reach the atmosphere. A fraction of organic matter which is not easily degradable, can be stored in the soil or the sediments.

Primary production is mostly performed on land surfaces by the vegetation, absorbing atmospheric CO_2. Most of the carbon absorbed by the vegetation returns to the atmosphere by respiration of the vegetation and during the degradation of plant detritus at the surface of soils. Well-aerated soils like forests and grasslands can also assimilate carbon from the atmosphere through oxidation of atmospheric CH_4. On the contrary, methanogenesis occurs in water-saturated soils, and these soils are sources of CH_4 for the atmosphere. The less easily degradable fraction of the soil organic matter is stored in the soil and a part of it is transferred to the waterscape as organic and inorganic carbon. At the global scale, terrestrial ecosystems are considered as a sink of carbon and a very significant sink of CH_4.

Production of organic matter in the aquatic ecosystem is mostly performed by the phytoplankton in the water column. Organic matter both from the production in the water and imported from land, is degraded by aerobic or anaerobic *respiration* in the water column and the sediments. *Aerobic respiration* occurs in the oxygen rich part of the water column, and produces CO_2. For most ecosystems, there is no oxygen in the sediments and *anaerobic respiration* occurs below, generating CH_4. In some aquatic ecosystems, the *oxic-anoxic interface* is established *in the water column*. In this case, *aerobic respiration* occurs in the top layer of the water column and *anaerobic respiration* occurs in both the bottom of the water column and in the sediments. CO_2 is produced both in the water column and the sediments. Methane produced in the anoxic sediments diffuses upward. It is estimated that more than 80 per cent of the CH_4 never reaches the atmosphere because of microbial oxidation in the oxic part of aquatic ecosystems. In most aquatic ecosystems respiration is higher than primary production. *This observation implies that most of the aquatic ecosystems are a source of carbon to the atmosphere*. The reason for this is due to the input of organic matter from upstream catchments. At the global scale, lakes, rivers, wetlands are a source of CO_2 and CH_4 to the atmosphere.

Gas exchange between aquatic ecosystems and the atmosphere occurs by *three different pathways*:

1. Both CO_2 and CH_4 can be transferred by *diffusion* from or to the aquatic ecosystems through the air-water interface. This pathway is called *diffusive flux* and it is based on the difference of partial pressure of a gas between the air and the water.
2. *Bubbling fluxes* correspond to the direct transfer of *methane* from the sediment to the atmosphere. In sediments receiving large amount of organic matter by sedimentation, methanogens are very active and CH_4 accumulates in the sediments. Bubbles develop if CH_4 concentration in the sediment pore water exceeds its maximum solubility in water. Bubbling fluxes mainly occur in shallow part of lakes and reservoirs (<10 m).
3. In vegetated littoral zones, CO_2 can be absorbed from the atmosphere or from the water. CH_4 can diffuse from the sediments/soils to the atmosphere through the root system and the plant tissues. Plants act as CH_4 pipes: vegetated areas emit 10 times more CH_4 than adjacent non-vegetated area.

The water column of aquatic ecosystems can be well-mixed or stratified all-year round or alternate seasonally, which has a strong influence on the temporal variations of GHG emissions. Some aquatic ecosystems are stratified most of the year and de-stratify under certain circumstances related to meteorological and hydrological situations. The GHG accumulated below the thermocline during stratified periods are emitted during a very short period of time at the beginning of the de-stratification (known as the *turnover*). In cold regions, GHG can also accumulate under ice and be released at spring during ice melting.

After the creation of a reservoir, the carbon transfer described above between the atmosphere, the land surface and the waterscape are significantly modified. As for natural aquatic ecosystems, GHG production in reservoirs is fuelled by input of organic and inorganic carbon transferred from the terrestrial ecosystems to the reservoir and by the primary production within the water body. In addition, all the carbon that was stored for decades to thousands of years in the soils and the vegetation is flooded and constitutes a source of carbon for the newly created aquatic ecosystem. The same processes as those described for natural water bodies occurs in the water column and the sediment of reservoirs. GHG are exchanged with the atmosphere by the same pathways as natural water bodies. In addition to these pathways, GHG can be emitted downstream of the dam (downstream emissions). This additional pathway includes diffusive emissions from the river below the dam and the degassing at the power station.

Care must be taken when GHG inventories are done, as carbon output from forestry, agriculture, urbanisation, etc. going into reservoirs may be counted twice. The construction of reservoirs may lead to increased human activity as reservoirs and surrounding infrastructures often attract other activities. Many reservoirs receive water, organic material, nutrients and different types of carbon from human activities upstream or within the reservoir. These inputs may also have a large impact on the GHG emissions from the reservoir. Emissions caused by these other non-reservoir or non-hydropower activities should not be related to the hydropower construction and hydroelectric production. Typical examples of such inputs are sewage from urban areas, nutrients and carbon load from agriculture and increased amount of easy degradable organic matter like leaves and small branches from forestry.

Factors like dam and hydropower operations, water depth, changes in water depth and residence time of water in the reservoir are also very important for the GHG emission status. As all these parameters and factors vary both in time and space, and emissions show a large variations from site to site and from time to time.

General trends are observed regarding gross GHG emissions from reservoirs:

- In tropical and boreal reservoirs, emissions were shown to decrease from approximately 3 to more than 10 years following the reservoir creation, to reach natural lakes emission range.
- Downstream emissions also decrease with time, but can be still very significant more than 10 years after flooding depending on the operation of the dam and hydropower plant.
- In boreal reservoirs, it is commonly recognized that gases accumulate under ice and are released as diffusive fluxes on spring ice break-up.
- Highest emission rates are observed in tropical regions.

Net emissions refer to the difference in gross emissions over the whole river basin before and after the reservoir creation. At the global scale, land surfaces are carbon sinks and the flooding of land to create a reservoir will suppress a sink. In many cases it is difficult to calculate or estimate the pre-impoundment GHG exchanges, especially in existing reservoirs where no pre-impoundment 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 concept also requires an estimation of the sources of carbon and to keep track on displacement of emissions. In many catchments the sources of carbon will be forests located in the upper part of the catchment. Prior to impoundment, the resulting GHG emission would occur in the downstream river, while the same emission may occur from the reservoir when impounded.

The construction details of the hydropower plant and hydro operations also play a key role in controlling the GHG flux from a reservoir. If the water intake to the power turbines is located near the surface of the reservoir or through flexible gates drawing water mostly from the surface of the reservoir, the risk of downstream degassing of methane is much lower. If water to the turbines is fed from the oxygen-depleted water closer to the bottom of the reservoir, CH_4 and CO_2 may be emitted downstream the power plant. The use of bottom gates for releasing water or flushing the reservoir may also increase the risk of downstream GHG emissions for the same reason. Hydro operations ensuring that water stays inside the reservoir only for short times will reduce the risk for emitting CH_4.

When forests, grasslands, wetlands and agricultural land are flooded to create a reservoir, the question of biomass removal is often raised. There are both positive and negative aspects to biomass removal prior to inundation, but for long-term emission rates from the created reservoir it is unlikely that removal or not plays a significant role. The biomass has already absorbed carbon from the atmosphere when growing before inundation or removal. If this biomass was not flooded or removed, it would have continued to absorb CO_2 from the atmosphere and emitted carbon back to the atmosphere when degrading. Parts of this biomass would also be stored in the soil, and parts would be transported to the aquatic ecosystem and emitted or stored. If the biomass is flooded, growth would stop and the easiest degradable material will be transformed to CO_2 and methane and emitted within the first years. In addition, the flooding would also mobilize carbon, GHG and nutrients in the soil. Organic matter that was stored on land over decades and centuries may then lead to the release of nutrients and GHG. This *trophic upsurge* caused by flooded biomass and soil is known as a "GHG boost" in the early years of a new reservoir. Less degradable biomass as large tree trunks will probably degrade over decades or even longer time. If the biomass is removed prior to inundation, the net GHG emissions resulting from the removal depend on how this biomass is treated. Another important aspect is that re-growth of vegetation will usually occur between biomass removal and reservoir impoundment, leaving fresh and labile biomass (young leaves) to be degraded within the reservoir. However, biomass removal may improve the water quality for the first years after inundation. Biomass removal may be considered at least along the shorelines of a future reservoir due to other reasons like economic value of trees, oxygen depletion and water quality degradation during the first inundation, navigation and fisheries, tourism, etc.

For an accurate estimation of the atmospheric emissions from a reservoir, the seasonal variation of the fluxes by the whole reservoir system including the lake, the degassing and the river downstream must be studied. Emissions can vary by more than one order of magnitude within a year because of the seasonal variations of organic carbon supply, thermal stratification, irregular convective mixing, depth, hydro operations and flushing rates in the reservoir. Many authors have reported their measurements and calculations in scientific journals and reports, but it is difficult to compare them as many different methods and sampling strategies are used. The GHG Measurement Guidelines for Freshwater Reservoirs issued by UNESCO/IHA gives a good overview of methods and guidance in their application. Measurement methodology vary according to pathway to measure, scope of measurements and budget available. There may also be large spatial variations in emissions from different parts of the reservoir depending on physical characteristics and hydro operations which need to be considered when designing measurement campaigns.

All measurements of natural processes will always be subject to bias and errors in the measurements itself and in the extrapolation and interpretation of results.

2 Introduction

The atmosphere contains many gases and most of them have an effect of keeping the air temperature of the earth higher than it would have been without these gases. This is known as the greenhouse effect, and the most important so-called greenhouse gases are water, ozone, carbon dioxide, nitrous oxide and methane. All these gases are found naturally in the atmosphere. C*arbon dioxide* (CO_2), *nitrous oxide* (N_2O) and *methane* (CH_4) are the three main *greenhouse gases* (GHG).

Due to human activities, the concentration of these greenhouse gases has increased since the 19th century, causing the temperature at the earth's surface to increase. In order to manage and mitigate the negative impacts of the global warming, it is very important to understand the sources and reasons of the increased greenhouse gas concentration. This report will try to clarify the role of hydro reservoirs with respect to greenhouse gas emissions.

Hydro reservoirs are natural or artificial bodies of water used to store water and regulate flow for time scales varying from minutes to several years. Reservoirs are constructed for purposes like irrigation, water supply, navigation, flood control, drought protection and hydropower, and many reservoirs serve several of these usages, so-called multi-purpose reservoirs. Figure 1 shows photos of different shapes of reservoirs.

***Figure 1**. Photos of different types of hydropower reservoirs*

Since the early 1990's, hydropower reservoirs have been identified as a potentially significant source of carbon dioxide and methane for the atmosphere in boreal[1-4], temperate[5] and tropical[6-14] regions. Greenhouse gas emissions from reservoirs are still subject to large uncertainties, and there is a strong need for more observations and better understanding of the processes included. Flux measurements from the water-atmosphere or land-atmosphere interface are reported in the literature from several countries (Figure 2), but very few studies document the real impact of creating a reservoir in a river system in terms of GHG emissions.

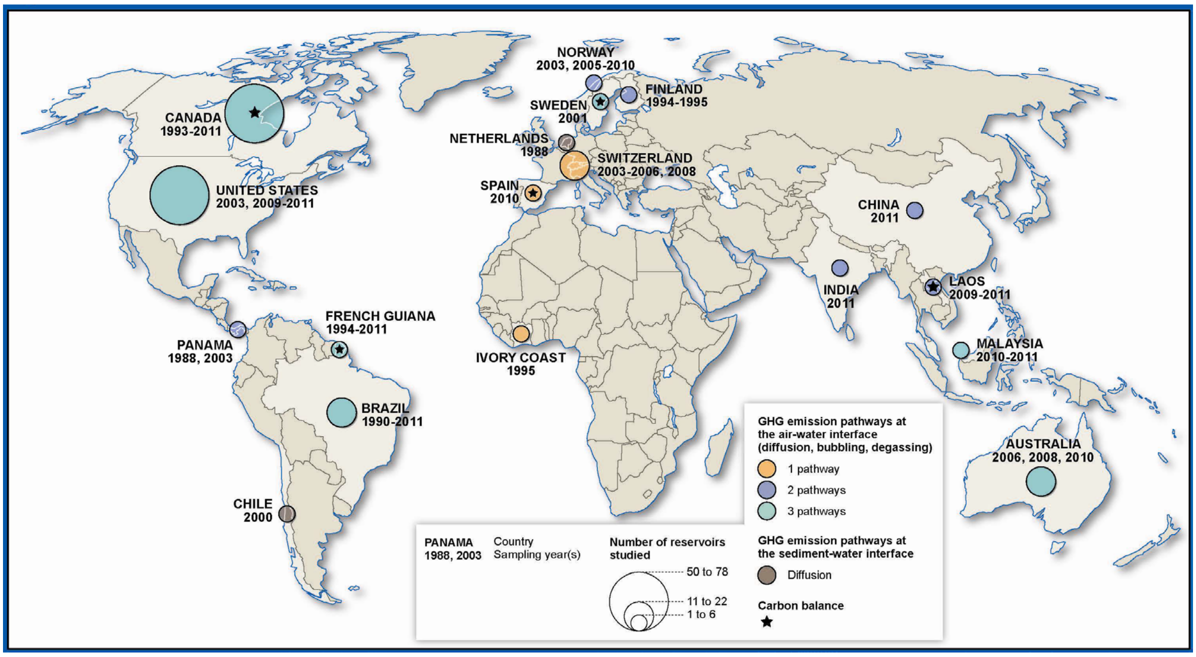

Figure 2. *Locations of GHG measurements in reservoirs.*

Key parameters that effect the GHG emissions are known to be concentrations of dissolved oxygen, water temperature, organic matter concentrations, supply of nutrients and biomass of plants, algae, bacteria and animals in the reservoir. Factors like dam and hydropower operations, water depth, changes in water depth and residence time of water in the reservoir are also very important for the GHG emission status. As all these parameters and factors vary both in time and space, emissions may also show large variations from site to site and from time to time.

3 Carbon cycle, storage and GHG processes

3.1 The carbon cycle

The main processes of the carbon cycle are presented in Figure 3.

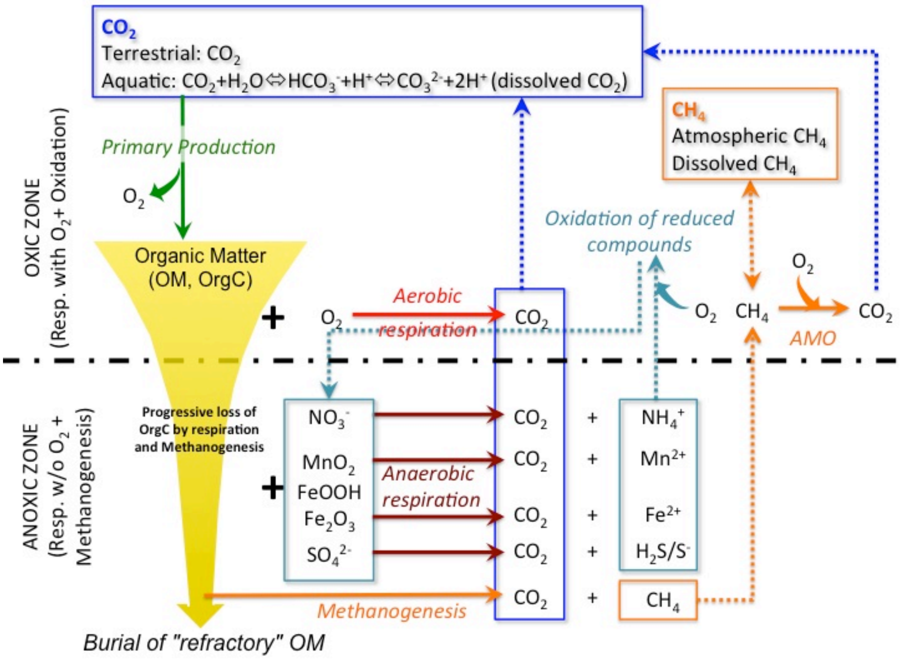

***Figure 3**. Principle sketch of the carbon cycle.*

The *primary production (PP)* is the base of the food chain on earth. *Carbon dioxide* (CO_2) is used to produce *organic matter (OM)* and *oxygen (O_2)* by *photosynthesis*. Photosynthesis occurs in the presence of light, water and nutrients. The carbon from taken up in OM is called *organic carbon (OrgC)*.The organisms responsible for the PP are called *primary producers* or *autotrophs*. The primary producers are basically the plants in terrestrial ecosystems and mostly in aquatic ecosystems. Autotrophs in terrestrial ecosystems use directly atmospheric CO_2 whereas in aquatic ecosystems they use CO_2 dissolved in water that is *Dissolved Inorganic Carbon (DIC)*.

Living organisms that are not able to perform photosynthesis are called *heterotrophs*. The heterotrophs are animals, fungi and most of the bacteria. They produce biomass by the incorporation of OrgC from OM previously produced by autotrophs.

The pool of OM in an ecosystem is the sum of the biomass of the living or dead autotrophs and heterotrophs (*autochthonous OM*) and all OM coming from other ecosystems in the surroundings (*allochthonous OM*).

All living organisms, autotrophs and heterotrophs, degrade OM to produce energy. This process is called *respiration*. During this process, big molecules are broken into smaller ones. Living organisms use different chemical compounds containing oxygen in order to *oxidize* OM. This first step is *aerobic respiration*, using O_2 and it is performed by both autotrophs and heterotrophs. This occurs therefore in oxygenated zones of the environment (*oxic zones*). Oxic zones can co-exist with O_2-depleted zones (*anoxic zones*). In anoxic zones, some specialized bacteria are able to perform *anaerobic respiration*. A fraction of the *reduced* *compounds* produced during anaerobic respiration diffuse from the anoxic zone to the oxic zone and are oxidized (consuming O_2) by other bacteria. This contributes to the creation of anoxia. All the CO_2 produced during these processes contribute to the pool of CO_2 in the atmosphere or the pool of dissolved CO_2 in the water.

The very last step of OM degradation *is methanogenesis* or *methane (CH_4) production* which occurs strictly in anaerobic conditions (in anoxic zones), producing CO_2 and CH_4. At the oxic-anoxic interface, methanotrophic bacteria transform most of the CH_4 diffusing from anoxic zones into CO_2 by using O_2. This process is called *aerobic methane oxidation (AMO)* and contributes to creation of anoxic conditions. The fraction of CH_4 which was not consumed by AMO is either dissolved in water or reach the atmosphere.

In marine ecosystems, anaerobic CH_4 oxidation is known but its occurrence in freshwater ecosystems has to be confirmed.

A fraction of the OrgC is neither assimilated nor used for energy production by the living organisms because it is not easily degradable. This fraction of *refractory OM* is buried either in soils for terrestrial ecosystems or in the sediments for aquatic ecosystems.

3.2 Terrestrial carbon cycle

3.2.1 Carbon reservoirs

Terrestrial ecosystems have four carbon reservoirs. Two reservoirs are below ground: the *soil* and the *lithosphere* (rocks and the crust of the earth). The two active above-ground reservoirs are the *biosphere* (plants, animals and bacteria) and the *atmosphere*.

The main carbon reservoir on Earth is the lithosphere which contains 66000 MPgC (66.10^{24}gC) in sedimentary carbonate rocks. This is the most passive reservoir where significant exchange of carbon with other reservoirs on Earth occurs at millennial timescales.

At the soil surface, the OM is mixed with minerals. The soil can be divided in two sub-reservoirs. The deepest soil sub-reservoir is the third largest carbon reservoir (1200 PgC) on Earth and contains mostly very resistant (refractory) OM, with a carbon residence time of 10 to 1000 years. The upper part of the soil is composed of dead and living biomass like root systems of the vegetation, fungi, bacteria and animals. With a residence time of carbon being less than 10 years, this sub-reservoir is highly active in terms of exchange with other carbon reservoirs and contains 20 per cent of the soil carbon (300 PgC).

The biosphere is composed of all living organisms at the Earth surface. This is basically the above-ground part of the vegetation (the roots belong to the soil) and all living animals. The vegetation represents the main part of the carbon stock in this reservoir (500 PgC). The biosphere is very dynamic in terms of exchange of carbon with the soil and the atmosphere.

3.2.2 Carbon transfer

Vegetation absorbs atmospheric CO_2 to perform *primary production* (PP) by photosynthesis during the day in the presence of light. The plants also *respire* and re-emit CO_2 to the atmosphere. The difference between the primary production and the respiration is *Net Primary Production* (NPP), which corresponds to the amount of organic carbon (OrgC) being actually stored in the plant biomass. At the global scale, it is considered that about half of the primary production is respired directly back to the atmosphere. A significant amount of the stock of OrgC from the vegetation is transferred to:

i. the atmosphere by *forest (and vegetation) fires* and by the production of *Volatile Organic Compounds* (VOC);
ii. the soil mainly by *detritus (litter, dead wood fall, dead animals and faeces)* and secondary by *forest fires*.

Figure 4 shows an illustration of the terrestrial carbon transfer.

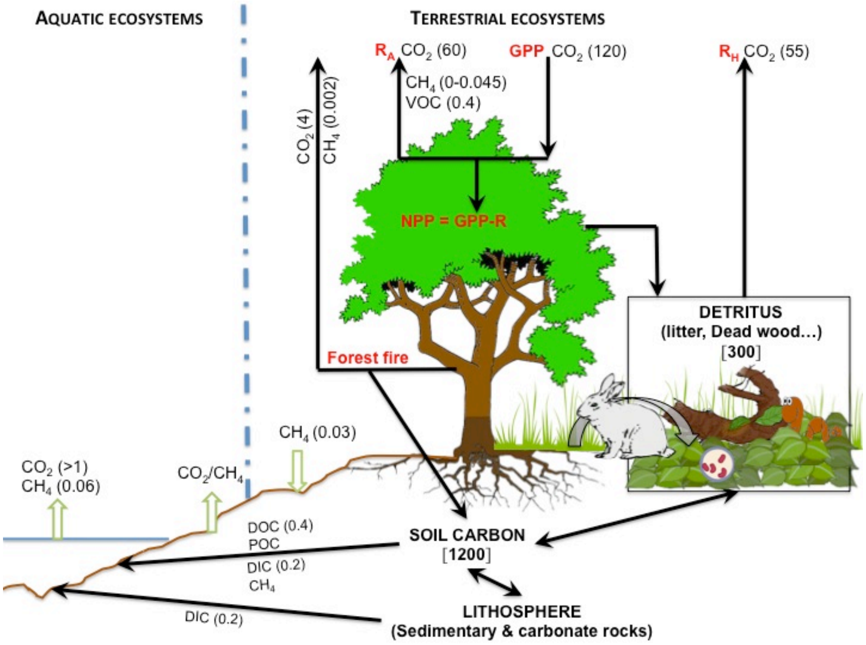

Figure 4. *The terrestrial carbon cycle.*

This mixture of OM from different origin is degraded by heterotrophs both in anaerobic and aerobic respiration. This intense recycling of OM in the soil generates a significant flux of CO_2 to the atmosphere which almost equals the NPP (96 % of NPP).

Methane (CH_4) plays a minor role in the terrestrial carbon cycle but its aerobic oxidation by bacteria in soils is a major component of the global methane cycle. At the earth surface, soils are considered to be the only sink of atmospheric methane. Locally and temporarily, methane can be produced by *methanogenic* bacteria in flooded soils and emitted to the atmosphere. Water prevents oxygen penetration and allows the establishment of the required anoxia. Recently, it was shown that trees could produce and transport methane produced in deep soil and emit it to the atmosphere[15,16]. This is still under debate and these fluxes should be used with caution.

Quantifying and predicting all carbon transfer are challenging since they rely on numerous controlling factors. Among these factors, light and climatic parameters (temperature and humidity) are the most important. In forest ecosystem at night-time, respiration is the only active process and there is a net CO_2 flux from the ecosystems to the atmosphere. At daytime, photosynthesis dominates over respiration, and there is a net uptake of CO_2 by the forest.

The *Net ecosystem CO_2 exchange* (NEE) is the difference between the assimilation of CO_2 by photosynthesis and the respiration from the vegetation and the soil. NEE varies with meteorological conditions, over seasons and with the stage of vegetation development. During dry periods, NEE is significantly reduced by restricting photosynthesis and respiration as compared to periods when soil moisture is higher. On monthly to seasonal time scales, ecosystems experience the effects of the seasonal change in the amount of sunlight received, the meteorological factors and also the evolution of the leaf surface area. As a consequence, temperate forests in summer stock carbon, whereas carbon is released during winter. In tropical forests with evergreen vegetation, carbon sequestration (storage) can be efficient all year long if soil water content is not limiting. The growth of young forest allows high OM storage whereas an old forest emits as much CO_2 as it absorbs because old trees grow more slowly than young ones.

Considering all carbon sources and sinks but excluding CH_4 and VOC as presented by IPCC[17], world terrestrial ecosystems would store 0.3 per cent of all carbon spiralling between atmosphere, the vegetation and the soil. 99 per cent of all CO_2 absorbed by the biosphere returns to the atmosphere. According to this terrestrial carbon cycle, terrestrial ecosystems are considered as autotrophs since primary production prevail on respiration.

If CH_4 and VOC are added to the budget, it appears that the stock of carbon in terrestrial ecosystems is close to equilibrium. It does not mean that terrestrial ecosystems are not storing carbon but it emphases that the current knowledge on the carbon transfers on Earth is still approximative.

3.3 Aquatic carbon cycle

3.3.1 Organic and inorganic carbon cycling in the waterscape

Surface and subsurface water flows (runoff) are the main vectors for the transport of carbon from the terrestrial to the aquatic ecosystems. Approximately, terrestrial ecosystems export 50 per cent of OrgC (Dissolved Organic Carbon, DOC) and 50 per cent of dissolved inorganic carbon (DIC) to the aquatic ecosystems. DOC comes from surface OM and is then transported mostly by surface run-off. DIC is produced in soils and bedrock by chemical weathering (mineral dissolution) caused by water infiltration in these two carbon reservoirs. Therefore, DIC is transported by subsurface flow. The imported carbon (DIC and DOC) and nutrients are considered as allochtonous. Carbon may also be exchanged directly between the waterscape and the atmosphere. Figure 5 shows an illustration of the carbon cycle in the waterscape.

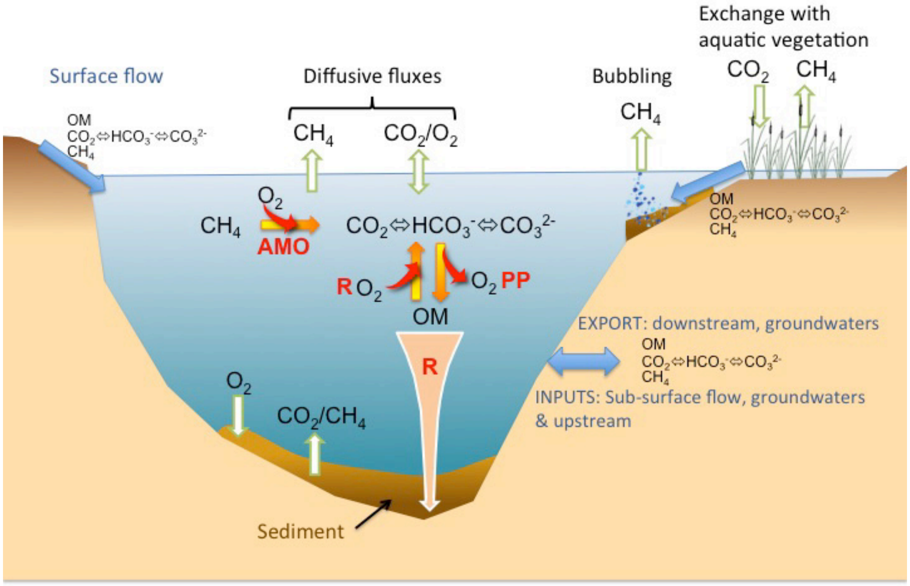

Figure 5. *Carbon cycle in the waterscape (lakes, rivers, wetlands).*

Primary producers provide autochtonous OM to the ecosystem performing photosynthesis in the euphotic zone (water column where light is available). Algae and phytoplankton use autochtonous and allochtonous DIC whereas *macrophytes* (aquatic plants on the littoral zone) absorb the allochthonous atmospheric CO_2.

Organic matter (OM) is degraded by aerobic or anaerobic *respiration* in the *water column* and the *sediments*. In the oxygenated (oxygen rich) part of the water column, *aerobic respiration* occurs. For most ecosystems, there are no oxygen in the sediments. In this case, the *oxic-anoxic interface* is located either *at the sediment-water interface or within the first millimetres of the sediment* when O_2 penetrates it. The *anaerobic respiration* occurs below, in the anoxic sediment. In some aquatic ecosystems (some lakes, wetlands, hydro reservoirs, rivers and estuaries) the *oxic-anoxic interface* establishes *in the water column* for various reasons. In this case, *aerobic respiration* occurs in the top layer of the water column and *anaerobic respiration* occurs in both the bottom of the water column and the sediments. Some of the compounds produced during the degradation of OM or oxidation at the oxic-anoxic interface are used as nutrients by primary producers for photosynthesis. The CO_2 produced during OM degradation diffuses upward.

The less degradable fraction of the allochthonous and autochthonous OM settles down and is buried in the sediment.

3.3.2 Methane cycling in the waterscape

Methane production (methanogenesis) occurs mostly (if not only) in the sediments, when all oxidants of OM are consumed by bacteria. Methane diffuses upward, from the anoxic sediment to the water column. According to the location of the oxic-anoxic interface, *Aerobic Methane Oxidation (AMO)* takes place at the surface of the sediment or in the water column.

In vegetated shallow parts of reservoirs, OM produced by PP of plants fuels methanogenesis which can be more than 10 times higher than in un-vegetated sediments. Oxygen diffuses from the atmosphere to the root through the plant tissues in order to provide O_2 for respiration in the root system. AMO takes place at the oxic-anoxic interfaces around the roots.

It is estimated that more than 80 per cent of the CH_4 produced in anoxic zones never reaches the atmosphere because of AMO in oxic layers of aquatic ecosystems.

3.3.3 GHG flux between water and the atmosphere

Gas exchange between aquatic ecosystems and the atmosphere occurs by *three different pathways*.

i. Both CO_2 and CH_4 can be transferred by *diffusion* from or to the aquatic ecosystems through the air-water interface. This pathway is called *diffusive flux* and it is based on the difference of partial pressure of a gas between the air (P_a) and the water (P_w). If P_w is higher than P_a the gas diffuses from the water to the atmosphere because a chemical compound always diffuses from the most concentrated layer to the less concentrated. Several parameters control the intensity of the diffusive fluxes: the gradient itself (the bigger it is, the bigger the flux is) and also some physical parameters like wind speed, water current velocity, rainfall, and temperature enhance the fluxes.

ii. *Bubbling fluxes (or ebullition*) correspond to the direct transfer of *methane* from the sediment to the atmosphere with little interaction with AMO. In sediments receiving large amount of OM by sedimentation, methanogens are very active and CH_4 accumulates in the sediments. Bubbles develop if CH_4 concentration in the sediment pore water exceeds its maximum solubility in water. Bubbling fluxes mainly occur in shallow part of lakes and reservoirs (< 10m) where the hydrostatic pressure is not high enough to increase the solubility of CH_4. The release of the bubbles is triggered by atmospheric pressure variations, variations in water current velocity, rapid changes of the water level above the sediment, increase of temperature (CH_4 solubility decrease). Ebullition is episodic and thus it is difficult to accurately quantify it. Bubbling fluxes are probably always underestimated, thus they must be determined as often as possible.

iii. In vegetated littoral zones, CH_4 can diffuse from the sediments/soils to the atmosphere through the root system and the plant tissues. Plants act as CH_4 pipes: vegetated areas emit 10 times more CH_4 than adjacent non-vegetated area.

3.3.4 Impact of hydrophysical parameters and seasonal variation

The physical mixing of water bodies has a strong impact on the position of the oxic-anoxic interface in either the water column or the sediment of aquatic ecosystems. The mixing of a water body depends on factors like current velocities, in- and out-flows, wind speed, air temperature changes, the temperature difference between the water and the air, the depth of the water body and ice cover.

Some *well-mixed water bodies* (most of rivers and estuaries, some lakes, reservoirs and wetlands), has more or less constant temperature and oxygen content throughout the depth. Most water bodies are *thermally stratified* when the physical mixing is not high enough. During summer in cold climates and year around in temperate and warm climates, the water temperature is higher at the surface than at the bottom. As the density of water is highest at 4 °C, the top layer of water bodies in cold climates during winter is normally colder (between 0 and 4 °C) than the bottom layer. Figure 6 shows a schematic drawing of a stratified (layered) and non-stratified lake or reservoir.

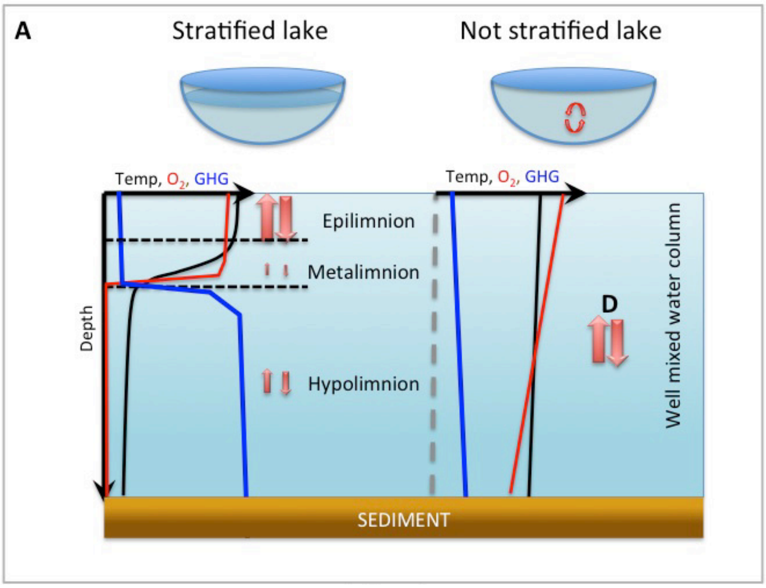

Figure 6. *Stratified and non-stratified lake.*

The water temperature regulates the *diffusion (D) up or downward* of the chemical compounds in the water column. Diffusion is fast when the temperature is almost homogenous. In the *metalimnion* (the transition zone between the bottom and top layer), the sharp evolution of temperature reduces the diffusion of about 1000 times. It acts thus as a physical barrier for the transfer up and down of chemical compounds. The consequences are described below:

Oxygen diffuses slowly from the top layer to the bottom layer (*hypolimnion*). In addition, the oxidation of reduced compounds and methane diffusing upward from the hypolimnion consumes oxygen at the base of the metalimnion. These two factors are responsible for the establishment of the oxic-anoxic interface in the metalimnion, also known as the *oxicline*. Chemical compounds like GHG produced in the sediment or at the bottom of the water column tends to accumulate in the bottom layer (hypolimnion).

The water column of aquatic ecosystems can be well-mixed or stratified all-year round or alternate seasonally, which has a strong influence on the temporal variations of GHG emissions. Some aquatic ecosystems are stratified most of the year and de-stratify under certain circumstances related to meteorological and hydrological situations. The GHG accumulated below the thermocline during stratified periods are emitted during a very short period of time at the beginning of the de-stratification (known as the *turnover*). In cold region, GHG can also accumulate under ice and be released at spring during ice melting.

The seasonal and inter-annual variations in emissions from all aquatic ecosystems, whatever their physical dynamics, depend also on:

i. OM inputs from the watershed. These inputs fuel the respiration and thus the production of GHG. They are for instance higher during rainy periods and seasons.
ii. The light availability is higher during summer and enhances primary production (if nutrients are available). In turn, the production of easily degradable allochthonous OM fuel respiration.
iii. The temperature: During warm periods like spring and summer, both the primary production and the respiration are enhanced.

Like terrestrial ecosystems, the generalization of the GHG emission patterns from aquatic ecosystems is challenging since they rely on numerous controlling factors and retroactions (physical, meteorological, biological, microbiological, chemical factors).

In most aquatic ecosystems respiration is higher than primary production (PP). *This observation implies that most of the aquatic ecosystems are a source of carbon to the atmosphere*. The carbon emissions, mostly in form of CO_2, are actually fuelled by the input of allochthonous OM which are usually higher than the production of autochthonous OM. This means that the reason for aquatic ecosystems being a source of carbon to the atmosphere is due to the input of OM from upstream catchments. *Care must be taken when GHG inventories are done, as carbon output from forestry, agriculture, urbanisation, etc going into reservoirs may be counted twice*. CO_2 emissions and OM sedimentation in all aquatic ecosystems were overlooked until recently but it appears that their role in the global carbon cycle is as important as the role of terrestrial ecosystems. Methane emissions from aquatic ecosystems contribute only to 6 per cent of total carbon emissions from man-made and natural aquatic ecosystems but it contributes to 20 per cent of total CH_4 emissions on Earth.

4 Characteristics of reservoir emissions

There is a wide range in emission rates depending on climate, catchment characteristics, age of reservoir, reservoir area, retention time and carbon loading amongst other factors[18]. Gross annual emissions can vary between 87 and 29,000 kt CO_2eq pr year in tropical reservoirs[19], whereas it can vary between 39 and 1,700 kt CO_2eq pr year in boreal and temperate reservoirs[20]. The sub-tropical Nam Ngum reservoir in Lao PDR was even found to absorb more carbon than emitted[21].

Reservoirs can emit GHGs by four major pathways, the first three of which are also observed in natural water bodies: (1) diffusion at the reservoir surface, (2) bubbling, (3) vegetation, and (4) downstream emissions, which include degassing (diffusive emissions in the turbulent waters downstream of reservoirs) and diffusion and bubbling in the river downstream of the generating station[5, 22]. Diffusive emissions from the reservoirs have been studied most, since they have been recognized first, and also the easiest to measure. For CH_4, however, bubbling from sediments to the reservoir surface and degassing downstream turbines and spillways could be significant emission pathways. The lack of data available is partly explained by the difficulty of measuring and their late recognition.

General trends are observed regarding GHG emissions from reservoirs:

- In tropical (Petit Saut[13]) and boreal (Eastmain-1[23]) reservoirs, emissions were shown to decrease approximately 3 to more than 10 years following the reservoir creation, to reach natural lakes emission range (Figure 7).
- Downstream emissions also decrease with time, but can be still very significant more than 10 years after flooding depending on the operation of the dam and hydropower plant[19].
- In boreal reservoirs, it is commonly recognized that gases accumulate under ice and are released as diffusive fluxes on spring ice break-up[24,25].
- Highest emission rates are observed in tropical regions[26].

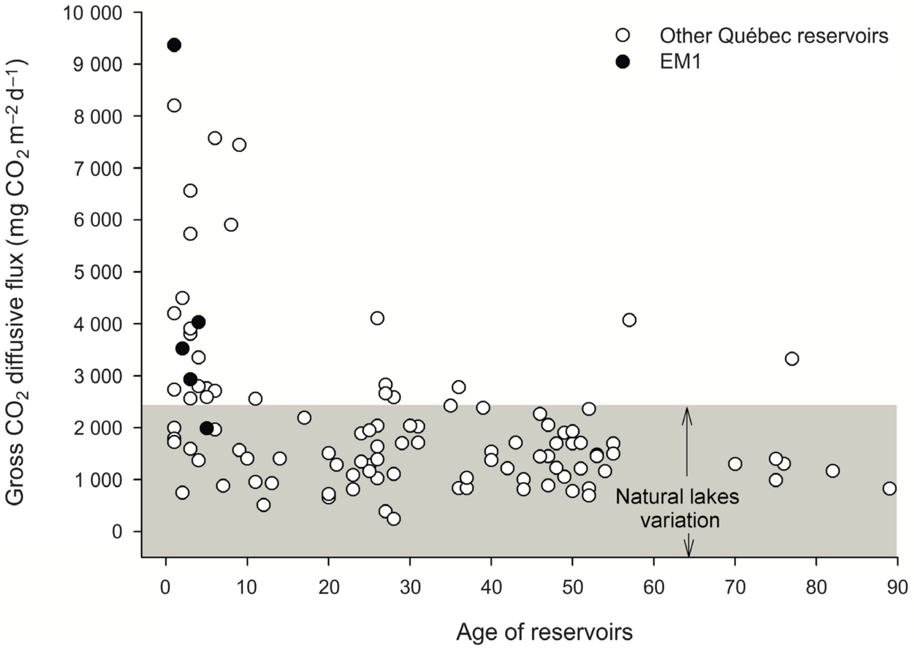

Figure 7[23]*. Evolution of gross summer CO_2 diffusive emissions per square meter per day with reservoir age in Quebec, Canada.*

5 Anthropogenic impacts to the carbon balance and GHG status

The construction of reservoirs may lead to increased human activity as reservoirs and surrounding infrastructures often attract other activities. Many reservoirs receive water, organic material, nutrients and different types of carbon from human activities upstream or within the reservoir. These inputs may also have a large impact on the GHG emissions from the reservoir. Emissions caused by these other non-reservoir or non-hydropower activities should not be related to the hydropower construction and hydroelectric production. Typical examples of such inputs are sewage from urban areas, nutrients and carbon load from agriculture and increased amount of easy degradable organic matter like leaves and small branches from forestry. It is also very important to avoid double-counting of emissions, as many of these other sources of emissions are already counted for in other sector's GHG budget. Special care should be taken when considering emissions related to upstream forests. Trees absorb CO_2 from the atmosphere when growing and release most of the carbon back to the atmosphere through respiration and degradation. A mature forest will more or less be carbon neutral. A large portion of the emissions from degrading forest will naturally come through freshwater systems, as water is transporting 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[27]. Some carbon will also be stored in the sediments of rivers, lakes, reservoirs and wetlands, while the rest are transported to the ocean.

The construction details of the hydropower plant and hydro operations also play a key role in controlling the GHG flux from a reservoir. If the water intake to the power turbines is located near the surface of the reservoir or through flexible gates drawing water mostly from the surface of the reservoir, the risk of downstream degassing of methane is much lower. If water to the turbines is fed from the oxygen-depleted water closer to the bottom of the reservoir, dissolved methane may be following the water and degassed downstream the power plant. The use of bottom gates for releasing water or flushing the reservoir, may also increase the risk of downstream methane emissions of the same reason. Hydro operations ensuring that water stays inside the reservoir only for short times will reduce the risk for emitting GHG. Water will then have a short *residence time*.

Methodologies to measure or estimate direct anthropogenic emissions (urban and industrial activities) are usually well defined and available (Intergovernmental Panel on Climate Change, governments and municipalities). To measure the indirect effect of anthropogenic activities on aquatic system emissions, GHG parameters should be measured upstream and downstream from the source. If there is no difference, we may assume no anthropogenic effect.

5.1 Effects of biomass removal

When forests, grasslands, wetlands and agricultural land are impounded to create a reservoir, the question of biomass removal is often raised. There are both positive and negative aspects to biomass removal prior to inundation, but for long-term emission rates from the created reservoir it is unlikely that removal or not plays a significant role. The biomass has already absorbed carbon from the atmosphere when growing before inundation or removal. If this biomass was not inundated or removed, it would have emitted carbon back to the atmosphere when degrading. Parts of this biomass would also be stored in the soil, and parts would be transported to the aquatic ecosystem and emitted or stored. If the biomass is inundated, growth would stop and the easiest degradable material will be transformed to CO_2 and methane and emitted within the first years. In addition, the flooding would also mobilize carbon, GHG and nutrients in the soil. Organic matter that was stored on land over decades and centuries may then lead to the release of nutrients and GHG. This *trophic upsurge* caused by flooded biomass and soil is known as a "GHG boost" in the early years of a new reservoir. Less degradable biomass as large tree trunks will probably degrade over decades or even longer time. If the biomass is removed prior to inundation, the net GHG emissions resulting from the removal depend on how this biomass is treated. If the biomass is burned, this will cause a direct carbon emission comparable to how much carbon this biomass has absorbed through their life time. If the biomass is used for other purposes, it may be possible to avoid emitting some of the carbon back to the atmosphere. However, the operations required for biomass removal and the transport to alternative use may also lead to significant GHG emissions by forestry machines, logging equipment and trucks. Another important aspect is that re-growth of vegetation will usually occur between biomass removal and reservoir impoundment, leaving fresh and labile biomass (young leaves) to be degraded within the reservoir.

It is also important to note that a large part of the biomass is located in the soil and virtually impossible to remove before inundation. In some cases this portion may be above 50 per cent[2].

Biomass removal is included in some Environmental Impact Assessment and recommended by the World Bank. The main reasons for biomass removal are not related to greenhouse gas emissions and may be done to:

1. avoid loss of economic value from valuable timber in the area to be inundated.

   In reservoirs with no economic value in harvesting the timber due to either high harvesting or transport costs or non-valuable timber, this may not apply.

2. reduce forest biomass to be inundated to reduce oxygen depletion due to decomposition of this material which may have a severe impact of the aquatic life in the reservoir the first period after inundation.

   In reservoirs at low temperatures, short residence time or large water storage volumes of good water quality to prevent oxygen depletion even with large amounts of flooded biomass, this may not be relevant.

3. ensure that the reservoir shoreline and other navigable parts of the reservoir are free of dead vegetation which may impede marine transport, fisheries and other activities like swimming, boating and tourism in the reservoir.

   In reservoirs with no commercial interest this is probably not relevant, but it may be wise to remove trees from the shoreline for navigation and safety reasons.

For each reservoir these factors should be analysed carefully together with the impacts on GHG emissions and other environmental impacts before deciding on biomass removal.

5.2 Measurements

Aquatic emissions occur in various forms:

A. Diffusion at the air-water interface;
B. Bubbling from the sediment to the air-water interface; and
C. Degassing at turbines and spillways.

Hence, the methodology used will vary according to the pathway to measure and budget available. Also, depending on where and how the emissions are measured they will represent an integration of one or two pathways as explained below.

A. Three types of measurement are possible for diffusion. 1) Diffusive emissions are usually measured with a floating chamber placed on the water surface or by measuring gas concentration in the water. Chambers can be used in a continuous mode if gas instruments are brought in the field or in a discontinuous mode if gas samples taken from the chamber are analyzed later on in a laboratory. In both case, the increase or decrease in gas concentration in the chamber is used to calculate a flux. 2) If gas concentrations in the water are measured, theoretical equations are used to estimate diffusive emissions. 3) If a tower can be installed in the reservoir or on a small island within the reservoir, Eddy covariance can be used to estimate emissions from the reservoir. In that case, emissions would represent the integration of diffusion and bubbling.

B. Bubbling emissions can be measured with funnels or with floating chambers. In the latter case, bubbling emissions are measured concomitantly with diffusive emissions. The later case is easier and cheaper because the same technique is used to estimate both pathways.

C. Degassing is estimated by measuring gas concentration upstream and downstream from generating stations and spillways. The upstream concentration should be measured at the depth of the generation station uptake.

Terrestrial emissions occur at various levels: from the soil, shrubs and trees. Hence, measuring emissions above the tree level represent an integration of the emissions. Eddy covariance can be used to measure terrestrial emissions. Figure 8 shows some of the instruments used for measurements in the aquatic zone.

Diffusive emissions – Floating chamber in continuous (left) or discontinuous (right) mode

Water sample bottle for diffusive and degassing emissions   *Bubbling emissions – Funnel*

***Figure 8**. Some instruments for measurements.*

Many authors have reported their measurements and calculations in scientific journals and reports, but it is difficult to compare them as many different methods and sampling strategies are used. The GHG

Measurement Guidelines for Freshwater Reservoirs issued by UNESCO/IHA[18] gives an overview of methods and guidance in their application.

Barros et al[26] analysed published measurements of GHG emissions from 85 reservoirs mainly in Brazil, North America and Scandinavia, and developed an empirical model of how emissions relate to age of the reservoir and latitude. Both CO_2 and CH_4 showed a trend of decreasing emissions with age and towards higher latitudes. They estimated that 16 per cent of the carbon emitted to the atmosphere as CO_2 or CH_4 from human-made reservoirs originates from hydropower reservoirs, representing 4 per cent of all total carbon emissions by freshwater systems.

Table 1 gives some examples of measured *gross* GHG emissions from selected reservoirs around the world. Emissions are given as mg *Carbon* per m^2 and day, and not as mg CO_2 or mg CH_4.

*) Note that negative values mean that CO_2 is absorbed and not emitted.
^) Data to be published from responsible author.

Reservoir	Country	Latitude	CO_2 emission [mg C/m^2 d]	CH_4 emission [mg C/m^2 d]	Age	Reference
Tucuruí	Brazil	3°45' S	2181 - 2845	13-98	15-22	12, 14, 26
Petit Saut	F. Guyana	5°03' N	1224 - 1296	20-180	9-11	8,9,11, 13,26
Xingó	Brazil	9°37' S	1636 - 2683	121	10	14, 21
Nam Leuk	Laos	18°27' N	-127* - 459	9,6 – 142,9	10-11	21
Nam Ngum	Laos	18°32' N	-255* - -32*	1,2 – 7,2	38-39	21
La Grande 2	Canada	53°50' N	354,5	5,0	17	2,26
Follsjø	Norway	62°58' N	21,8 – 199,2	0 – 26,0	35-40	^

Table 1. Gross GHG emissions measured at different reservoirs around the world.

Unfortunately, it is not yet possible to find enough consistent data for calculated *net* GHG emissions from reservoirs. Some attempts have been done, and preliminary analysis from Follsjø reservoir feeding the Trollheim power plant indicates total net emissions of 0,44 g C per kWh produced^. Studies from Brazil has found that fossil fuelled power plants emit 0,25 to 125 times as much C per kWh as gross emissions from hydropower plants[14], when fossil fuels are considered to emit 551-929 g C per kWh with efficiency ranging from 30-50 per cent depending on type of plant and source of fossil energy [14].

6 Net emissions

It is important to understand the gross and net emissions concept to understand the impact of reservoir creation on the environment. Because reservoirs are affected not only by internal processes but by processes occurring elsewhere in the river basin, in both aquatic and terrestrial components, emissions from the whole river basin should be included in analysis.

Gross emissions refer to specific measurements performed either in the terrestrial or aquatic ecosystem. Components of the terrestrial ecosystem may include forest (natural or secondary growth), grassland, farmland, human settlement and industry. Components of the aquatic ecosystem may include lakes, rivers and reservoirs. Wetlands can either be considered as a terrestrial or aquatic component depending on their type. Total gross emissions from the river basin should include the sum of the terrestrial and aquatic emissions at a certain moment in time for the whole river basin.

Net emissions refer to the difference in gross emissions over the whole river basin before and after the reservoir creation (Figure 9). Gross emissions before reservoir impoundment should be estimated over a few years (e.g. 3 years) if possible to include some temporal variation and the selected period should be as near as possible to the impoundment (e.g. 3 years before impoundment). Gross emissions after the reservoir creation should be estimated over the lifetime of the project (e.g. 100 years) to account for reservoir aging. There might also be land use changes not directly related to the creation of the reservoir. If these land use changes lead to changes in GHG emissions, it is important to allocate them to the correct activity and not double-count emissions by also adding emissions to the hydropower reservoir. On site measurements should (if possible) be performed during the first five-ten years following impoundment and then estimated for the remaining years.

Source of variation to include in measurements and estimations should include:

- Variation inherent to the reservoir
    - Initial increase in gross GHG emissions usually observed during the first years following impoundment[13,23];
    - Water level variation due to dam management;

- Variation from the river basin, outside the reservoir influence
    - Fire, pests and diseases will influence natural land and farmland emissions;
    - New and abandoned settlement and industry will influence terrestrial emissions and leakage to the aquatic component;

- Variation inherent to climate
    - Draught, flood, temperature may influence terrestrial and aquatic processes;

At the global scale, land surfaces are carbon sinks and the flooding of land to create a reservoir will suppress a sink. In many cases it is difficult to calculate or estimate the pre-impoundment emissions, especially in existing reservoirs where no pre-impoundment 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 and burial of organic matter and carbon.

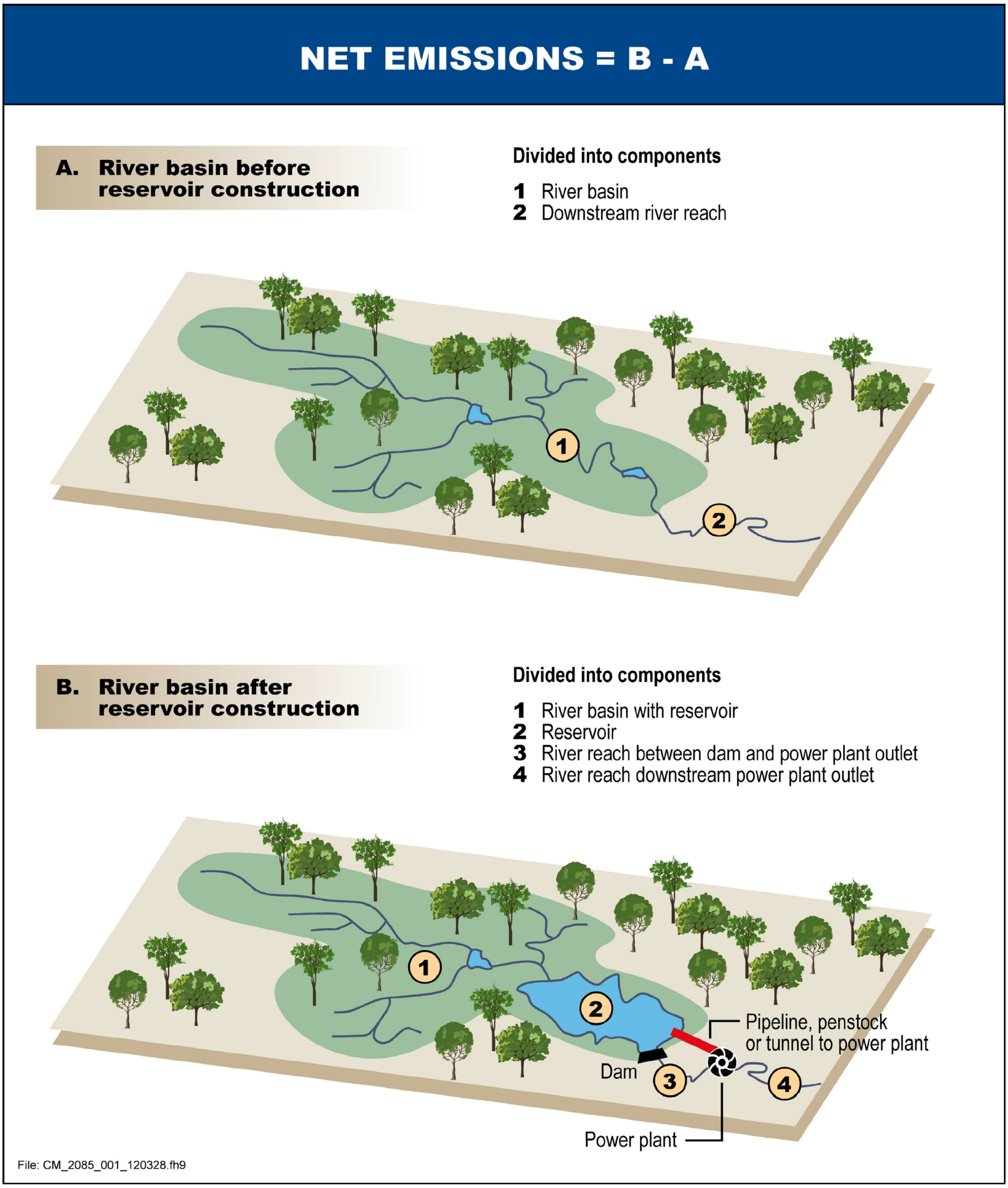

Figure 9. *Net emission concept.*

The net emission concept also requires an estimation of the sources of carbon and to keep track on displacement of emissions. In many catchments the sources of carbon will be forests located in the upper part of the catchment (from section 1 in Figure 9). In the pre-impoundment case the resulting GHG emission would occur in the downstream river (section 2 in the drawing A of Figure 9), while the same emission will be added to the emissions from the reservoir (section 2 in the drawing B of Figure 9) and not in the downstream river (section 4 in the drawing B of Figure 9).

7 Variations and sources of error

For an accurate estimation of the atmospheric emissions from a reservoir, the seasonal variation of the fluxes by the whole reservoir system (including the lake, the degassing and the river downstream) must be studied. As shown at the Petit Saut and Balbina reservoirs, atmospheric emissions vary by more than one order of magnitude within a year because of the seasonal variations of organic carbon supply, thermal stratification, irregular convective mixing, depth, hydro operations and sediment flushing in the reservoir. As shown at the Petit Saut Reservoir with a monthly dataset over ten years, seasonal variations of emissions were higher than inter-annual variations.

The monitoring of reservoirs should be compartmentalized to reflect the distinct parts of the reservoir and predominant process quantified in each of these parts. Six types of sampling stations must be chosen for long term monitoring

- Stations located along the longitudinal axis of the reservoir at its upstream reach to capture the dynamics of material carried with the inflows
- Stations located along the longitudinal axis of the reservoir
- Stations located in vegetated and non-vegetated littoral zones of the reservoir
- Stations located in embayments when they exists
- Stations close to the dam to understand the mixing of the water column upstream of the dam. Whenever it is possible, samples must also be taken in the turbines
- Stations in the river below the dam. Emissions must be studied along the river course until CO_2 and CH_4 partial pressure reach the natural background. The number of sampling stations must be determined depending on the length of the river course impacted by the dam.

All measurements of natural processes will always be subject to bias and errors in the measurements itself that must be taken into account in the extrapolation and interpretation of results. For GHG status of reservoirs, this is particular sensitive since the temporal and spatial variations are very high and since measurements are taken only from a very limited part of the system as it is impossible to measure gas flux over large areas.

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