WATER GLOBAL PRACTICE • TECHNICAL NOTE

Greenhouse Gases from Reservoirs Caused by Biogeochemical Processes

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Contents

Figures

Maps

Tables

Acknowledgments

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Executive Summary

Greenhouse gas (GHG) emissions from reservoirs—created to produce hydropower, achieve water security, or provide flood protection—may be significant and should be considered in the planning and design of new dam infrastructure. This note provides guidance to World Bank Group (WBG) staff on how to assess GHG emissions from reservoirs at an early stage of the preparation process.

The emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from reservoirs have been a source of extensive debate, owing to the divergent results generated by the research community, which has been examining this area for only the last three decades or so. The biogeochemical processes leading to GHG emissions are very complex and emission measurements are cumbersome. Consequently, it is difficult to estimate emissions from existing reservoirs and even more difficult to predict them for future reservoirs.

However, much research has been conducted and published during the last decade, and scientific papers from 2017 indicate that the science and methodologies to estimate GHG emissions from reservoirs are converging. As a result, predictive tools are now available for practitioners involved in dam development. One such tool is the GHG Reservoir Tool (*G-res* tool), developed and launched in May 2017 by a research team led by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Hydropower Association (IHA). A complementary tool is the framework developed by the International Energy Agency Technology Collaboration Programme for Hydropower (IEA Hydro), which (i) recommends procedures for primary data collection and process-based modeling approaches to simulate reservoir GHG emissions, and (ii) provides guidance on how to manage and mitigate those emissions.

These predictive tools are based on the principle agreed by the Intergovernmental Panel on Climate Change (IPCC) for the estimation of *net* reservoir emissions. Rivers are major conveyors of carbon from terrestrial areas to lakes and the sea. Terrestrial areas are generally net carbon *sinks* while aquatic systems are net carbon *emitters*. Changes in GHG fluxes to the atmosphere resulting from the introduction of reservoirs in a river system must therefore be viewed from a catchment perspective. *Net GHG emissions* caused by a reservoir are the difference between total fluxes of CO_2 equivalent emissions for the river basin before and after the creation of that particular reservoir.

The *G-res* tool builds on this principle of calculating the net anthropogenic GHG emissions, that is, what the atmosphere will see when a new, man-made reservoir is introduced into the landscape. A recent application of the *G-res* tool to a global database of reservoirs[1] indicates that man-made reservoirs account for about 0.5 percent of global anthropogenic GHG emissions, which is less than previously estimated. The main reasons for this lower estimate are that only emissions directly attributable to the reservoirs are considered and that site-specific factors have governed the emissions rather than linearly extrapolating average measured emissions from a few reservoirs to a total global estimated area of reservoirs (as was done in the past).

The purpose of this note is to provide guidance to WBG staff on how to assess GHG emissions from reservoirs in preparation of dam infrastructure projects, in accordance with the latest research and the data and tools available today. This note provides a layman's description of the major biogeochemical processes responsible for GHG emissions from reservoirs and makes concrete recommendations for estimating the volume of GHG emissions caused by those biogeochemical processes for planned reservoirs.

Moreover, it includes a bibliography, listing key scientific studies for readers who seek more detailed information, a glossary, and directions for converting the emission volumes of different GHGs into carbon dioxide-equivalent amounts.

In the case of dam infrastructure projects with inundation for which the WBG may provide financing, GHG emissions from reservoirs should be analyzed as part of the Environmental and Social Impact Assessment (ESIA). This analysis and estimation of GHG emissions from the reservoir should be based on data available from the early phases of project preparation (Prefeasibility study and Environmental Screening). Doing so will allow managing and mitigating potentially significant reservoir emissions in the project planning and design, as well as the inclusion of specific actions in the Environmental and Social Management Plan (ESMP) to address these emissions.

Because the emissions of different reservoirs have been shown to vary by several orders of magnitude, it is advisable to use a stepwise process in which the complexity of the assessment of reservoir emissions is adjusted to reflect the severity of GHG emissions and their importance to the specific investment project. It is suggested that the following steps be taken in the assessment and estimation of reservoir GHG emissions:

1. Secondary data compilation, documentation, and initial screening, which, in the case of hydropower projects, would focus on the power density
2. Estimation of net emissions using secondary data and the *G-res* tool, including reliability assessment of the result
3. Refined estimation, based on primary data collection and process-based modeling guided by the IEA Hydro framework.

Steps 2 and 3 should only be conducted if warranted by step 1. The methods and results of the reservoir emissions assessment should be reported as a subchapter in the ESIA or as a separate dedicated report, and they should be summarized in the project appraisal document (PAD). A template for the presentation of this assessment in the PAD is provided (appendix C).

For all projects, secondary data on key variables affecting reservoir emissions should be compiled and documented to enable an initial screening and, if required, to provide input data for further analysis. If the initial screening indicates that reservoir emissions are *not negligible*, the *G-res* tool should be applied to predict future net reservoir emissions for the planned investment. However, the extent of uncertainty of the *G-res* tool results should be acknowledged and a thorough reliability check of the results should be conducted. If the assessment shows that the results of the *G-res* tool are highly uncertain, or if the reservoir emissions estimate has to be highly reliable, more detailed assessments are advised, including primary data collection and process-based modeling in accordance with the IEA Hydro framework.

For dam infrastructure projects with *significant* estimated reservoir GHG emissions, possible mitigation measures should be considered and specified in the ESMP. It is suggested that a detailed GHG Management Plan (a subplan of the ESMP) be prepared, which should include specific targets, actions, and monitoring. GHG emissions management may include infrastructure design—such as ensuring aerobic conditions upstream of the intake—and management of organic material and nutrient effluents from the upstream catchment, aimed at reducing gross GHG emissions and improving the water quality of the reservoirs.

Note

1. *The Global Reservoir and Dam (GRanD) Database* (Lehner et al. 2011). This database includes more than 6,500 dams with a storage capacity larger than 1 km^3 and was corrected to exclude regulated *natural* lakes. The global estimate of GHG emissions was also corrected to include emissions from small impoundments.

Reference

Lehner, B., C. Reidy Liermann, C. Revenga, C. Vorosmarty, B. Fekete, P. Crouzet, P. Doll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rodel, N. Sindorf, and D. Wisser. 2011. *Global Reservoir and Dam Database, Version 1 (GRanDv1): Reservoirs, Revision 01*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Abbreviations

CH_4	methane
CO_2	carbon dioxide
$CO_2e(q)$	carbon dioxide equivalent
ESIA	Environmental and Social Impact Assessment
ESMP	Environmental and Social Management Plan
FAO	Food and Agriculture Organization
GHG	greenhouse gas
G-res	GHG reservoir tool
GRanD	Global Reservoir and Dam (database)
GWP	global warming potential
IEA Hydro	International Energy Agency Technology Collaboration Programme on Hydropower
IFI	International Financial Institution
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt-hour
MW	megawatt
N_2O	nitrous oxide
UAS	unrelated anthropogenic source
UNESCO	United Nations Educational, Scientific and Cultural Organization
WBG	World Bank Group

Important definitions of gross and net emission for WBG staff to note:

In the science of reservoir GHG emissions, "*net* emissions" refer to the difference between the volume of emissions measured *after* impoundment and the volume of emissions (or uptake) that occurred *prior to* impoundment, that is, the volume of *additional* emissions that is the result of introducing a reservoir into the landscape. By contrast, "*gross* emissions" refer to the emissions that are measured from the reservoir surface and the immediate river stretch downstream of the reservoir after impoundment.

In World Bank accounting of GHG emissions for investment projects (and similarly by other IFIs[1]), "net emissions" are the difference in emissions of the investment project and the counterfactual. In this context, the counterfactual may be either a "without project" scenario or an "alternative scenario" that reflects the most likely alternative means of achieving the same project outcomes or level of service. The "gross emissions" are the absolute emissions of the investment project.[2]

In this technical note, "net emissions" allude to the definition used by the science of reservoir GHG emissions (that is, the first definition given above).

The unit "tons" refers to "metric tons" ("tonnes") throughout this report.

Notes

1. *International Financial Institution Framework for a Harmonised Approach to Greenhouse Gas Accounting,* November 2015.

2. In case of a hydropower project for which the most likely alternative to produce the same amount of power is a coal power plant, the *net reservoir* emissions become part of the *gross hydropower project* emissions. Thus, the *net project emissions* are defined as the net reservoir emissions plus construction emissions, minus the emissions of a coal power plant producing the same amount of power as the hydropower project.

Chapter 1
Purpose of this Technical Note

Reduction of greenhouse gas*[1] (GHG) emissions is fundamental to the mitigation of climate change. It has become increasingly important to estimate and report on GHG emissions to enable the implementation of mitigation measures to limit or reduce total emissions. In most cases, such estimation is fairly simple, using known emission factors per surface area or per produced energy unit. However, GHG emissions from reservoirs created for the purpose of electricity generation, water security, or flood protection are very difficult to estimate, and no single emission factor or formula can be applied.

The purpose of this note is therefore to provide guidance to World Bank Group (WBG) staff on how to assess GHGs from reservoirs in preparation of dam infrastructure projects. It is an update of the World Bank (2013) Interim Technical Note with the same title. The note no longer has an interim status, which it was given in 2013 on account of anticipated new research published in recent years.

The technical note is limited to the GHG emissions resulting from the biogeochemical processes that are initiated when a river is dammed and the area upstream is flooded. As GHG emissions are a vital part of GHG accounting for projects involving reservoirs (such as storage dams for flood management, irrigation, water supply, or hydropower), the note provides input to the WBG's methodology for estimating the carbon footprint* of a project.[2] Yet it does not include guidance on how to define the counterfactual scenario for alternative development projects.

The aim has been to create a short and concise note, written in easily understandable, not overly technical language, covering the most important and relevant facts relating to GHG emissions from reservoirs. Given the complexity of the dynamic physical, chemical, and biological processes, not all scientific processes are described in detail and some are simplified. Further details and an in-depth description of these processes may be found in the key references provided in the bibliography.

Like the 2013 Interim Note, this updated version discusses: (i) the major biogeochemical processes causing GHG emissions from reservoirs; (ii) the state of current knowledge, and (iii) recommendations for assessing GHG emissions caused by biogeochemical processes for planned reservoirs. *Besides a general update on the state of the art, the main change with respect to the previous version is the introduction of the G-res tool, developed by UNESCO/IHA, and the IEA Hydro framework as the recommended tools for the quantification of reservoir emissions.* The note briefly describes these tools and explains how they can be applied to WBG dam infrastructure investment projects. Moreover, it provides a bibliography, listing key scientific studies for readers who seek more detailed information, and a glossary, as well as detailed directions for converting (emission) volumes of different GHGs into carbon dioxide-equivalent amounts (appendix A).

GHG emissions from reservoirs are still a relatively new area of research. Therefore, it should be no surprise that research conducted over the last 20-30 years has shown disparity in GHG emission magnitudes from reservoirs, which has led to a debate on methodologies and the reliability of results. However, during the last decade, research has significantly improved our knowledge and understanding of the subject and a recently published scientific paper by a large number of recognized researchers in the field of GHG emissions (Prairie et al. 2017) indicates that research is converging. Unlike in 2013, when the Interim Technical Note was published, various tools and models are now available for use in the preparation of large dam infrastructure. Yet more research will be required to refine these tools,[3] and WBG staff must take care when applying them. Staff must also ensure that they always use the latest (software) versions and be clear and frank in discussing the uncertainties still underpinning the science.

Notes

1. Terms marked by an asterisk (*) at their first occurrence in the main text are defined in the Glossary.
2. For example, *Guidance Manual: Greenhouse Gas Accounting for Energy Investment Operations, Transmission and Distribution Projects, Power Generation Projects, and Energy-Efficiency Projects, Version 2.0,* January 2015.
3. Few studies have been conducted on essential GHG pathways (such as methane bubbling and downstream degassing), where research is still geographically uneven.

Chapter 2
Basic Overview of Greenhouse Gases from Reservoirs

2.1 The CO_2 Cycle in a River Basin

Changes in land use and/or changes to the natural cycles of water and energy affect the interactions among the terrestrial, aquatic, and atmospheric environments, and therefore have an effect on GHG emissions. When a river is dammed, the flow dynamics are changed, riverine sediment and organic material are trapped, and terrestrial ecosystems* are flooded. These changes alter the previous cycle and fluxes of carbon dioxide* and other GHGs within the project footprint.

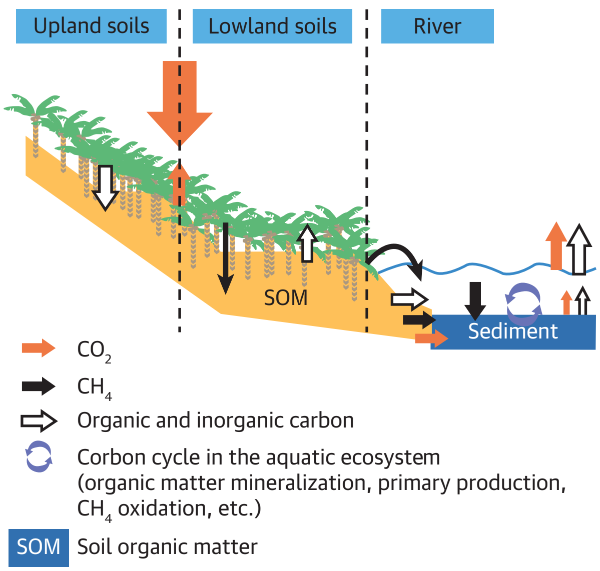
The main GHGs that may be emitted from a reservoir are carbon dioxide (CO_2), methane* (CH_4), and nitrous oxide* (N_2O). CH_4 and N_2O have stronger warming effects than CO_2 and may be important even if emitted in relatively small amounts.

To account for differences in the Global Warming Potential* (GWP) of GHGs, the combined emissions of CO_2, CH_4, and N_2O are expressed as CO_2 equivalents* (CO_2eq).[1] Since these three GHGs have different lifespans in the atmosphere, a specific period needs to be set to compare their respective GWPs; this period is normally 100 years. According to the *2013 IPCC Fifth Assessment Report* (AR5), to obtain CO_2eq emissions for a 100-year period, the quantities of CH_4 produced should be multiplied by 34 and those of N_2O by 298.

To understand the impact of reservoirs on GHG emissions, it is essential to understand the main processes in the cycle of CO_2 and other GHGs in a river basin (figure 2.1).

- Atmospheric CO_2 is taken up by plants through photosynthesis* but is lost in parallel through respiration* to the atmosphere, either directly from vegetation or through decomposition* of dead organic matter. The balance of these CO_2 fluxes creates the growth of biomass (live or dead) in the terrestrial ecosystem, contributing to the biomass* carbon pool. Live biomass, and its carbon, may be removed, for example, through harvesting or fires. In these cases, the carbon is eventually fed back to the atmosphere, primarily in the form of CO_2.
- Dead organic matter that has not been directly decomposed or respired is eventually absorbed into the soil or transported to the river through rainfall and overland flow. Carbon is thus either stored in the soil or transported out of the terrestrial ecosystem to the riverine ecosystem as part of the erosion process. Carbon can also be leached from dead organic material or soil and enter river systems directly in dissolved form.
- In rivers and lakes (with or without reservoirs), carbon can be leached from the bed sediment to the water phase, and the dissolved CO_2 can be lost to the atmosphere at the surface. As part of the aquatic ecosystem, CO_2 from the atmosphere or dissolved in the water can also be consumed by aquatic plants and phytoplankton, feeding higher trophic level organisms (such as zooplankton and fish) that will later decay and create new dead organic material, thereby adding to the bed sediments.
- CH_4 is mainly created under anoxic* conditions (no oxygen available) in the soil or in bed sediments of a water body. Such conditions also occur at the bottom of flooded areas. If the water column is strongly

FIGURE 2.1. Carbon Fluxes in Terrestrial and Aquatic Landscapes



Source: UNESCO/IHA 2010.
Note: CO_2 = carbon dioxide; CH_4 = methane.

stratified on a seasonal basis, CH_4 can be produced and accumulate in the anoxic zone. If the CH_4 is released to the water column as dissolved CH_4, it is either oxidized (and transformed to dissolved CO_2) or, if there is a lack of oxygen in most of the water column, lost directly as CH_4 to the atmosphere. CH_4 may also be transported up through the water column and into the atmosphere in gas form—either by diffusion at the air-water interface or through ebullition* (bubbling*).

- In some circumstances, N_2O is created as a by-product of nitrification*, under aerobic* conditions (relating to, involving, or requiring free oxygen), or denitrification*, under anaerobic* conditions. As a result, creation of N_2O mainly occurs in the riparian zones of water bodies, where saturation varies with water levels.

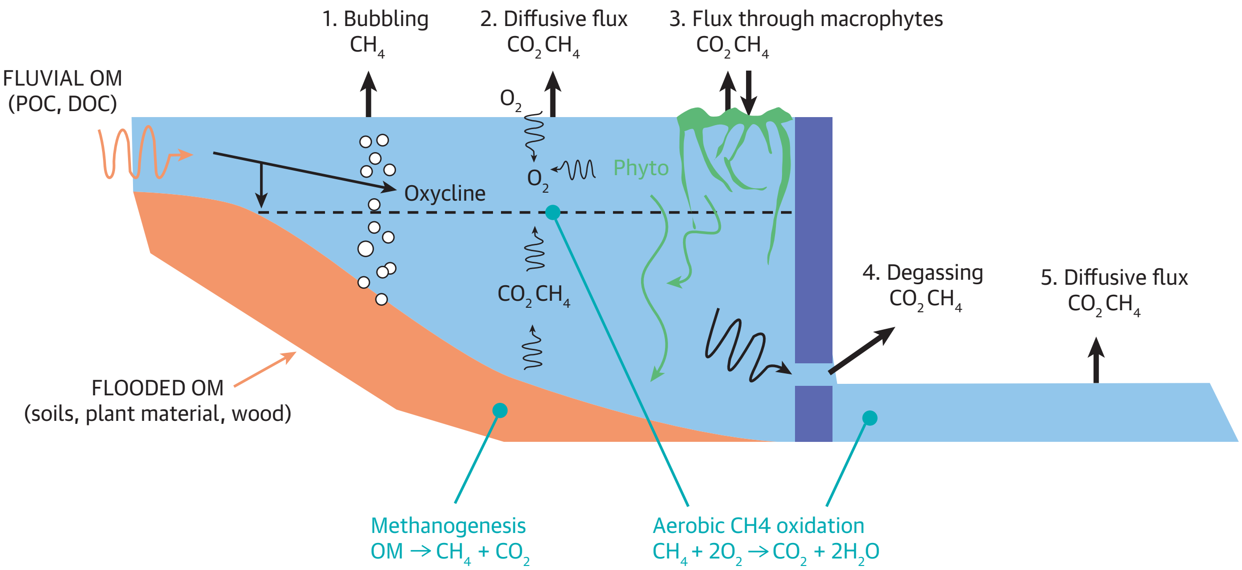
The construction of a dam and impoundment of a reservoir alters the GHG cycle. This will result in a change in flux of GHGs to the atmosphere compared with the situation before the reservoir was created. More specifically, the following changes may occur:

- The reservoir area changes from the previously *terrestrial* system into an *aquatic* system, thereby changing the conditions for interactions of GHGs with the atmosphere for this area.
- Following inundation, conditions are created for decomposing vegetation and the carbon contained in the soil of the flooded area, thereby changing the amount of GHGs released into the atmosphere from the reservoir area or in downstream rivers when the water is discharged.
- The reservoir may provide for seasonal growth and decomposition of vegetation in the drawdown zone, resulting in the absorption and subsequent release of GHGs into the atmosphere.
- The reservoir may provide anoxic conditions for creating CH_4 rather than CO_2, especially if the water column is seasonally stratified.
- The reservoir partially traps riverine organic material and nutrients transported in the river system, and may thereby change the circumstances under which they are transformed into GHG emissions compared to where they otherwise would have been carried—further down the river system (until reaching a natural lake, wetland, or ocean).

In a reservoir, the flooded and inflowing carbon will be exported to the atmosphere, stored in the bed sediments, or transported further down the river system. These three processes occur in parallel to varying degrees, depending on the topographical, geological, and climatological conditions, as well as the biological configuration of the water body.

Once a reservoir has been created, GHGs can reach the atmosphere through several pathways (figure 2.2). The main pathway is through diffusive flux* of both CO_2 and CH_4 from the surface of the reservoir. However, significant GHGs can also be flushed through the intake

FIGURE 2.2. **Main Fluxes of Carbon for a Reservoir**



Source: UNESCO/IHA 2010.
Note: CO_2 = carbon dioxide; CH_4 = methane; DOC = dissolved organic matter; OM = organic matter; POC = particulate organic carbon.

of a reservoir and be released into the atmosphere through degassing* (due to change of pressure) at the outlet or as diffusive flux at the downstream river surface. In shallow areas of the reservoir, methane can also reach the atmosphere without being dissolved, through bubbling.

2.2 Data on GHG from Reservoirs

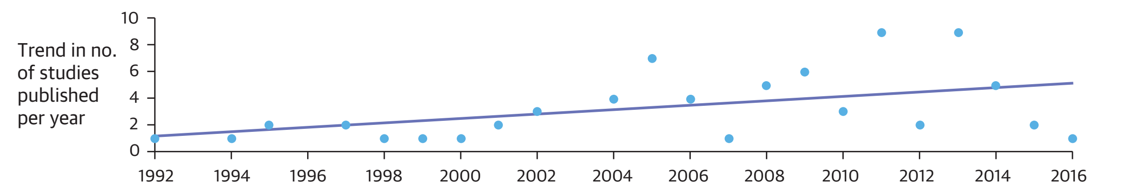
Research on GHG emissions from reservoirs is a relatively new scientific activity and most studies have been conducted during the last 25 years. A sample of key references is given in the bibliography, including a short description of the key findings.

Given the lack of data on GHG emissions, many studies have focused on measuring the different forms of GHG emissions from reservoirs. An analysis of published studies related to observations of GHG emissions from reservoirs shows how the data compilation has developed (figure 2.3). Up to about 10 years ago, the main data on GHG emissions from reservoirs came from tropical climate zones in Brazil and French Guiana (the latter mainly related to just one reservoir—the Petit Saut). During the last decade, measurement campaigns have become increasingly distributed, spreading over boreal and temperate climate zones. However, the studied reservoirs are still concentrated in specific regions, with very few observations of GHG emissions from reservoirs in Asia and Africa (maps 2.1-2.4).

Data availability also differs much depending on type and pathway. Of the 223 reservoirs analyzed in recent research by Prairie (2017), the distribution of data is as follows: diffusive CO_2 - 198 reservoirs; diffusive CH_4 - 137 reservoirs; bubbling CH_4 - 39 reservoirs; and degassing CH_4 - 35 reservoirs. Deemer et al. (2016) used GHG emission data from a total of 267 reservoirs, of which 229 yielded data on CO_2, 142 on diffusive CH_4, 50 on bubbling CH_4, and 58 on N_2O (maps 2.2-2.4) (figure 2.4). This shows that data on N_2O and on CH_4 bubbling and degassing are still relatively rare.

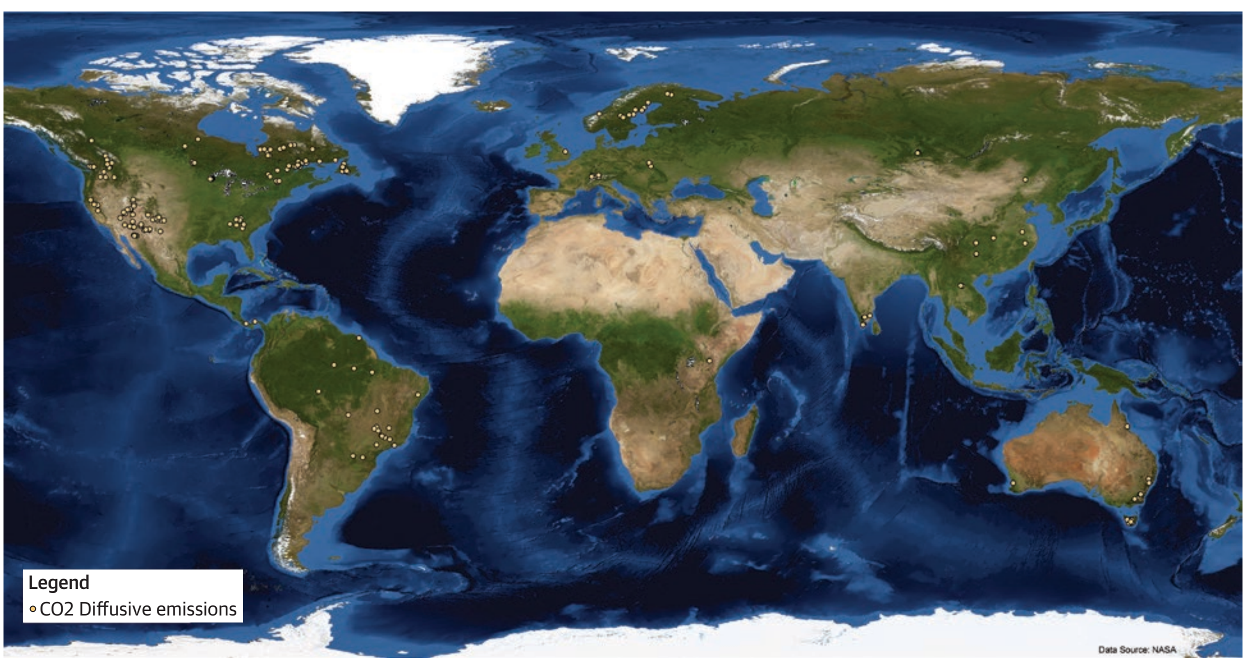
FIGURE 2.3. Analysis of Scientific Papers Published Related to Measured GHG Data from Reservoirs

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	No. of studies
Brazil				•		•	•		•		••		•	•••	••	•	•	•	•	•	•	••				20
French Guyana						•		•		•				••	•		•									7
Panama			•														•									2
USA	•												•	•								•				4
Canada				•										•	•		•	•••	•	•	•				•	11
Australia										•										••		•	••			6
Finland											•															1
Sweden													••													2
Poland																		•		•						2
Switzerland																			•							1
Germany																						•				1
China																		•		••		••	•	•		7
India																	•						•			2
Laos																				•		•	•	•		4
Zambia/Zimbabwe																				•						1
Kenya																						•				1

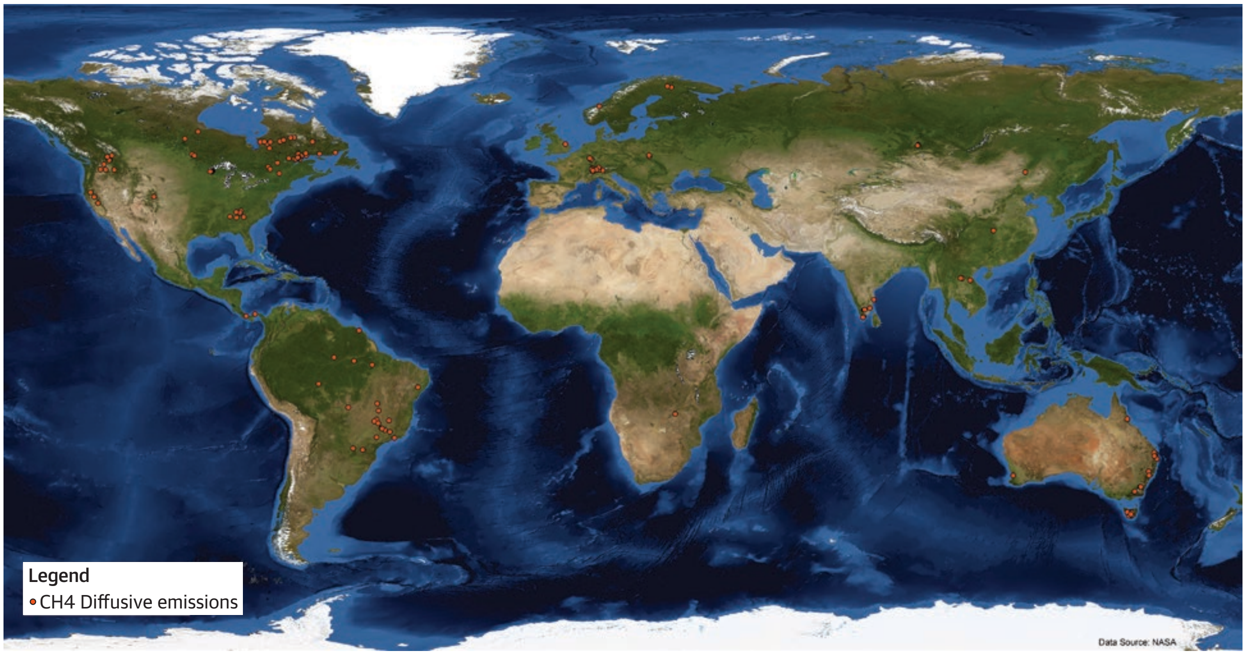


Sources: World Bank 2013 and UNESCO/IHA 2017.

MAP 2.1. Location of Reservoirs with Measured Diffusive Flux of CO_2

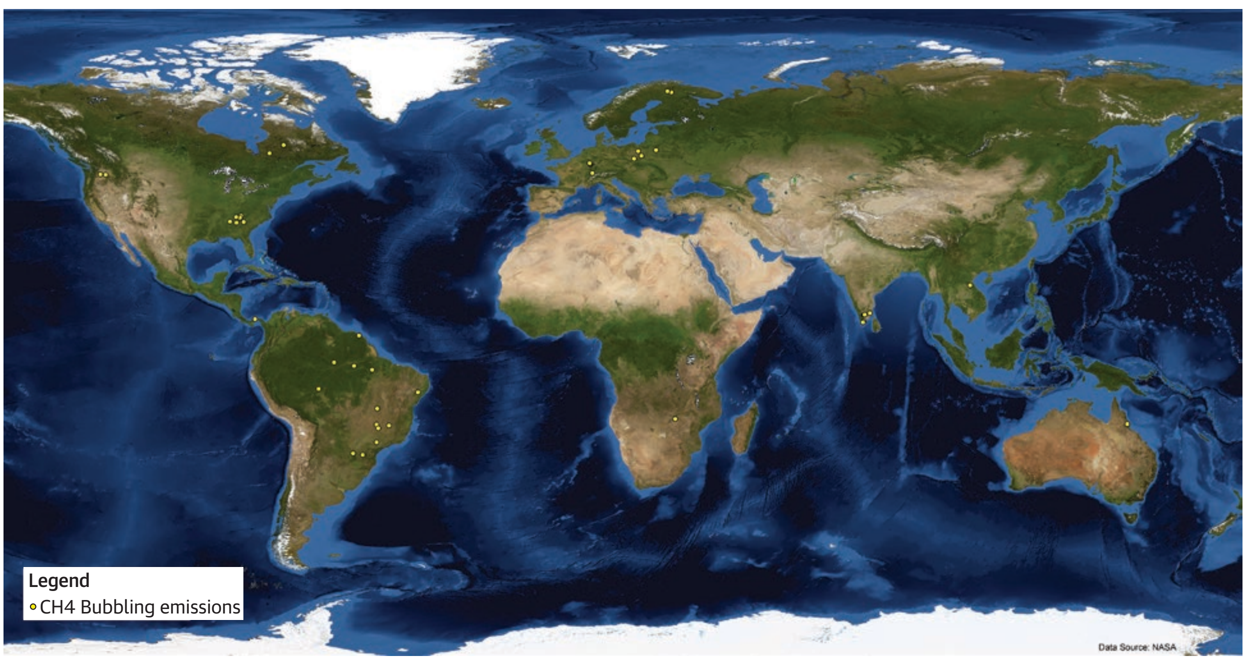


MAP 2.2. Location of Reservoirs with Measured Diffusive Flux of CH_4

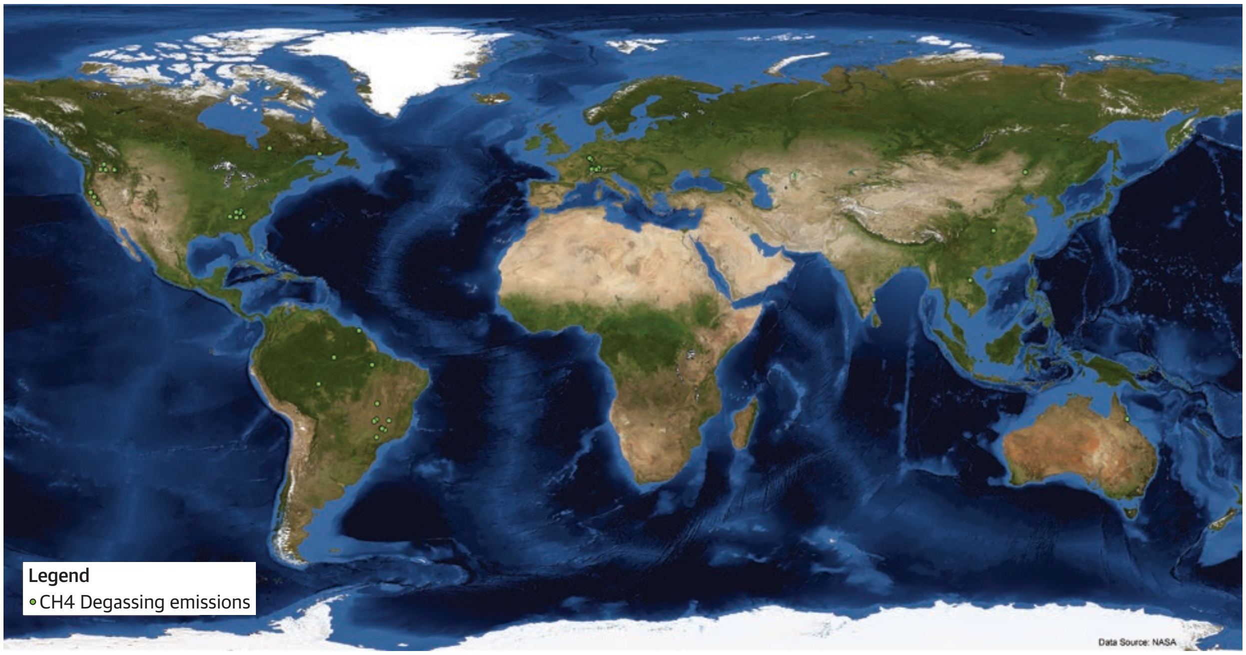


Source: Based on data from UNESCO/IHA.

MAP 2.3. Location of Reservoirs with Measured Ebullition (Bubbling) Flux of CH_4



MAP 2.4. Location of Reservoirs with Measured Degassing of CH_4



Source: Based on data from UNESCO/IHA.

Another challenge with the observations of GHG emissions is that measurement methods had not been standardized until recently. A standardized methodology for measuring GHG emissions from reservoirs was only published in 2010 by UNESCO/IHA; it was based on consultations and is widely accepted in the scientific community. Diffusive fluxes are mainly measured with the help of floating chambers placed on the surface of a reservoir. Fluxes are quantified by observing changes in the concentration of gases in the chamber over time. Bubbling of CH_4 is normally measured through submerged funnels. Degassing occurring at low-level outlets of the dam is estimated by measuring differences in the respective CO_2 and CH_4 concentrations upstream and downstream of the outlet. Besides giving recommendations on the equipment to use, the standardized methodology provides guidance on the temporal and spatial frequency of the measurements, which are essential to getting reliable estimates of GHG emissions. Further work on measurement programs and data analysis was published by IEA Hydro (2012).

Estimates of total reservoir emissions are costly as they require field campaigns that cover long periods of time and large areas. Thus, only a few reservoirs in the world have records going back longer than a few years. Some dam reservoirs for which more extensive measurements have been done are Petit-Saut (French Guiana), Nam Theun 2 (Lao People's Democratic Republic), Eastmain 1 and La Grande 2 (both in Canada), and Tucuruí and Samuel (both in Brazil).

2.3 Most Important Factors Influencing GHG Emissions from Reservoirs

Thanks to research, a better understanding of the processes governing GHG emissions from reservoirs has gradually emerged (see Bibliography). What follows is a summary of the main findings that are generally agreed within the scientific community. Only the main factors affecting GHG emissions from reservoirs are described in this section.

One of the principal factors affecting emissions from reservoirs is the *availability of carbon*, the so-called carbon stock.* The more carbon present in the soil and in flooded biomass or transported into the reservoir from upstream rivers, the more likely GHGs will be emitted. Because the presence of carbon in soil and biomass decreases as it is transformed into GHGs and released into the atmosphere, the rate of emissions normally exponentially decreases with *age of the reservoir*.

Another major factor, which is especially important for determining the type of GHG produced and thus the warming potential of CO_2 equivalents, is the *dissolved oxygen* concentration* in the water of the reservoir. In reservoirs, seasonal stratification* due to temperature differences between surface and deeper water and poor vertical mixing may produce anoxic conditions in the deeper, colder water. The water depth and the stratification of the water column into an anoxic zone (hypolimnion*) below the aerobic zone (epilimnion*) have a large impact on the emission of GHGs. Dissolved CH_4 is produced in anoxic conditions and can be oxidized to CO_2 in aerobic conditions. If anoxic conditions exist in most of the water column, it allows fluxes of CH_4 to the atmosphere. The greater the thickness of the overlying epilimnion layer in the water column, the less likely it is that diffuse CH_4 emissions will be produced. This is because the *production* area and volume become smaller while the *oxidizing* area and volume (where CH_4 can transform to CO_2) are enlarged.

The *water and air* temperatures have been found to generally show the highest correlation with measured GHG emissions. This is because higher temperature affects many of the processes that contribute to higher emissions. First, temperature directly influences the decomposition rate of organic matter, with higher temperatures governing higher rates. Secondly, the lower the water temperature, the more oxygen can be dissolved in water and, conversely, the higher the water temperature, the less oxygen can be dissolved. High air temperature at the water surface also gives a large temperature difference between surface and deeper water, which favors stratification. Thus, temperature affects both the production and emission of CO_2 and CH_4 from reservoirs.

Water quality and nutrient content (eutrophication status) also have a large effect on the concentration of dissolved oxygen in reservoirs. The poorer the quality of inflowing water (e.g., high content of nutrients and organic matter), the higher the oxygen demand created in the reservoir, favoring anoxic conditions and methane production. For this reason, the land cover and land use in the upstream catchment areas affect the GHG emissions from reservoirs. Anthropogenic* sources of pollution such as effluents of untreated domestic and industrial sewage can have a particularly large impact on GHG emissions from reservoirs.

Similarly*, inflows and the shape of the reservoir* affect the level and distribution of dissolved oxygen in the reservoir. The inflow and bathymetry influence the water retention time* in the different parts of the reservoir. Water retention time in turn affects how much time is available for biological processes to occur. The volume and variation of inflows also affect how much oxygen is transported into the reservoir and how well the inflowing fresh water is mixed with the water already present in the reservoir.

Water depth and extension of littoral zone are important for the amount of methane that can be transferred directly from the bed sediment to the atmosphere through bubbling. Bubbling is more likely to happen in shallow waters, since solubility increases with pressure. At greater depths, the pressure is high and the CH_4 is more likely to be dissolved following its creation. Because CO_2 has much higher solubility than CH_4, bubbling of CO_2 is low even in shallow waters.

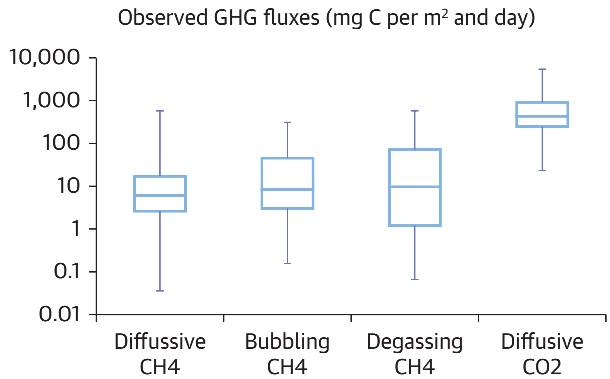
Mixing of surface and deeper water and stratification are also affected by *wind speed*. Furthermore, wind speed at the surface affects the diffuse fluxes of CO_2 and CH_4 from the water phase to the atmosphere. Higher wind speed increases fluxes by increasing the turbulence of the water at the air-water interface.

Because of the sudden decrease in pressure when water is released from a low-level (deep) outlet of a dam, the solubility of gases will drastically decrease and dissolved CH_4 in particular may be degassed just downstream of the reservoir. Even if oxygen is available in this environment, the depth and time available for oxidation is short, enabling CH_4 to be transferred directly to the atmosphere. Therefore, the *configuration of dam intake and outlets*, especially their position in relation to the thermocline depth in the reservoir, affects total GHG emissions. Other infrastructure features, such as artificial aeration weirs in the downstream river stretch, may also affect the ratio of CO_2 or CH_4 and thus the total GHG emissions expressed as CO_2 equivalents.

2.4 Extreme Temporal and Spatial Variation

All the above factors affect how the GHG stock is created and released into the atmosphere. They interact in a complicated manner to govern the biological processes such as organic matter production, respiration, methanogenesis*, CH_4 oxidation, and gas exchange between the atmosphere and the reservoir. As a result, GHG emissions vary widely in time and space. CH_4 emissions, in particular, may vary extremely; this has a major impact on methane's warming potential, as reflected by the fact that the factor 34 has to be applied to arrive at its CO_2 equivalent. Measurements of GHG emissions from reservoirs differ by several orders of magnitude, as can be

FIGURE 2.4. Measured GHG Emission Fluxes at Reservoirs



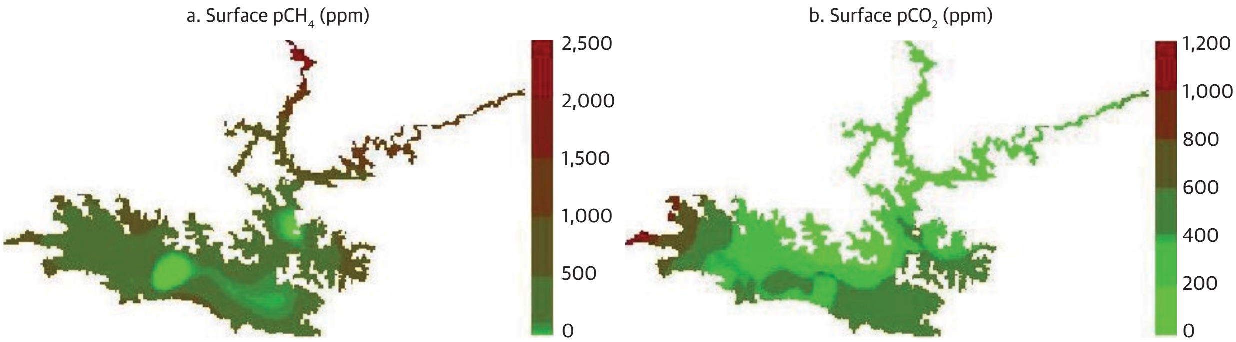
Source: From data by UNESCO/IHA (2017), based on values stated in published articles, recalculated to mg C per m^2 total reservoir area and day for comparison.
Note: mg C = milligrams of carbon; CO_2 = carbon dioxide; CH_4 = methane. The boxes denote the first (25%), median, and third (75%) quartiles, while the whiskers denote the minimum and maximum values.

seen in figure 2.4. If carbon burying is included as part of sediment deposition, the amount of CO_2 emitted from reservoirs has in some cases even been found to be negative over the period of the measurement campaign.[2]

GHG emissions from new aquatic systems created by reservoirs will also change over the long term as the flooded organic material is decomposed and biochemical conditions change. Upon inundation, easily decomposed organic matter starts decaying, causing high gross emissions during the initial phase. As this matter is depleted, gross emission rates will increasingly depend on the amount of newly decaying material being transported into the reservoir by inflowing rivers.

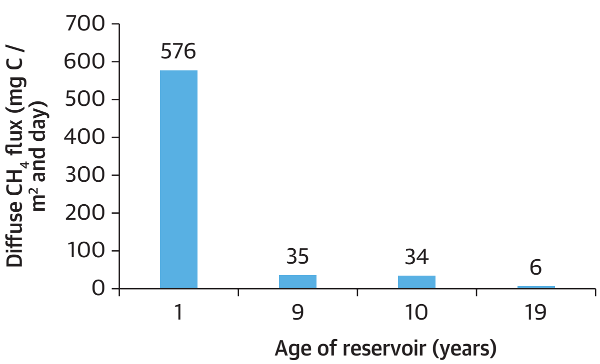
Measured gross emissions have high spatial variability within a reservoir (figure 2.5) and show large differences between different reservoirs—in terms of total emissions, type of GHG, and pathways by which the GHG is emitted. Measured emissions also show high seasonal variation and generally a decreasing trend with age of the reservoirs, the highest values

FIGURE 2.5. Measurement of the GHG Fluxes in the Batang Ai Reservoir, Malaysia, Showing the Extreme Spatial Variability



Source: University of Quebec at Montreal.
Note: p = partial pressure; ppm = parts per million.

FIGURE 2.6. Measurement of Diffuse Fluxes of CH_4 in the Petit Saut Reservoir (Impounded in 1994)



Source: Based on data from UNESCO/IHA. Original data from Galy-Lacaux et al. 1997; Abril et al. 2005; Guérin et al. 2006; and Cailleaud 2015.
Note: mg C = milligrams of carbon; CH_4 = methane.

TABLE 2.1. Measurements of N_2O and Comparison of CO_2 Equivalents with Diffusive CH_4 and CO_2

	mg N_2O-N per m² and day[a]	In CO_2 equivalents (mg CO_2eq per m² and day)		
		N_2O[a]	Diffusive CH_4[a]	CO_2[b]
Min	-0.089	-27	1.6	85
25%	0.031	9.5	119	913
Median	0.057	17	275	1,585
75%	0.133	40	774	3,336
Max	5.768	1,718	26,134	20,014

Sources: Deemer et al. 2016 and UNESCO/IHA.
Note: mg = milligrams; CH_4 = methane; CO_2 = carbon dioxide; CO_2eq = carbon equivalents; N_2O = nitrous oxide.
a. Data from Deemer et al. 2016. Negative values mean the reservoir works as a sink.
b. Data from UNESCO/IHA.

being registered in the first 5-15 years after inundation (figure 2.6).

N_2O emissions have been studied in a limited number of reservoirs so far. The results indicate that, similar to methane, N_2O creation and emission vary greatly (table 2.1). In general, N_2O contributes less to GHG emissions from reservoirs than CO_2 and CH_4, even when expressed in CO_2eq based on application of the high warming potential (Descloux et al. 2017, Sturm et al. 2014, and Guérin et al. 2008). Deemer et al. (2016) estimated that it only accounted for 4 percent of total global reservoir emissions.

Notes

1. See appendix A for conversion from GHG units into CO_2 equivalents.
2. See Sikar 2009 and Chanudet et al. 2011 for examples of reservoirs that have been reported as carbon sinks. However, whether carbon burial can be subtracted from atmospheric emissions is still being debated (see Prairie et al. 2017).

Chapter 3
What Does The Atmosphere See?

3.1 Gross and Net Fluxes of Greenhouse Gasess

A fundamental concept for accurately describing GHG emissions from reservoirs created by biogeochemical processes is the difference in gross[1] and net fluxes. Rivers are major conveyors of carbon from terrestrial areas to lakes and the sea (figure 3.1). Terrestrial areas are generally net carbon sinks* and aquatic systems are net carbon emitters. Changes in GHG fluxes to the atmosphere because of the introduction of reservoirs in a river system must therefore be viewed from a catchment perspective. *Net* GHG emissions created by the reservoir are the difference between total fluxes of CO_2 equivalents for the river basin before and after the reservoir has been constructed.

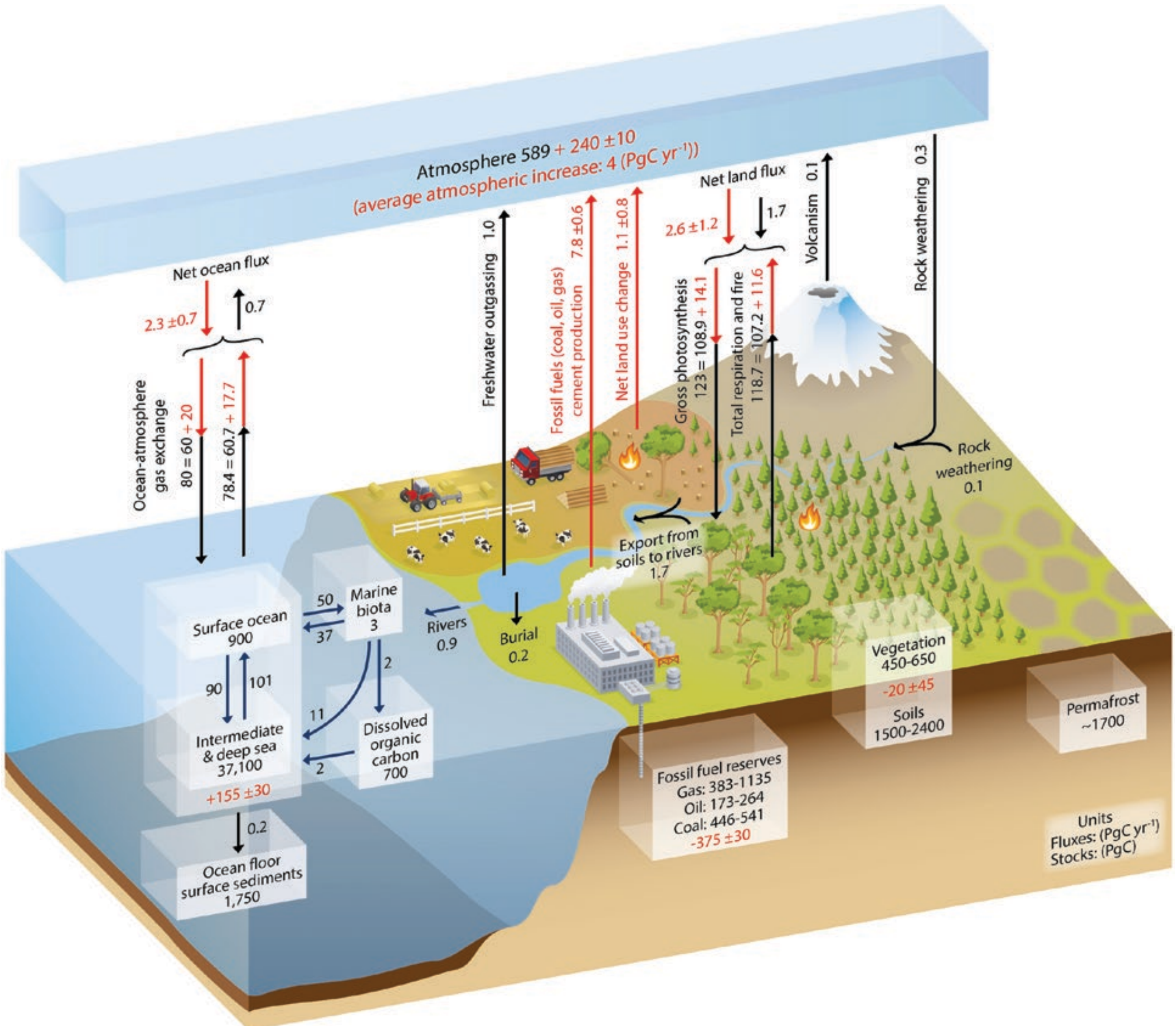
Reservoirs are one of many anthropogenic influences on the biogeochemical GHG cycle in a river basin. Sources of carbon for a reservoir are normally both *natural* (e.g., soil and vegetation) and *anthropogenic* (e.g., inflow of organic matter from untreated sewage or flooded waste deposits). Changes in GHG fluxes due to the introduction of a reservoir must therefore also be considered in the context of artificial influences already in place in the river catchment.

In 2011, the Intergovernmental Panel on Climate Change (IPCC) defined biogeochemically generated *net emissions* from reservoirs as gross emissions minus pre-impoundment emissions and minus unrelated anthropogenic sources (UAS). This definition was also adopted by the International Energy Agency in their program on Managing the Carbon Balance in Freshwater Reservoirs in 2012 (IEA Hydro 2012). This is also the definition used in this technical note and the one recommended be adopted by the WBG.

A recent scientific paper by Prairie et al. (2017) highlighted the importance of the concept of "what the atmosphere sees," as the result of building new dams. The paper was co-authored by 14 experts representing 12 prominent global research centers on GHG emissions from reservoirs. Referring to recent publications showing that global emissions from natural freshwater systems are larger than previously estimated (e.g., Raymond et al. 2013), it argues that only 25 percent of gross CO_2 emissions measured at reservoirs are visible to the atmosphere; the remaining 75 percent of emissions are simply displaced and would have been emitted anyway, in the absence of the reservoirs. Prairie et al. (2017) also emphasize the need to estimate pre-impoundment emissions to enable the calculation of the net GHG emissions that are "visible" to the atmosphere. Accounting for pre-impoundment emissions can either *increase* the net value (e.g., in the case of inundating a forest area previously working as a carbon sink) or *decrease* the net value (e.g., if a dam floods vast wetlands or raises a natural lake).

What matters to the atmosphere from the introduction of a reservoir is, therefore, limited to the processes where the changes create a *net* increase in CO_2 equivalent fluxes. It is important to note that the net emissions described above refer only to the biochemical processes in the river system that affect the GHG fluxes to the atmosphere. In a complete life-cycle emissions assessment for a project involving a reservoir, the baseline must be set according to alternative future scenarios (such as when hydropower replaces thermal power) and include emissions related to the implementation of the entire project (among other things, emissions deriving from the construction works themselves).

FIGURE 3.1. The Global Carbon Cycle



Source: IPCC 2013.
Note: 1 PgC = 1 Petagram of Carbon (= 10^{15} grams of carbon).

3.2 The *G-res* Tool

Following the framework proposed by Prairie et al. (2017), the UNESCO/IHA research project of 2015-17 developed the GHG Reservoir Tool (hereafter called the *G-res* tool) (UNESCO/IHA 2017). The *G-res* tool builds on the principles of the global carbon cycle* (figure 3.1) as defined by IPCC (2013) and the definition of net reservoir emissions as defined by IPCC (2011). The objective of the tool is to "*quantify the portion of GHG emissions that can be legitimately attributed to the creation of the reservoir over its lifetime.*"

Average pre-impoundment emissions for the inundated area are calculated from land cover, soil, and climate. If the area to be inundated works as a carbon sink, the pre-impoundment emissions are negative. Unrelated anthropogenic sources are estimated based on land use, population, and known point sources in the catchment area.

Annual post-impoundment emissions are estimated through carefully developed statistical models relating GHG emissions to key governing variables such as temperature, age of reservoir, littoral area, solar radiance, phosphorus concentration in the reservoir, and soil carbon content. Models are developed for different gases and pathways—diffusive CO_2 flux, diffusive CH_4 flux, bubbling of CH_4, and degassing of CH_4. The statistical models are derived based on the measured gross emissions from 223 reservoirs studied over the last 25 years (see section 2.2). Data have been standardized, accounting for the different periods of the year during which the measurements were made. All CH_4 emissions are attributed to the new reservoir, while attributable CO_2 emissions are reduced by the emissions that are simply displaced by the new reservoir (figure 3.2). The factors used to determine the volume of displaced emissions are the availability of the carbon stock in the reservoir bed soil and the shape of the exponential decline in gross CO_2 emissions.

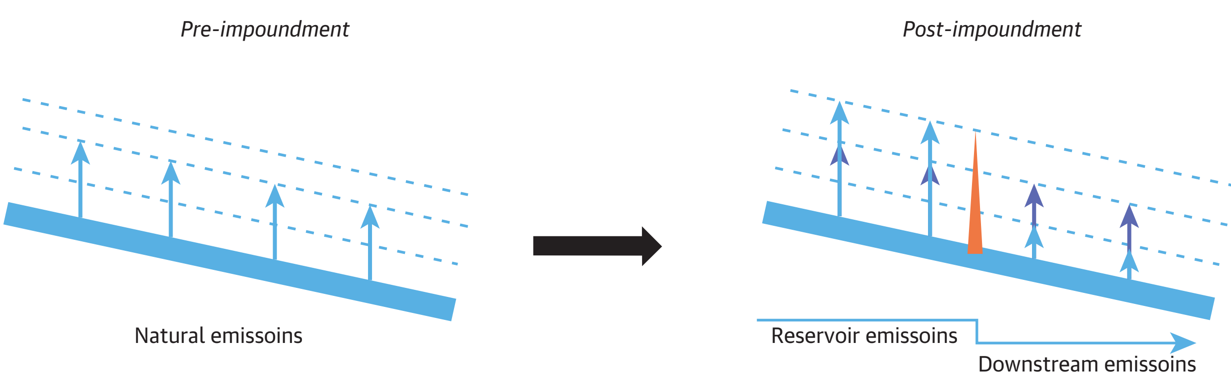
The annual net emissions of both CO_2 and CH_4 are calculated as the difference between post-impoundment emissions and the sum of pre-impoundment emissions and UAS. As defined by IPCC, the annual emissions are integrated over a 100-year period to estimate the life-cycle emissions attributed to the creation of the reservoir.

The *G-res* tool also enables the user to estimate the construction- and material-related emissions for the dam infrastructure by applying *standard* emission factors. These project-specific emissions are added to the reservoir emissions to arrive at an emissions estimate for the entire life cycle of the dam and reservoir.

The *G-res* tool goes further to suggest how the life-cycle emissions should be allocated by sector in the case of multipurpose dams and reservoirs. The allocation is based on the operating regime of the reservoir, that is, on what uses are prioritized.

The *G-res* tool is used through a web-based interface and is available online.[2] It is linked to global geographic databases to enable default estimations of variables such as climate zone, land cover, and soil types. The user can introduce more detailed data, if available from primary data collection or studies, to improve the GHG emission estimation. Use of the *G-res* tool is not very time-consuming—it can even require less than one day if all input data are available.

FIGURE 3.2. Displacement of CO_2 when a Dam is Constructed in a River



Source: IHA/UNESCO 2017.

3.3 The IEA Hydro Framework

Based on the cumulative research, and acknowledging the great complexity of estimating GHG emissions from reservoirs, the IEA Hydropower Implementing Agreement[3] has developed guidelines for the quantitative analysis of net GHG emissions from reservoirs. Three documents provide a framework for conducting site-specific primary data collection and modeling to estimate and manage reservoir GHG emissions (see Bibliography):

- Volume 1 - Measurement Programs and Data Analysis (October 2012)
- Volume 2 - Modeling (November 2015)
- Volume 3 - Management, Mitigation and Allocation (Draft, June 2017)

Like the *G-res* tool, the IEA Hydro framework builds on the principles of net emissions as defined by IPCC (2011). While it does not provide a ready-to-use tool for estimating emissions, it describes in detail the steps involved in collecting field data, conducting data analysis, and developing process-based modeling tools for estimation of GHG emissions from a reservoir.

The framework is based on data collection and the five components of a new reservoir project (based on EPRI 2010): (i) the inundated area; (ii) the reservoir; (iii) the upstream catchment area; (iv) the reservoir outflow facilities; and (v) the downstream river. It provides a list of environmental and technical descriptors that should be reported in an analysis of GHG emissions from a reservoir.

In the case of new reservoirs, it recommends procedures for primary data collection and suggestions for integrating these into pre-impoundment emissions. For post-impoundment emissions, the framework provides suggestions and requirements for modeling approaches to simulate GHG emissions over the life span of the reservoir. Moreover, it provides recommendations on the setup, calibration, and validation of mechanistic models to describe the biogeochemical processes to create and emit CO_2 and CH_4 from a reservoir.

The recommendations given in the IEA Hydro framework are sourced from the experience of engineers, scientists, and academics, as well as experts from the hydropower industry. The recommendations also build on process-based modeling applications for reservoirs, such as the one used in Nam Theun 2, in Lao PDR (Chanudet et al. 2016). Process-based modeling of water quality and GHG emissions from reservoirs is still a relatively young science, and therefore few applications exist. Besides Nam Theun 2, a process-based model was recently applied to Eastman 1, in Canada, to simulate CO_2 emissions (Kim et al. 2016), and modeling is ongoing in Petit Saut, in French Guiana.[4]

The time frame for conducting primary data analysis and developing site-specific models is considerable—normally at least 1–2 years. The primary data collection usually needs to cover several seasons. The modeling involves various components, such as hydrodynamic modeling, water quality modeling, and GHG modeling, which are all very complex and time-consuming to set up, calibrate, and validate.

3.4 Global Estimates of GHG Emissions from Reservoirs

Several studies have been published in the last decades aimed at estimating the total contribution of GHGs from reservoirs to global emissions (table 3.1). The first estimate of global emissions from reservoirs in the year 2000 indicated a very high volume, in the order of 7 percent of global GHG emissions from all sources (St. Louis et al. 2000).[5] The typical methodology used by these studies is to take the average specific emissions from observations (see sections 2.2. and 2.4) and *extrapolate* these, in common units such as mg per m^2 and year, to a global reservoir surface area.

One major source of uncertainty in these estimates is the total area of (man-made) reservoirs. Because of

TABLE 3.1. Allocation of GHG Emissions for Multipurpose Reservoirs Followed with *G-res* Tool

Importance	Explicit prioritization	Operating rule curve
Primary	Ranked 1 to 3 in operational hierarchy.	Operating rules are designed to maximize these service benefits for part or all of the year.
Secondary	Ranked lower than 3 in operational hierarchy, or places constraints on operation.	The service places operational constraints on the operating level of the reservoir for part or all of the year.
Tertiary	Provides benefits, but does not alter the operation of the reservoir.	The service provides benefits but has little impact on the operation of the reservoir.
Importance	**Apportionment (%)**	**Notes**
Primary	80	If there is more than one service in the level, split equally.
Secondary	15	Where there are no secondary services, the apportionment (15%) is split between the primary services.
Tertiary	5	Where there are no tertiary services, the apportionment (5%) is split between the secondary services.

Source: UNESCO/IHA 2017.
Note: G-res = GHG Reservoir.

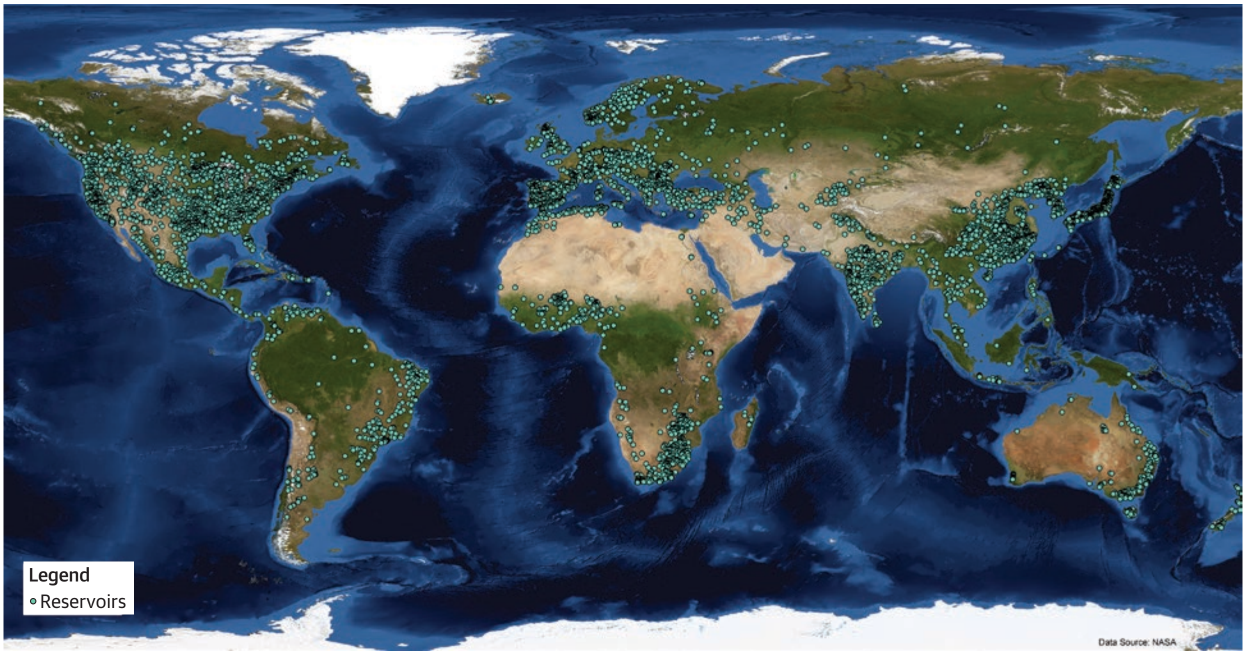
incomplete records and the fact that the area varies with the seasons, it is difficult to estimate the total area of freshwater lakes and reservoirs. It is estimated that lakes cover a global area of 3.7–4.2 million km^2 (Downing et al. 2006). In this context, a breakthrough was achieved for reservoirs with the Global Reservoir and Dam (GRanD) Database developed by the Global Water System Project (Lehner et al. 2011). The GRanD is a geographic database that contains many variables on 6,862 reservoirs with more than 0.1 km^3 of storage capacity worldwide. It includes nearly all dammed reservoirs in the world (map 3.1).

To get an estimate of the net *additional* surface area created by dams, the GRanD database had to be adjusted somewhat. The database *includes* large natural lakes such as Lakes Victoria, Baikal, Winnipeg, Onega, Vanern, Ontario, and Saima. These seven large lakes alone add up to 163,000 km^2, or 36 percent of the total area of 452,000 km^2 covered by the GRanD database. As they are all partially regulated, they are considered reservoirs. However, the regulation of these lakes causes an increase in surface area that is insignificant compared to their previous natural state. Thus, these changes do not contribute to increases in the net surface area. On the other hand, the GRanD *excludes* the relatively large number of small dams (those with a smaller than 0.1 km^3 storage capacity). By statistically extrapolating the distribution of dams, Lehner et al. (2011) estimated the missing net additional water surface created by these dams[6] to be 306,723 km^2.

Starting from the framework proposed by Prairie et al. (2017) for estimating the emissions that are attributable to reservoirs, Prairie (2017) applied the *G-res* tool individually to all the reservoirs in the GRanD database, excluding the largest natural lakes,[7] to estimate the global net reservoir emissions. The initial value obtained was further corrected to account for the high number of small reservoirs. The results, presented in table 3.2, indicate that the global emissions from reservoirs are lower than previously estimated—in the order of 0.5 percent of global anthropogenic emissions.

Two factors in particular explain why the estimates by Prairie (2017) are lower than previous global estimates. Firstly, applying the principle to only include emissions attributable to the reservoir means that displaced emissions[8] are not included. This resulted in a lower net carbon dioxide emissions from

MAP 3.1. Distribution of Reservoirs in the GRanD Database



Sources: Lehner et al. 2011; IHA/UNESCO.

TABLE 3.2. Global Estimates of Reservoir Area and GHG Emissions

Reference	Global reservoir area (km²)	CO_2 (Tg CO_2eq/year)	CH_4[a] (Tg CO_2eq/year)	Global contribution[b]
St. Louis et al. (2000)	1,500,000	1,000	2380	9.2%
Lehner et al. (2011)	306,000	—	—	—
Barros et al. (2011)	500,000	176	680	2.4%
Bastviken et al. (2011)	340,000	—	136	—
Hertwich (2013)	330,000	279	331	1.7%
Deemer et al. (2016)	311,000	135	606	2.0%
Prairie (2017)	350,000	45	105–164[c]	0.4–0.6%

Note: — = not available; n.a. = not applicable; CH_4 = methane; CO_2 = carbon dioxide; CO_2eq = carbon dioxide equivalent; Tg = teragram (= 1 million metric tons).

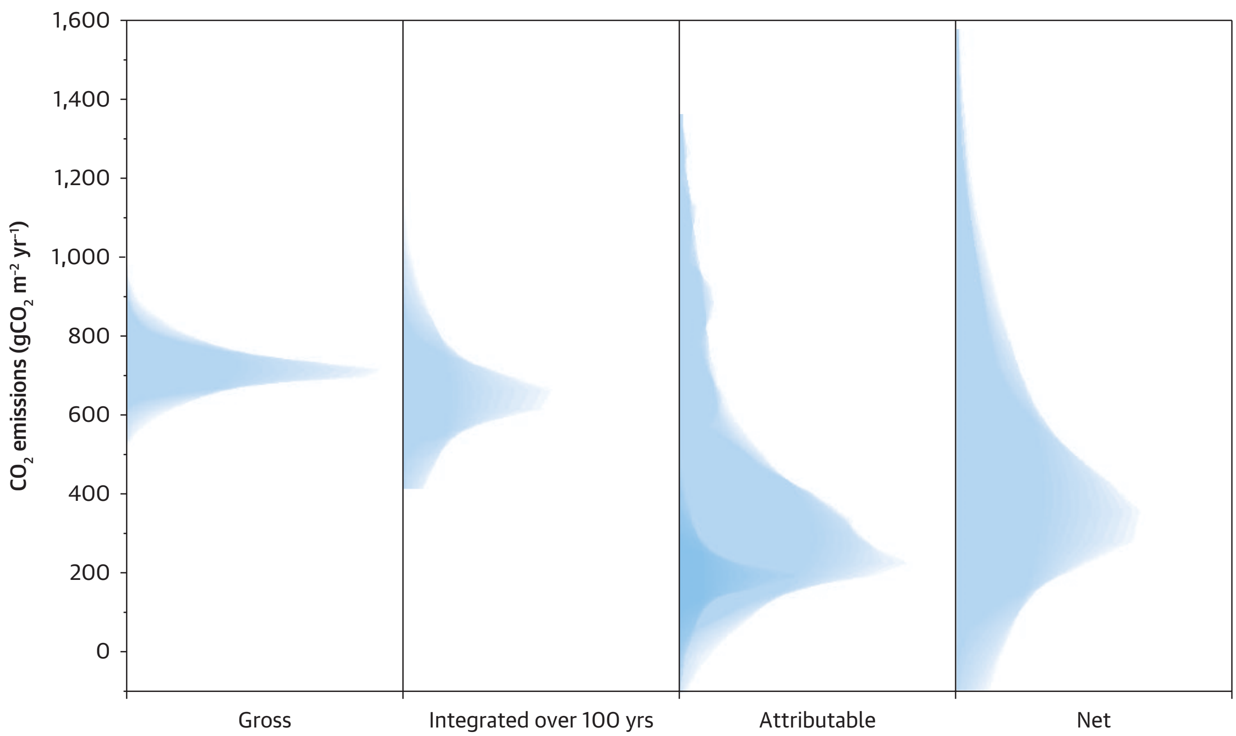
a. Using a warming potential of 34, as defined in the *2013 IPCC Fifth Assessment Report*.

b. Using a global estimate of anthropogenic GHG of 36.2 billion tons/year as of year 2015.

c. High value if assuming CH_4 degassing in all dams, low value if degassing is not included. Degassing only occurs if the dam outlet is located at low levels of the reservoir. Since the GRanD database contains no data on the location of the dam outlet, it is not possible to determine at which dams degassing occurs.

reservoirs than previously estimated (figure 3.3). Secondly, using site-specific factors to govern CH_4 emissions for each dam in the GRanD, rather than extrapolating average measured emissions from a relatively few reservoirs to a total global surface area, gives lower global emissions. This is because the reservoirs where methane emissions have been measured are not fully representative of the global distribution of reservoirs. Furthermore, because distribution of CH_4 emissions is highly skewed,

FIGURE 3.3. Illustration of Changing Distribution of CO_2 Emissions for All Reservoirs over the World When Considering Net Rather than Gross Values



Source: IHA/UNESCO.
Note: CO_2 = carbon dioxide. Previous global estimates CO_2 emission considered the gross values. The reservoirs used for this figure have been taken from the GRanD database.

individual high values in a small sample may have a very large effect on the average.

The estimate by Prairie (2017) still has uncertainty and is affected by the assumptions made. For example, it only includes emissions of CO_2 and CH_4, but ignores N_2O, for which data are still scarce. The limited research on N_2O has, however, indicated that nitrous oxide emissions are generally small compared to the emissions of CO_2 and CH_4. Deemer et al. (2016) estimated that N_2O accounts for 4 percent of total reservoir GHG emissions. On the other hand, their estimate of global reservoir area is higher than the estimate by Lehner et al. (2011), which indicates that some of the reservoirs in the GRanD database to which the *G-res* tool has been applied are actually regulated natural lakes. Assuming that the Lehner et al. value is more reliable would give about 10 percent lower global GHG estimates. Furthermore, Prairie et al. do not consider UAS, as they argue that although emissions from UAS are not directly attributable to the reservoir, they are anthropogenic and thus "seen by the atmosphere." According to verbal communication with UNESCO/IHA, applying the strict IPCC (2011) definition of net emissions would decrease the global estimate by 10–15 percent.

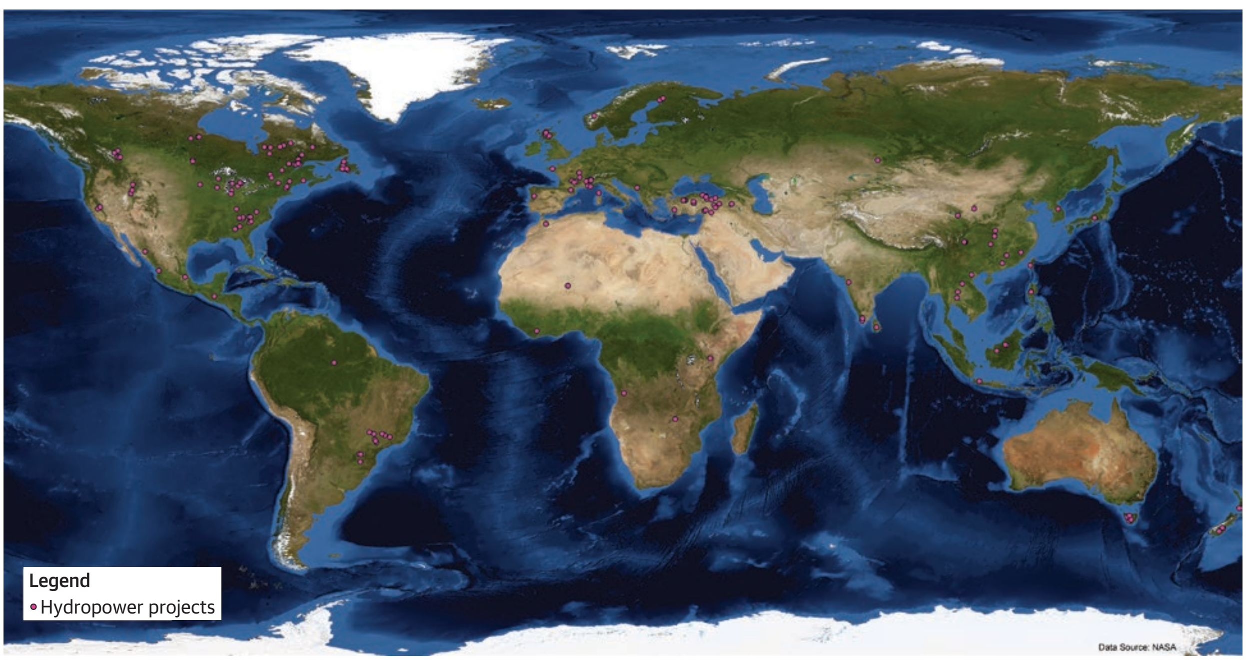
The *G-res* tool used for the estimation of reservoir GHG emissions by Prairie (2017) is also associated with uncertainties. The relationships between emissions and governing variables are still based on a limited number of observations, especially for CH_4 bubbling and degassing. The statistical models, however, are most reliable for the center of the data distribution, which gives some robustness to the global average estimate.

As figure 3.1 illustrates, the natural emissions from rivers and lakes form a large part of the carbon cycle. Raymond et al. (2013) estimate the total annual emissions from streams, rivers, lakes, and reservoirs to be 2,100 TgC (teragrams of carbon). The results from Prairie (2017) indicate that reservoir emissions are only a fraction (less than 1 percent) of total emissions from freshwaters bodies. Previous estimates (Barros et al. 2011) indicated a higher value of 4 percent.

Estimating the emissions from hydropower reservoirs and their relation to the power produced at the global level is more difficult. One reason for this is that detailed information on installed capacity (MW)—power generated (GWh/year) in particular—is not available for the reservoirs in global databases (such as GRanD). Another reason is that it is difficult to correctly assign reservoir area to power produced because most reservoirs are multipurpose and a single reservoir often serves many hydropower plants in a cascade or complex transfer scheme. For example, assigning all reservoir emissions to a relatively small hydropower unit installed at the spillway of an irrigation dam would misrepresent the role of power production as a driver for reservoir creation.

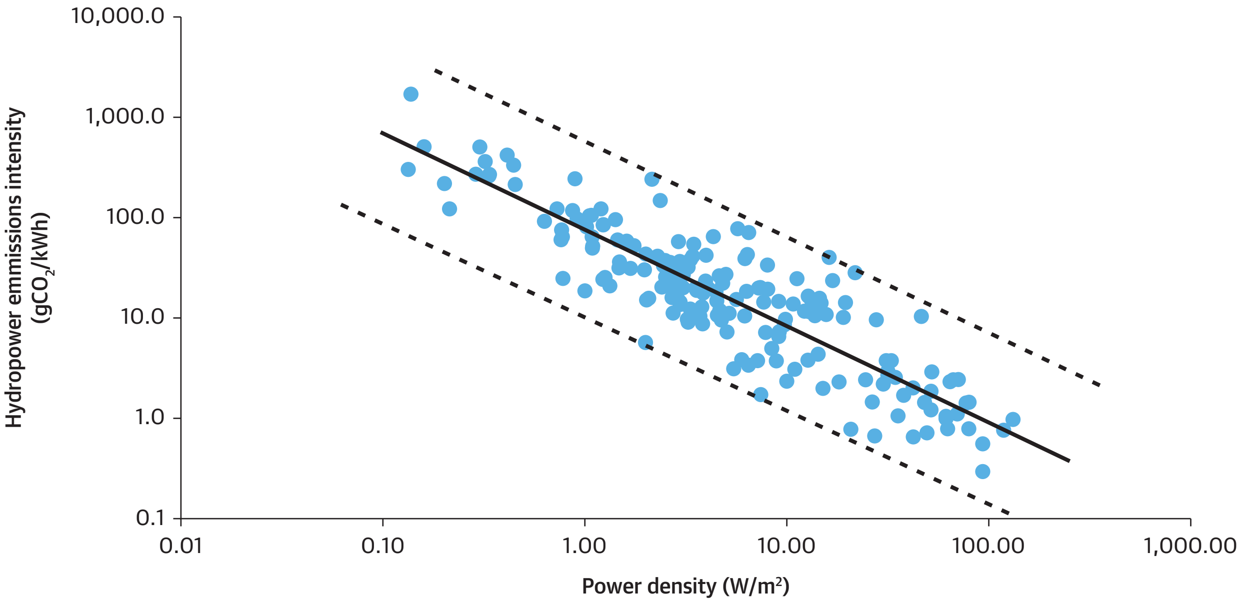
Based on the work by UNESCO/IHA, the *G-res* tool was recently applied (IHA 2017) to a global database of single-purpose hydropower projects where the installed capacity and energy production had been verified and proven to be linked to the reservoir specifically created for the project (map 3.2). The database includes 180 hydropower projects with installed capacity ranging from 1.2 to 2,735 MW and reservoir areas ranging from 1.4 to 5,400 km^2. The resulting GHG emissions from the *G-res* tool are plotted against the power density (W/m^2) in figure 3.4.

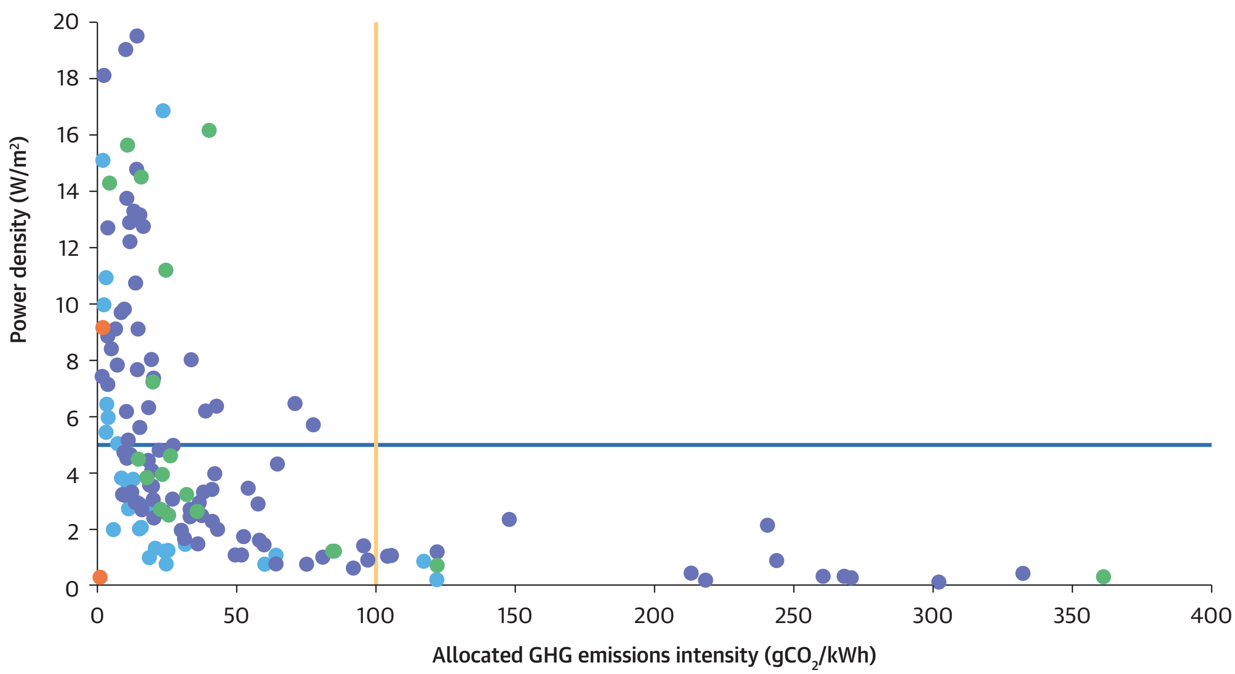
MAP 3.2. Single-Purpose Hydropower Projects with Verified Installed Capacity and Power Production



Source: IHA.

FIGURE 3.4. **GHG Emissions Estimated through the *G-res* Tool for a Global Set of Single-Purpose Hydropower Projects**





Source: Data courtesy of IHA.

Note: W/m² = watt per square meter; gCO_2/kWh = grams of carbon dioxide per kilowatt-hour.

The results indicate a very strong logarithmic relationship between emissions and power density, although the envelope curves show that GHG emissions may vary with more than one order of magnitude for a specific power density. Figure 3.4 indicates that extremely high GHG emissions per kWh (same order of magnitude as fossil fuel plants) can be produced by a hydropower storage project, be it only at low power densities—that is, where installed turbine capacity is relatively small compared to the surface area created by the reservoir. However, figure 3.4 also shows that a low power density does not necessarily entail high emissions, as most hydropower projects below 5 W/m^2 still have emission profiles below 100 g CO_2eq/kWh, which is considerably lower than any fossil fuel alternative.

Figure 3.4 also confirms that there is no obvious relationship between the climate zone and reservoir emissions. In theory, temperature affects GHG emissions, but this result indicates that temperature is only one of many parameters affecting the resulting emissions. Thus, great care should be taken before using just one factor to predict reservoir emissions.

Notes

1. *Gross emissions* from reservoirs are defined as the emissions measured from the reservoir surface and the immediate river stretch downstream of the reservoir; gross emissions are normally the ones measured (see sections 2.2 and 2.4).
2. It was launched on May 10, 2017, and available at www.hydropower.org/gres-tool.
3. The IEA Hydropower Implementing Agreement is a working group of the International Energy Agency member countries and others that have a common interest in advancing hydropower worldwide. Under Annex XII (Hydropower and the Environment), this program has conducted a project on Managing the Carbon Balance in Freshwater Reservoirs.
4. Ongoing work by the Environmental Defense Fund (EDF), verbal communication V. Chanudet, May 2017.
5. The figure of 7 percent was derived on the basis of a lower GWP for methane than is used today (21 instead of 34), and a total amount of global emissions of 33.9 billion tons/year. If a GWP of 34 is applied to the 2015 year global emissions, the resulting figure would be 9 percent, as indicated in table 3.2.
6. Estimated 2.8 million impoundments larger than 0.1 ha worldwide, 16.7 million impoundments when including dams larger than 0.01 ha.
7. Only the obvious large natural lakes were removed, which probably explains the larger surface area estimated by Prairie (2017) and Lehner et al. (2011).
8. These would have occurred even without the creation of the reservoir.

Chapter 4
Recommendations for Preparing Dam Projects

4.1 General Framework

In the case of dam infrastructure projects inundating terrestrial landscapes for which the WBG may provide financing, it is recommended that the biochemically generated GHG emissions from the reservoirs be studied as part of the Environmental and Social Impact Assessment (ESIA). Doing studies of potential GHG emissions from reservoirs as part of the ESIA enables comparison of alternative design options within the framework of the investment project and provides inputs for the economic analysis.

The inclusion of a GHG assessment in the ESIA does not change the boundaries of a regular impact assessment. It can be anticipated that changes to GHG emissions will occur at the reservoir area and the river stretch downstream of the reservoir. Thus, inputs for the GHG assessment include data from the catchment area and the project area, which are normally also needed for the ESIA.

The recommended framework for the GHG assessment is described in figure 4.1. Because GHG emissions have been shown to vary by several orders of magnitude for different reservoirs, it is prudent to follow a stepwise process in which the complexity of the analysis is adjusted to reflect how severe and important GHG emissions are for the specific investment case.

The first important step to take, required for all new dam investment projects, is proper documentation of GHG aspects of the project. This step enables initial screening and provides input data for further analysis. The recent development of the *G-res* tool, which is open-source and fairly easy to use, makes it possible to be generous in the initial screening phase and only characterize GHG as *negligible* in cases where it is very obvious (as in the case of true run-of-river projects and retrofitting where the inundated area will not change). The next step is to apply the *G-res* tool using secondary data to simulate future reservoir emissions for the planned investment. Considering the uncertainty still remaining when using the *G-res* tool (see section 3.4), it is essential to assess the reliability of the results obtained with the *G-res* tool. If the estimate is deemed reliable, it can be used as input for the economic analysis and for suggesting suitable options for managing the reservoir's GHG emissions; this information should be included in the Environmental and Social Management Plan (ESMP). On the other hand, if the results are attributed low reliability, it is recommended that more detailed assessments be conducted, including primary data collection and modeling according to the IEA Hydro framework. Each of these steps is described in more detail in the following sections.

4.2 Documentation and Initial Screening

The first step for all infrastructure projects with inundations is to provide an overall description of the main factors affecting future, potential GHG emissions from the planned reservoir options. Table 4.1 gives a list of standard information that is useful to compile.

The next step is to make a qualitative assessment of the reservoir's capacity to supply a carbon stock and to create and release different types of GHGs, based on the compiled information. A structured process as described in figure 4.2 can be used.

FIGURE 4.1. **Recommended Approach for Assessing GHG Emissions for New Dams**

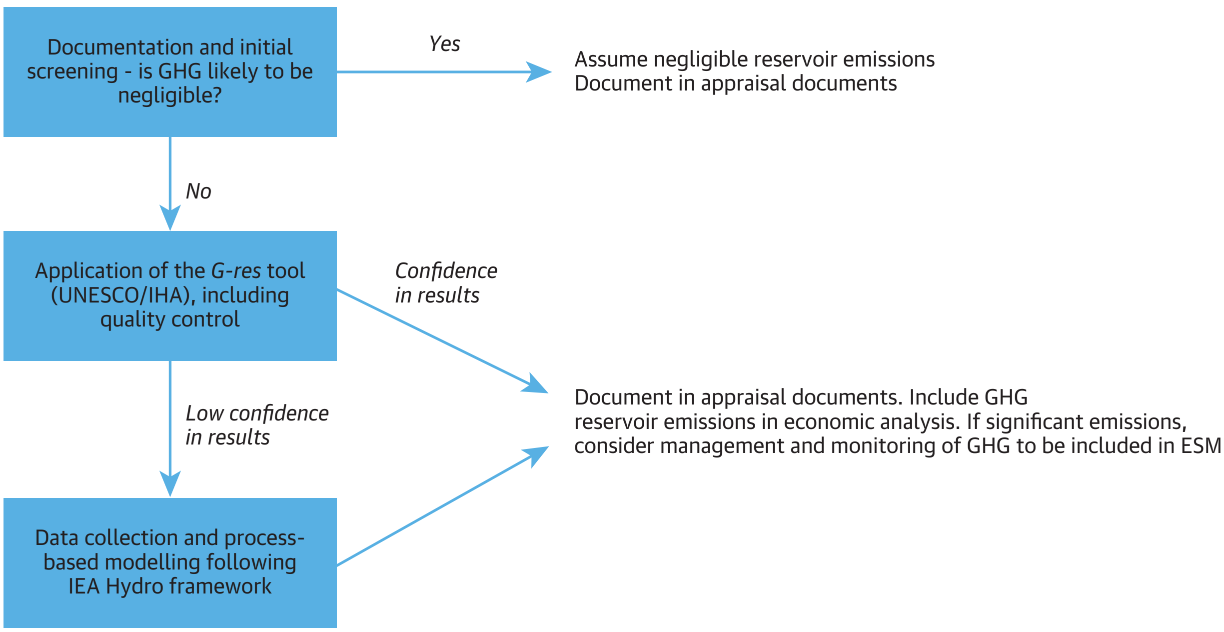


TABLE 4.1. **Basic Information to Assess Future Potential GHG from a Reservoir**

Factor to retrieve	Proposed methodology
Size and shape of inundated area and volume of reservoir	This information is available from the technical prefeasibility and feasibility studies. If not available, use existing topographical maps or Digital Elevation Models, for instance, SRTM (https://www2.jpl.nasa.gov/srtm/), to delineate inundated area up to planned full supply level.[a] When natural lakes are used as reservoirs, estimate how much new inundated area will be created by the damming. Calculate surface areas, volumes, and maximum and average depth.
Climate, temperature, and rainfall in reservoir area	These data are normally available from the first phases of the ESIA. If not available, use global databases such as the WorldClim (www.worldclim.org).
River inflow to the reservoir and water retention time	These data are available from the technical prefeasibility and feasibility studies. If not available, use records of river flows upstream from the reservoir to estimate inflow (see, e.g., www.bafg.de/GRDC/EN/01_GRDC/grdc_node.html). Divide average annual inflows by the reservoir volume to get the average retention time.
Type and extent of flooded vegetation	This information is normally available from the first phases of the ESIA. If not available, use global maps of ecoregions (e.g., European Space Agency www.esa-landcover-cci.org).
Type of flooded soil and extent of soil carbon	This information is normally available from the first phases of the ESIA. If not available, use global databases such as the Harmonized World Soil Database by FAO, IIASA, ISRIC, ISSCAS, and JRC (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML).

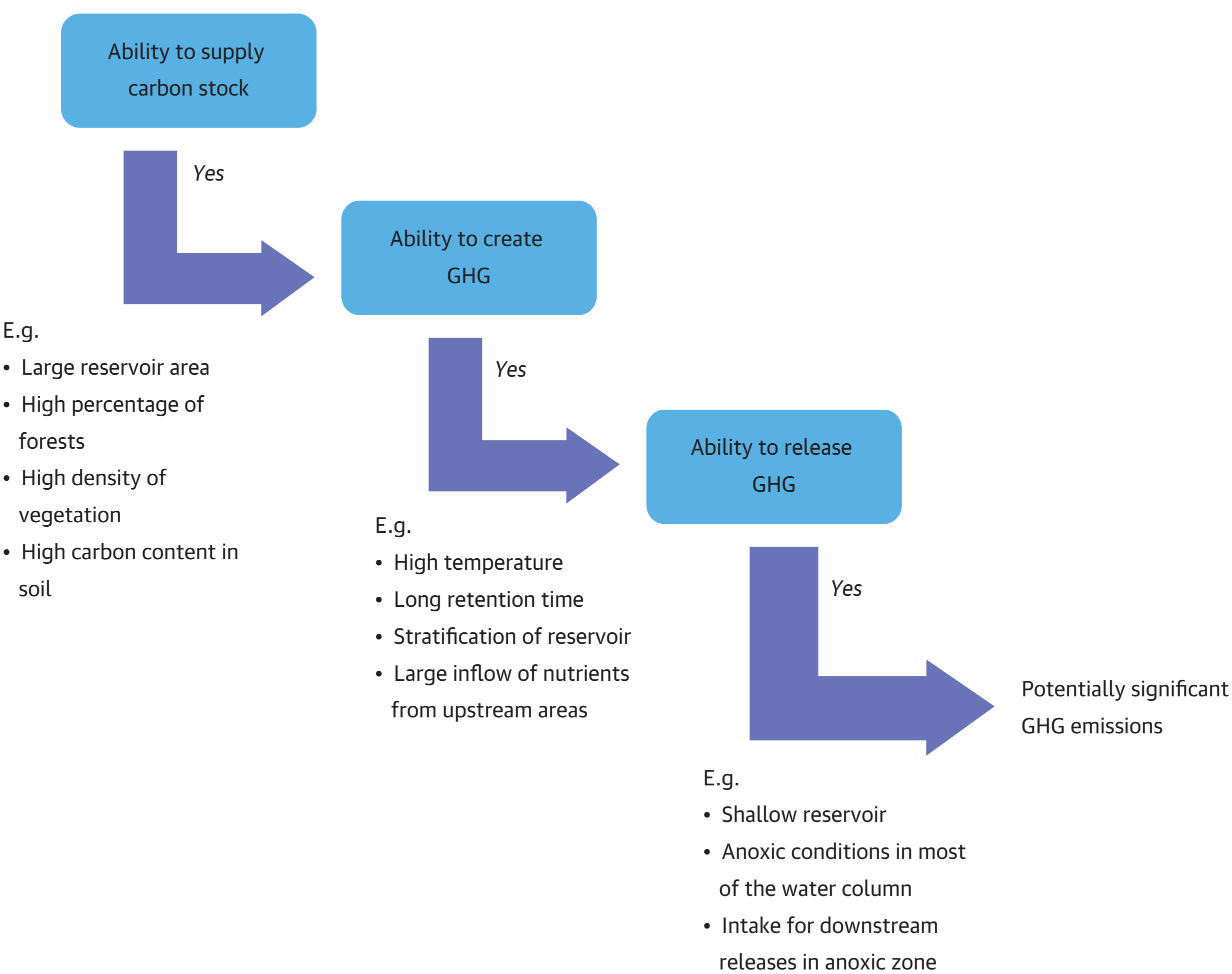
table continues next page

TABLE 4.1. Basic Information to Assess Future Potential GHG from a Reservoir (continued)

Factor to retrieve	Proposed methodology
Land cover and use in catchment area and water quality of inflowing rivers	This information is normally available from the first phases of the ESIA. If not available, use population density (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4) together with global land cover maps (see above) to conduct an overall assessment of land use and potential sources of organic matter and nutrients.
Characteristics of dam and construction methods	This information is normally available from the technical prefeasibility and feasibility studies. Use information on civil works to describe the type of dam and provide a rough estimate of dam, excavation, and material volumes, as well as transport distances during construction. In the case of hydropower, information is needed on installed capacity and plant factor, which are used to calculate power density (W/m^2). Retrieve basic geometry of the dam and intakes to assess how far from the reservoir bed level the bottom outlet and intake structures are located.

Note: ESIA = Environmental and Social Impact Assessment; IIASA = International Institute for Applied Systems Analysis; FAO = Food and Agriculture Organization; ISRIC = International Soil Reference and Information Centre (World Soil Information); ISSCAS = Institute of Soil Science, Chinese Academy of Sciences; JRC = Joint Research Centre (of the European Commission); SRTM = Shuttle Radar Topography Mission.
a. The *full supply level* corresponds to the normal maximum operating water level of a water storage body when not affected by floods; it represents 100% capacity.

FIGURE 4.2. Proposed Thinking Process for Documentation and Initial Screening



The compiled data and qualitative assessment should be used for the initial screening. The main purpose of this activity is to screen out any dam infrastructure that is likely to cause *negligible* GHG emissions and where no further studies are required. Due to the extreme variability of GHG emissions from reservoirs, no simple, single threshold can be used. Instead, a number of variables need to be taken into account. A few recommendations are given in table 4.2.

Since the *G-res* tool is fairly simple to use, it is best to be conservative in the screening. If it is difficult to qualitatively assess the risk of significant GHG emissions, it is prudent to go to the next step and apply the *G-res* tool. If the information has been collected and

TABLE 4.2. Guidance for Screening Out Projects with Negligible Reservoir GHG Emissions

Hydropower projects
The counterfactuals to hydropower project investments are normally other forms of power generation or energy demand management programs. The initial screening can therefore focus on the relative difference between potential reservoir emissions and the emission factors of the likely counterfactual. Using the strong relation to power density (figure 3.4), an early estimate can be made based on the proposed installed capacity and the estimated reservoir surface area. • Irrespective of other factors, if the power density is higher than 100 W/m^2, which would be the case in most run-of-river projects, the global data indicate that reservoir emissions are normally below 1 g CO_2/kWh, and even in extreme cases below 10 g CO_2/kWh. Compared to most counterfactuals for power production, this is relatively low (e.g., fossil fuel emission are in the order of 300–1,000 g CO_2/kwh), and reservoir emissions can be assumed negligible since they would be within the error margin of the emissions of the counterfactual. • If factors clearly disfavor high GHG emissions (such as cold climate, low carbon stock, deep reservoir), which would indicate that extreme emissions are unlikely, the upper envelope curve does not need to be considered and a lower power density threshold can be used to assume negligible reservoir emissions. For instance, a power density of 20 W/m^2 indicates a median reservoir emission of about 5 g CO_2/kWh. • Should the counterfactual have negligible emissions and the power density lie below 100 W/m^2, it is suggested that the threshold be set by the size of the reservoir. Using a threshold of 100,000 tons[a] CO_2eq (or 1,000 tons/year), as is used for other dam infrastructure, seems reasonable (see below). An analysis using the relation in figure 3.4 for different installed capacities (from 0.1 to 100 MW) shows that the resulting reservoir area threshold is fairly stable and varies only from 2.5–3.5 km^2 during median conditions, and from 0.5–0.7 km^2 under extremely favorable conditions for high GHG emissions (upper envelope).
Other dam infrastructure projects
For other dam infrastructure projects (e.g., water supply, flood control, irrigation), there is no obvious counterfactual and the reservoir emissions related to the project are generally assigned as a "cost" to the project. In this situation, the screening has to be based on the size of the reservoir and how significant the emissions may be relative to emissions caused by other sources. The construction emissions for large dam infrastructure lie in the order of 100,000–1,000,000 tons CO_2eq. It is thus suggested that 100,000 tons CO_2eq be used as the threshold when reservoir emissions may be negligible. This threshold corresponds to 1,000 tons CO_2eq per year, which is equivalent to 0.03 PPM (parts per million) of the global anthropogenic emissions. Based on the distribution of measured gross emissions (figure 2.4), this threshold can be used to give default threshold values for reservoir surface areas delineating when GHG emissions can be assumed negligible: • If factors seem to favor *high* specific emissions, use the 75th percentile for total CO_2 and CH_4 emissions (~3,500 tons/km^2 and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 0.3 km^2. • If factors seem to favor *low* specific emissions, use the 25th percentile for total CO_2 and CH_4 emissions (~500 tons/km^2 and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 2 km^2. • If factors affecting specific emissions are *mixed*, use the median for total CO_2 and CH_4 emissions (~1,000 tons/km^2 and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 1 km^2.

a. All tons refer to *metric* tons (or "tonnes").

analyzed qualitatively, little additional time will be required to enter input data and run the *G-res* tool.

The results of the screening should be reported as a subchapter of the ESIA. For the project appraisal document (PAD), a shorter version can be included. Appendix C gives a template for the presentation of input data and screening results in the PAD.

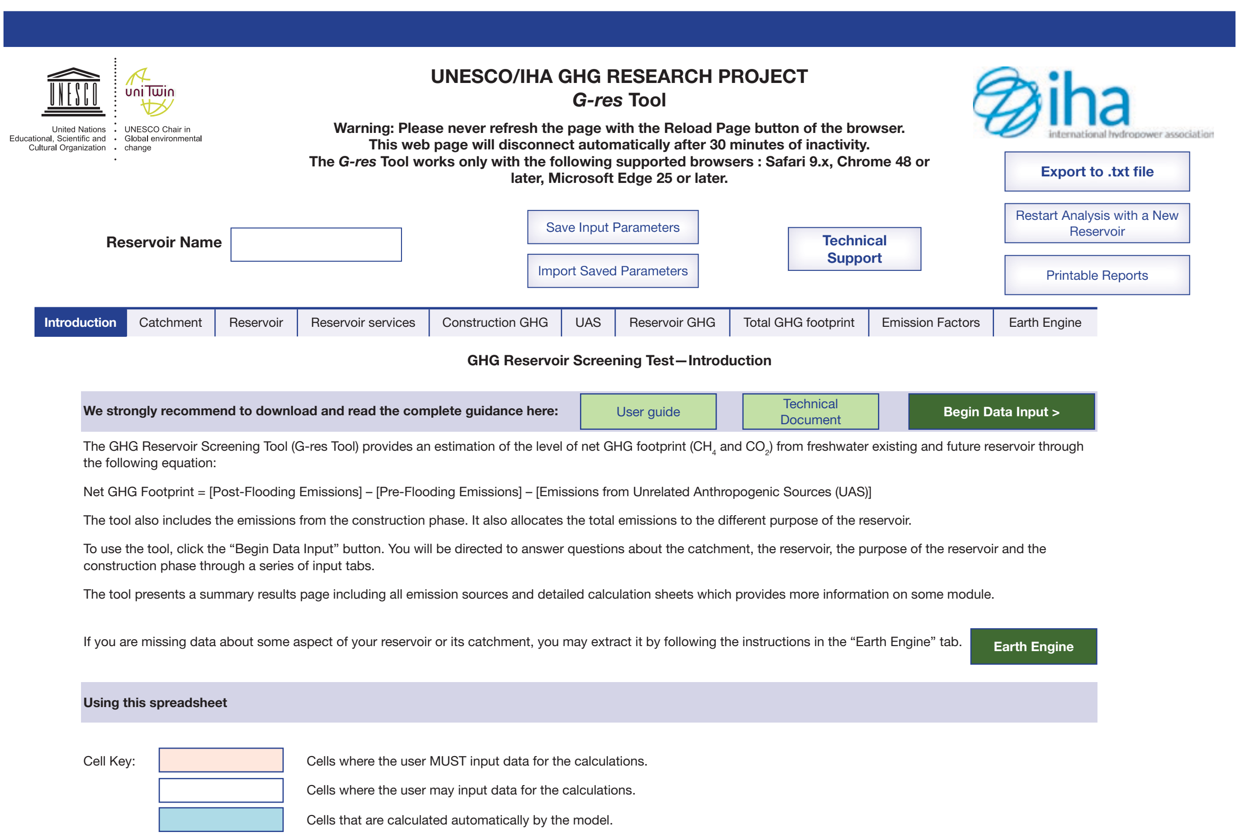
4.3 Quantitative Assessment of Net Emissions Using the *G-res* Tool

If potentially significant GHG emissions cannot be discounted through the above initial screening assessment, it is recommended that the *G-res* tool be applied, for which input is derived from secondary data. The *G-res* tool is available online (www.hydropower.org/gres-tool) and free to use. The site includes technical documentation on the scientific basis for the tool and a guide for its step-by-step use (figure 4.3).

The *G-res* tool needs the following inputs:

- **Upstream catchment**
  - Catchment area (required)
  - Catchment annual runoff (required)
  - Land cover (required)
  - Information on intensity of land use
  - Population in catchment area (required)
  - Potential point sources and general level of waste water treatment

FIGURE 4.3. The Interface of the Online *G-res* Tool



- **Area to be inundated by reservoir**
  - Reservoir area (required)
  - Climate zone (required)
  - Mean monthly temperature (required)
  - Average wind speed (required)
  - Mean global horizontal radiance (required)
  - Soil type and soil carbon content (required)
  - Land cover (required)
  - Information on intensity of land use
- **Reservoir**
  - Reservoir volume
  - Max and mean depth (required)
  - Planned normal operation level
  - Planned water intake elevation

These data are generally available in feasibility and environmental impact studies or can be found in global databases. The *G-res* tool offers possibilities to estimate the geographic data for the catchment and reservoir areas through open source Geographic Information System (GIS) software, which is linked to the latest global databases. An example of the application of the *G-res* tool is given in appendix B.

Entering the above data into *G-res* will give the user an estimate of reservoir emissions. It is also possible to include information on the dam construction (excavation, cement and steel volumes, transport distances), which would give a preliminary estimate of construction emissions. The *G-res* tool further allows defining multipurpose uses of the reservoir (primary, secondary, and tertiary use) and will allocate the total GHG emissions to these different uses.

The *G-res* tool interface is fairly easy to use. However, it is essential that a practitioner with experience in the field of dam development and construction use this tool to ensure that the quality of the input data is reasonable. It is equally essential that the *G-res* user be duly trained in the tool and have a basic understanding of GHG emissions from reservoirs. Because of the nonlinearity and the existence of thresholds in the underlying functions used to estimate reservoir emissions, the user's ability to conduct sensitivity analyses for key variables and assess the reasonability of the subresults (such as the different gases and pathways) is important to understand and gauge the robustness of the resulting emissions.

4.4 Assessment of Reliability in Estimated Emissions

The uncertainty associated with the *G-res* tool to quantify GHG emissions from a reservoir should be noted. Because of the use of different data, the reliability of the underlying models differs for different pathways. The estimated diffusive CO_2 and CH_4 have the highest reliability, while CH_4 bubbling and degassing have the lowest reliability. The uncertainty also increases toward the tails of the distribution, such as for reservoirs with very high emissions. By contrast, estimates are more reliable when close to the median (e.g., between the 25th and 75th percentile).[1] The user must therefore be trained to note when there are uncertainties in subtotals and overall estimates of GHG emissions.

The user interface of the *G-res* tool makes it relatively easy to conduct a sensitivity analysis to understand what input parameters have the largest effect on the estimated net emissions. If those input parameters are uncertain, it is also an indication that the estimated emissions have low reliability.

It is also important to put the *G-res* results into perspective—in terms of how they would affect the intended investment. This requires assessing whether the estimated level of emissions from the reservoir would significantly contribute to GHG emissions and whether the emissions' order of magnitude is such that they would have a significant impact on the economic return of the project. If the latter case applies, the emissions may need to be assessed further to get more reliable results. As in the case of the initial screening, the GHG emissions estimated using the *G-res* tool for the proposed investment should be compared with the emissions caused by the counterfactual. It is therefore essential to identify the most likely counterfactual and roughly estimate its emissions before comparing it with the *G-res* estimate for the proposed investment project. In the case of hydropower, this process is fairly straightforward, as the average emission factors per produced kWh are well-known for the power generation alternatives. If the *G-res* tool gives similar or higher emissions per kWh than the counterfactual—thereby highlighting the risk that the project may not be a mitigation project—a high-reliability estimate is desired, which may require further studies.

An alternative to the above approach is to conduct a rough economic analysis for the investment with and without a shadow carbon price. Moreover, such an analysis should not only be conducted for the reservoir emissions estimated with the *G-res* tool, but also for an interval that illustrates the uncertainty in this value, for example, ±25 percent and ±50 percent. If the analysis shows that the economic cost of carbon emissions may be significant compared to the total cost of the project, this suggests a highly reliable estimate is desired and further studies may be required. Conversely, if the economic analysis indicates that even in the scenario of 50 percent higher emissions the impact on the project's economic return is minimal, the *G-res* tool estimate may suffice.

If *significant* reservoir emissions are indicated, estimates derived through other means—to see if the values converge—should be considered. This is particularly relevant if the main sources of the high reservoir emissions as indicated by the *G-res* tool are CH_4 bubbling and degassing, and if the specific emissions lie above the 75th percentile. Suitable methods that can be used for comparison are those based on the availability of carbon stock, which give an idea of possible net emissions.[2] One such method is the methodology proposed by the *Interim Technical Note on Greenhouse Gases from Reservoirs Caused by Biogeochemical Processes* by the World Bank (2013), which uses the *2006 IPCC Guidelines for National Greenhouse Gas Accounting* together with assumptions on ratios between CO_2 and CH_4 production to estimate the reservoir emissions. In the case of hydropower, median emissions using the World Bank (2013) methodology are available in table format for different power densities and plant factors.[3]

Based on the above methods, the user needs to make a qualitative judgment about the reliability of the reservoir emissions estimated with the *G-res* tool. Any presentation of the *G-res* tool estimate should be accompanied with transparently acknowledging the uncertainty associated with the results.

The results of the *G-res* tool, and the reliability assessment, should be reported as a subchapter in the ESIA, or as a concise dedicated report. Sources and major assumptions for all input data should be included as well as subresults such as the contribution from different GHGs and pathways. The reliability of the results should not only be presented but also commented on. For the PADs, a shorter summary of the input data and results is acceptable. A template for the presentation of the results of the reservoir GHG emission assessment is given in appendix C.

4.5 Detailed Assessment Following the IEA Hydro Framework

If the reliability assessment indicates a need for further assessment of reservoir GHG emissions, and if the time (6 months to 2 years) and resources (order of magnitude of $50,000-$500,000) are acceptable considering the cost of the total investment, plans should be drawn up for primary data collection and modeling.

If the main reason for the unreliable estimation of reservoir emissions is the absence of or uncertainty in key input data for the GHG emissions estimate, the primary data collection should focus on closing those data gaps. The following types of field measurements should be conducted: (i) topographical surveys to confirm maximum and medium depths, and littoral area extent, of the proposed reservoir; (ii) surveys to confirm vegetation, land cover, and land use in the reservoir area; (iii) plot tests to confirm soil carbon content in flooded area; (iv) water quality sampling to confirm estimated organic material and nutrient concentrations in inflowing water; and (v) climatological measurements to confirm solar radiation and wind speed. Verified data can be used to update the *G-res* tool to get a more reliable estimation of the reservoir emissions.

On the other hand, if the uncertainty is associated with the *G-res* tool itself (e.g., due to very high levels of CH_4 bubbling or degassing) or if the requirement for reliability is high, more comprehensive primary data compilation is advised—to be able to estimate pre-impoundment emissions and provide detailed input data for the application of physical, process-based modeling for estimation of post-inundation emissions. This comprehensive data compilation should include additional, detailed bathymetric surveys, high-resolution climate data collection, and extensive water quality and soil sampling, as well as direct measurement of pre-impoundment emissions. Based on these data, hydrodynamic and biogeochemical models should be set up and calibrated to estimate water quality variables and reservoir emissions after impoundment.

Primary data compilation and modeling should be based on the guidelines and requirements of the IEA Hydro framework and be informed by the experience and lessons learned from previous data measurements and modeling exercises (see Bibliography). Detailed assessments would probably require the procurement of a dedicated team of experts in reservoir GHG emissions to conduct data collection and modeling. The methods, data, and results of such a detailed assessment should be described in a dedicated, detailed report. It is envisioned that such a report would be a subreport of the ESIA.

4.6 Management of GHGs and Post-Impoundment Monitoring

In the case of dam infrastructure projects for which potentially significant GHG emissions have been estimated, possible mitigation measures should be considered and specified in the Environmental and Social Management Plan (ESMP). IEA Hydro (2017) provides a general framework for managing and mitigating GHG emissions. More specifically, it proposes that a detailed **GHG Management Plan** (a subplan of the ESMP) be prepared—including proposed mitigation actions and specific targets—for projects where net reservoir GHG emissions are estimated to be significant. The GHG Management Plan should also include monitoring and regular reporting of GHGs emitted as well as the mitigation measures applied.

IEA Hydro (2017) gives a framework for systematically assessing possible mitigation measures for the five stages of project development:

- Project planning and design;
- Project implementation (construction and reservoir impoundment);
- Dam, power plant, and reservoir operation, including contributions of UAS;
- Catchment management, including contributions of UAS; and
- Downstream management.

GHG emissions management can, for example, include infrastructure design. Measures to increase oxygen concentrations upstream of intakes in Nam Theun 2 have been shown to decrease emissions of CH_4 degassing (Deshmukh et al. 2016) downstream of the outlet. Keeping intakes above the level of the hypolimnion is another mitigation measure that may have large potential to decrease methane emissions. During operation, one possible mitigation measure is to avoid a rapid drawdown, as this favors CH_4 bubbling. Further, although not considered part of the net emissions, UAS can contribute to a high volume of reservoir GHGs but this is to a large extent manageable. Organic material and nutrient effluents from the upstream catchment can also be managed and covered in the catchment treatment plans included in the ESMPs. Management of UAS reduces gross GHG emissions and improves the water quality of the reservoirs, an aspect that has both recreational and O&M benefits. Should mitigation measures be difficult to implement, offsetting reservoir GHG emissions through certified emission reductions (CER) or other carbon credits is a further possibility to consider.

Moreover, in the case of dam infrastructure projects with potentially significant GHG emissions, it is recommended that the post-implementation monitoring of GHG emissions from the reservoir and immediate river stretch downstream be streamlined. It should be emphasized that the purpose of this monitoring is *not* to provide an accurate estimate of *net* GHG emissions but rather to allow a rough comparison of *gross* emissions with the estimates calculated during the preparation phase and to monitor any changes (e.g., changes as a result of mitigation measures).

Such a monitoring program should also be included in the GHG Management Plan and could have the following characteristics:

- Focuses on *gross* emissions of CO_2 and CH_4 as measured by surface floating chambers;[4]
- Covers the reservoir along its longitudinal axis as well as the immediate river stretch downstream of the reservoir;
- Includes sampling of CH_4 concentrations upstream and downstream of the intake/outlet;
- Covers a period of at least 3 years and includes seasonal measurements.

Notes

1. The *G-res* tool interface has a feature to show where the estimated GHG emissions (per m^2) for each pathway of the studied reservoir are situated in the distribution curve of all dams in the GRanD database (with more than 6,500 reservoirs). This helps the user determine whether the results are extreme.
2. Assuming that inflowing carbon is only displaced by the introduction of the reservoir, the amount of carbon stored in soil and vegetation in the flooded area represents the upper limit of the net emissions created by the reservoir (see also World Bank 2013).
3. See *Guidance Manual: Greenhouse Gas Accounting for Energy Investment Operations, Transmission and Distribution Projects, Power Generation Projects, and Energy-Efficiency Projects, Version 2.0,* January 2015.
4. See, for instance, UNESCO/IHA (2010) for a description of monitoring methods.

Chapter 5
Future Research

The research on GHG emissions from freshwater lakes and reservoirs has made significant progress over the last decade. However, data are still scarce and unevenly distributed, and the understanding of the complex processes involved is still incomplete. Though there is general agreement on the main factors affecting GHG emissions from reservoirs, the statistical models of the *G-res* tool only consider a few of these factors significant for the prediction of emissions. This focus probably reflects the scarcity of data (which allow statistically significant improvements of the results) rather than the assumption that the variables not taken into account are unimportant. Continued research is, therefore, essential to enhance knowledge and groundtruth new predictive models, such as the *G-res*, through measurement campaigns. The IEA Hydro guidelines should also be supported by examples of their use.

It is anticipated that more and more data will become available from measurements. Remote sensing of GHG fluxes using satellites is one method that could substantially improve data collection over large reservoir areas and considerably increase the amount of available data. New data and new insights will allow the statistical models of the *G-res* tool to be updated and will be incorporated into similar predictive tools to be developed for practitioners. Process-based modeling is likewise expected to advance as more research and more powerful computers become available.

The development of predictive, online models (such as the *G-res* tool) represent a major milestone in the estimation of reservoir GHG emissions. As future data and research are channeled toward these tools, the practitioners in dams and hydropower will get access to more reliable tools. UNESCO/IHA is in the process of operationalizing the *G-res* tool so that it is duly maintained and updated as new research becomes available.[1] In addition, the increased focus on reducing GHG emissions is expected to result in stakeholders agreeing on what actually comprises *significant* emissions.

It is believed that the recommendations given in chapter 4 of this technical note will remain relevant for the most part, even as today's predictive tools are updated and improved, and agreed thresholds are introduced. The state of the art will certainly change and global estimates of reservoir emissions will be revised accordingly. It is important that WBG staff working in the field of hydropower and dam infrastructure development keep up-to-date on the developments in the area of GHG emissions from reservoirs and ensure that the latest research findings and tools are applied to WBG investments.

Note

1. Verbal communication, Yves Prairie and Richard Taylor, May 2017.

Appendix A
Conversion of GHG Units and CO_2 Equivalents

Conversion from Moles to G

In chemistry, a mole is considered Avogadro's number (6.02×10^{23}) of molecules (or anything) of a substance—in other words, depending on the density of the substance, the mass of that amount of the substance could vary widely. To convert from moles to grams you must first find the molar mass of the element or compound. Use the periodic table to read off the atomic mass of an element. If it is a compound, you must know the molecular formula, and then you find the total molar mass of the compound by adding up the atomic masses of each atom in the compound. The unit of the molar mass will be in grams per moles (g/mole). Once you have the molar mass, you can easily convert from grams to moles, and also from moles to grams.

Number of moles = (# of grams) ÷ (molar mass)

Number of grams = (# of moles) × (molar mass)

Conversion table for the most common GHGs in reservoirs:

Element	Atomic mass (g/mole)
N	14.0067
C	12.0107
O	15.9994
H	1.00794

GHG	Molar mass (g/mole)
CO_2	44.0095
CH_4	16.0107
N_2O	44.0128

CO_2 Equivalents

The international practice is to express GHG emissions in CO_2 equivalents (CO_2eq or CO_2e). Emissions of gases other than CO_2 are converted into CO_2eq by multiplying their respective volumes by their respective Global Warming Potentials (GWPs). From the *2013 IPCC Report*:

GWP relative to CO_2 at different time horizons for the most common GHGs in reservoirs:

Gas name	Chemical formula	GWP for given time horizon	
		20-yr	100-yr
Carbon dioxide	CO_2	1	1
Methane	CH_4	86	34
Nitrous oxide	N_2O	268	298

Source: 2013 IPCC Fifth Assessment Report (AR5).

Conversion from "G of GHG" to "G of Carbon"

The conversion between "g of GHG" and "g of carbon" is directly related to the ratio of the atomic mass of a GHG molecule to the atomic mass of a carbon atom. Essentially, this practice accounts for the carbon in the GHG molecule, as opposed to counting the entire molecule.

For **carbon dioxide**, the ratio of the atomic mass of a CO_2 molecule to the atomic mass of a carbon atom is 44:12.

- To convert from "g of C" to "g of CO_2" multiply by 44/12.
- To convert from "g of CO_2" to "g of C" multiply by 12/44.

- Sometimes you find this noted as gC-CO_2 or tC-CO_2 (to make clear that these "g of C" refer to carbon in a CO_2 molecule).

For **methane**, the ratio of the atomic mass of a CH_4 molecule to the atomic mass of a carbon atom is 16:12.

- To convert from "g of C" to "g of CH_4" multiply by 16/12.
- To convert from "g of CH_4" to "g of C" multiply by 12/16.
- It is important to make clear that these grams of C refer to carbon in a CH_4 molecule (i.e., NOT CO_2eq–in other words, not taking into account GWP). It is common to use gC-CH_4 or tC-CH_4.

Carbon Dioxide Equivalents Vs. Carbon Equivalents

While the international standard is to express emissions in *CO_2* equivalents (CO_2eq), many U.S. sources have expressed emissions data in terms of *carbon* equivalents (CE) in the past. In particular, the United States Environmental Protection Agency (US EPA) has used the carbon equivalent metric in the past for budget documents.

For the purposes of national GHG inventories, emissions are expressed as teragrams of CO_2 equivalent (Tg CO_2eq). One teragram is equal to 10^{12} grams, or 1 million tons.

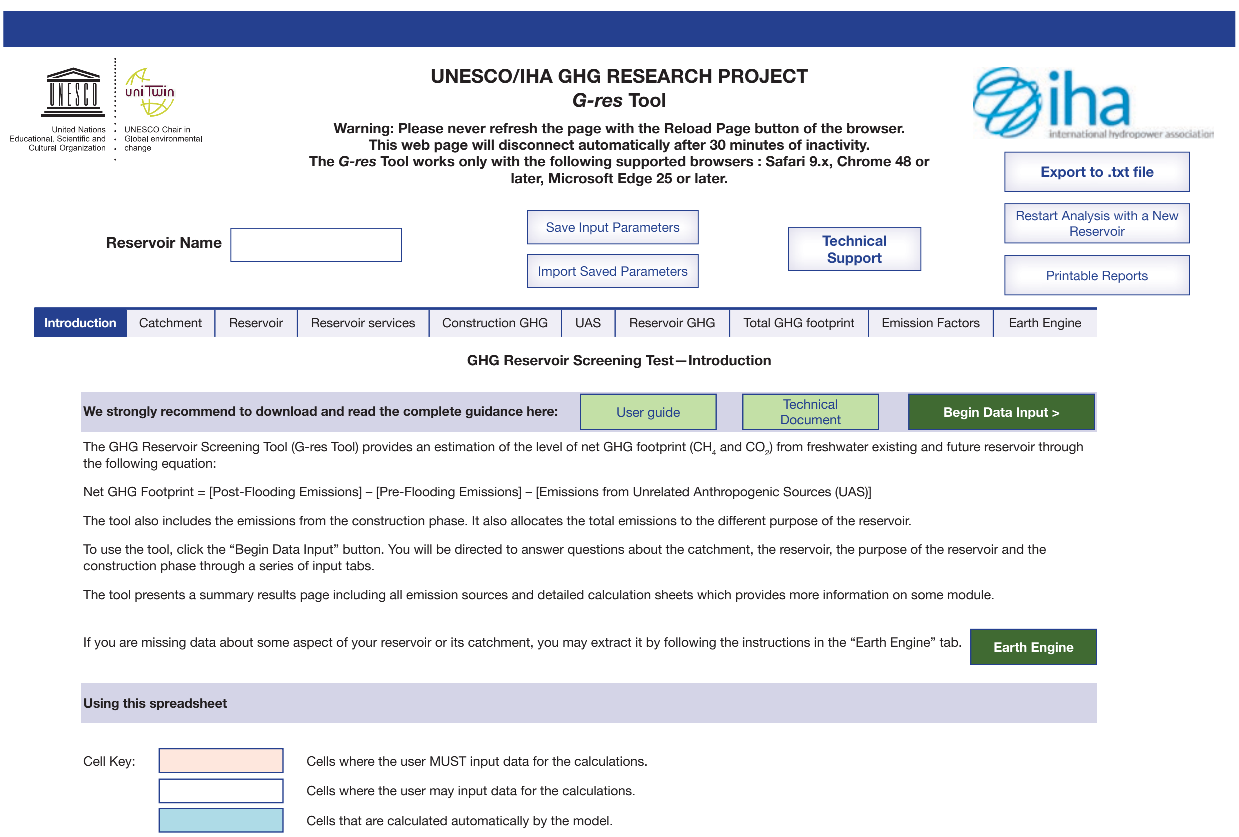
- To convert from CE to CO_2eq, multiply by 44/12.
- To convert from CO_2eq to CE, multiply by 12/44.

Appendix B
Example of *G-res* Application

Project Name	Trung Son
Country	Vietnam
Installed Capacity	260 MW
Yearly Generation	1,019 GWh/year
Climate	Tropical
Reservoir area	13.1 km^2

Sources of information:

- Project information and hydrology: Supplementary Environmental and Social Impact Assessment, Trung Son Hydropower Project, 2009
- Land cover: ESA-CCI (via Earth Engine linked to *G-res*)
- Soil: Harmonized World Soil Database, FAO/IIASA/ISRIC/ISSCAS/JRC (via Earth Engine linked to *G-res*)
- Temperature: Hijmans et al. 2005, Global Climate database (via Earth Engine linked to *G-res*)
- Solar radiation: NASA - SSE 2008 (via Earth Engine linked to *G-res*)
- Wind speed: GLOBE task team, NOAA (via Earth Engine linked to *G-res*)
- Population density: Center for International Earth Science Information Network, Columbia University (via Earth Engine linked to *G-res*)



United Nations Educational, Scientific and Cultural Organization

UNESCO Chair in Global environmental change

UNESCO/IHA GHG RESEARCH PROJECT

G-res Tool

Warning: Please never refresh the page with the Reload Page button of the browser. This web page will disconnect automatically after 30 minutes of inactivity. The *G-res* Tool works only with the following supported browsers : Safari 9.x, Chrome 48 or later, Microsoft Edge 25 or later.

International hydropower association

Export to .txt file

Restart Analysis with a New Reservoir

Printable Reports

Reservoir Name Trung Son

Save Input Parameters

Import Saved Parameters

Technical Support

Introduction | **Catchment** | Reservoir | Reservoir services | Construction GHG | UAS | Reservoir GHG | Total GHG footprint | Emission Factors | Earth Engine

Input Page 1/4—Catchment Data

Online Technical Document for Catchment

On this sheet, enter the data on the land cover types in the catchment area and the reservoir area.

Current Totals	tCO_2e/yr
Post-Impoundment	4643
Pre-Impoundment	–97
UAS	177

Catchment Area (km^2)	14660
Population in the Catchment	483323
Catchment Annual Runoff (mm/yr)	551
Community Wastewater Treatment—Please Select	Primary
Release of phosphorus from industrial sewage in the catchment (kg P/yr)	0
Industrial Wastewater Treatment—Please Select	Primary

User Guidelines

The user should select land cover data based on the most appropriate and relevant data for the reservoir and catchment area.

Where land cover categories differ with the categories presented in the *G-res* Tool, the user should rationalize the data being used into the same categories and check that the emission factors used in the *G-res* Tool are applicable to those land cover types.

"Intensity" is used to describe the level of human influence on the land use as part of the UAS module. Broadly this means whether for agriculture and forest it is heavily managed land, and for urban area whether the population density is high. Sensitivity analysis is encouraged.

Land Cover in the Catchment Area

Please choose units of inputs: %

Land Use Intensity
Low = Unmanaged Land
High = Managed Land

	%	**km^2**	**Past**	**Current**
Croplands	7 %	1026.2	Low	Low
Bare Areas	0 %	0		
Wetlands	0 %	0		
Forest	40 %	5864	Low	Low
Grassland/Shrubland	53 %	7769.8	Low	Low
Permanent Snow/Ice	0 %	0		
Settlements	0 %	0	Low	Low
Water Bodies	0 %	0		
Drained Peatlands	0 %	0		
No Data	0 %	0		

Reset Catchment Land Cover

User Notices

WARNING—Please be sure to add 0% to all land cover with no value.

Pre-Impoundment Land Cover in the Reservoir Area

Reservoir Area (km^2) 13.1

	% Mineral Soil	**% Organic Soil**	**% of Organic Soil that is Drained**	**Past Land Use Intensity** Low = Unmanaged Land High = Managed Land	**%**	**km^2**
Croplands	3.6 %	0 %	( )	Low	3.6 %	1
Bare Areas	0 %	0 %	( )		0.0 %	0
Wetlands	0 %	0 %	( )		0.0 %	0
Forest	5.3 %	0 %	( )	Low	5.3 %	1
Grassland/Shrubland	91 %	0 %	( )	Low	91.0 %	12
Permanent Snow/Ice	0 %	0 %	( )		0.0 %	0
Settlements	0 %	0 %	( )	Low	0.0 %	0
River Area before Impoundment	0.1 %		( )		0.1 %	0
Drained Peatlands		0 %			0.0%	0
No Data	0 %					

Reset Reservoir Land Cover

Edit Emission Factors

Net Input Page

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Restart Analysis with a New Reservoir

Printable Reports

Reservoir Name Trung Son

Save Input Parameters

Import Saved Parameters

Technical Support

Introduction | Catchment | **Reservoir** | Reservoir services | Construction GHG | UAS | Reservoir GHG | Total GHG footprint | Emission Factors | Earth Engine

Input Page 2/4—Reservoir Data

Online Technical Document for Reservoir

On this sheet, enter the key parameters that describe the reservoir.

Current Totals	**tCO_2e/yr**
Post-Impoundment	4643
Pre-Impoundment	–97
UAS	177

Country	Vietnam
Longitude of Dam (DD)	104.76
Latitude of Dam (DD)	20.59
Climate Zone (Reservoir Area)	Tropical
Impoundment Year	2016
Reservoir Area (km^2)	13.1
Reservoir Volume (km^3)	0.345
Mean/Normal Operating Level (m above sea level)	159
Maximum Depth (m)	50
Mean Depth (m)[1]	26.336
Littoral Area (%)[2]	5.408
Thermocline Depth (m)[3]	0.5
Water Intake Depth (m)[4]	14
Water Intake Elevation (m above sea level)	145
Soil Carbon Content Under Impounded Area (kgC/m^2)	3.4
Annual Wind Speed at 10 m (m/s)	1.7
Water Residence Time (WRT, yrs)[5]	0.0427
Annual Discharge from the Reservoir (m/s)[6]	256.1
Phosphorus Concentration (μg/L)[7]	26.4
Trophic Level	Mesotrophic
Reservoir Mean Global Horizontal Radiance ($kWh/m^2/d$)	3.8
Mean Temperature per Month (°C)	
January	16.4
February	18.1
March	20.4
April	23.9
May	26.9
June	28
July	27.6
August	27.5
September	26.5
October	24.2
November	21.5
December	18
Mean Annual Air Temperature (°C)	23.3

**To reset to automatically calculate value, press the reset button ( ) associated.

User Guidelines

Project specific information should be used. This may be obtained from current operations or from feasibility studies.
For reservoirs that are expected to exhibit fluctuations in certain parameters depending on season or operating regime, the user should determine the 'typical' values and then undertake a sensitivity analysis to determine whether those variations affect the overall result.

1) If Reservoir Area and Volume are available. Mean Depth will be calculated.

2) If Mean and Maximum Depth are available, % Littoral Area will be calculated.

3) If Reservoir Area, Maximum Depth, Mean Depth, Annual Wind Speed and Monthly Temperature are available, Thermocline Depth will be calculated.

4) If Mean/Normal Operating Level and Water Intake Elevation are available, Water Intake Depth will be calculated.

5) If Reservoir Area, Mean Depth, Runoff and Catchment Area are available, WRT will be calculated.

6) If Reservoir Runoff and Catchment are available, Discharge will be calculated.

7) If Catchment Land Cover, WRT, Runoff, Catchment Area and Population are available, Phosphorus Concentration will be calculated.

Next Input Page

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Restart Analysis with a New Reservoir

Reservoir Name Trung Son

Save Input Parameters

Import Saved Parameters

Technical Support

Printable Reports

Introduction | Catchment | Reservoir | **Reservoir services** | Construction GHG | UAS | Reservoir GHG | Total GHG footprint | Emission Factors | Earth Engine

Input Page 3/4—Reservoir Services Data

Online Technical Document for Reservoir Services

Many reservoirs provide multiple services.
In order to assess the GHG emissions associated with each of the services, it is necessary to allocate a proportion of the total emissions across the relevant services.

Allocation of Reservoir Purposes		**Percentage Allocation**
Flood Control	Tertiary	5
Fisheries		0
Irrigation		0
Navigation		0
Environmental Flow		0
Recreation		0
Water Supply		0
Hydroelectricity	Primary	95

Please indicate which allocation method was used to determine the importance of the services:

Operating Rule Curve

Please explain if another method was used:

The definitions of primary, secondary and tertiary services for these options are provided in the table below.
For more information on the allocation method that can be used to determine the importance of the services (Explicit Prioritisation or Operating Rule Curve), please see the user guideline.

Importance	**Explicit Prioritisation**	**Operating Rule Curve**
Primary	Ranked 1 to 3 in operational hierarchy.	Operating rules are designed to maximize the benefits of this service for part or all of the year.
Secondary	Ranked lower than 3 in operational hierarchy, or places constraints on operation.	The service places operational constraints on the operating level of the reservoir for part or the whole of the year.
Tertiary	Does not alter the operation of the reservoir.	The service has little impact on the operation of the reservoir.

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Technical Support

Introduction | Catchment | Reservoir | Reservoir services | **Construction GHG** | UAS | Reservoir GHG | Total GHG footprint | Emission Factors | Earth Engine

Input Page 4/4—Construction Data

Online Technical Document for Construction

If available, please input information that describes the amount of materials used in the construction phase. You can include your own value, or use the simple or more detailed parameters below. Please note that numbers included in each section will be added together. If the scheme used to 10,000 m³ of concrete, you only need to include it in the basic assessment or the more detailed assessment. Including it in both could lead to double counting. For transport, it is assumed that the delivery is by road so please include the last part of the journey to site, i.e., after any shipping.

Own Assessment

If you have undertaken your own assessment of GHG emissions associated with your scheme, you can include that value here.

Emission output kgCO_2e

Known Value for Construction	Total Construction emissions	

Basic Assessment

These are the basic materials likely to make up a significant part of the construction phase GHG emissions.

Earth and Rockfill	Material excavated and/or used for construction	470000	m³	2	km moved	10685967
Concrete	All concrete brought to site for the dam, tunnels, foundations	960000	m³	80	km delivery distance	357709440
Steel	All steel brought to site for reinforcement, pipelines, mechanical and electrical equipments	11100	tonne	80	km delivery distance	29936522

More Detailed Assessment

This provides a more detailed list of typical materials used. Use these values if you have more detailed information about the types of material used on the scheme.

Earthworks	Soft Excavation		m³		km moved	0
	Rock Excavation		m³		km moved	0
	Clearance and Removals		ha			0
Fill	Granular Fill		m³		km delivery distance	0
	Rock Armour		m³		km delivery distance	0
	Zoned Rockfill		m³		km delivery distance	0
	Rock bolts		number		km delivery distance	0
Concrete Works	Formwork		m³			0
	Facing Concrete		m³		km delivery distance	0
	Mass Concrete		m³		km delivery distance	0
	Reinforced Concrete		m³		km delivery distance	0
	Shotcrete		m³		km delivery distance	0
	Reinforcement		tonne		km delivery distance	0
Steelworks	Steel Penstocks		tonne		km delivery distance	0
	Steel Liner		tonne		km delivery distance	0
	Miscellaneous Steelwork		tonne		km delivery distance	0
Roads and Bridges	New Roads		km			0
	Refurbishment of Existing Roads		km			0
	PCC Vehicular Bridge Deck		m³			0
Equipment	Power Generation		MW			0
	Power Connection		kV		km length	0

Please record any assumptions, limitations and data sources here:

To UAS Summary Page

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Introduction | Catchment | Reservoir | Reservoir services | Construction GHG | **UAS** | Reservoir GHG | Total GHG footprint | Emission Factors | Earth Engine

Unrelated Anthropogenic Sources Emissions — Online Technical Document for UAS

Calculations of Phosphorus Loads

Total P in the reservoir (µg/L)	26.4
Reference Level of P (µg/L)	25.7
P from industrial sewage (µg/L)	0.0
P from human sewage (µg/L)	0.0
P from human land use (µg/L)	1.5
P over Reference Land (µg/L)	0.7
Share of UAS of the P in reservoir, evaluated as P (µg/L)	1.5

User Notices
Trophic state:
If the reservoir is oligotrophic, no UAS contribution is identified

Estimated Contribution of UAS to the GHG Emissions from the Reservoir

Calculated CH_4 emissions from the reservoir ($gCO_2e/m^2/yr$)	108.5
Amount of CH_4 of total estimates due to UAS (%)	**6%**
Estimated CH_4 release due to UAS ($gCO_2e/m^2/yr$)	**13.5**

Weighted sum model risk 66

Sensitivity to Nutrient Load

Climate	Tropical	High Climatic Sensitivity
Water residence time (yrs)	0.0	Low to Moderate Sensitivity

Comment on Risk Factor for the GHG Emissions:

Share of Anthropogenic Impact

		% of total UAS emissions		
UAS emissions from Land Use ($gCO_2e/m^2/yr$)	13.5	100%	Cropland	Low to Moderate Risk
			Forestry	Low to Moderate Risk
			Grasslands/Pasture	Low to Moderate Risk
			Settlements	Low to Moderate Risk
UAS Emissions from Sewage ($gCO_2e/m^2/yr$)	0.0	0%		
	Community sewage	0%		Low to Moderate Risk
	Industrial sewage	0%		Low to Moderate Risk

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Technical Support

Printable Reports

Introduction | Catchment | Reservoir | Reservoir services | Construction GHG | UAS | **Reservoir GHG** | Total GHG footprint | Emission Factors | Earth Engine

Predicted Emissions

Online Technical Document for Reservoir GHG

Net Predicted Annual CO_2e Emission

	Post-Impoundment	–	Pre-Impoundment	–	Unrelated Anthropogenic Sources	=	Net GHG Footprint
Emission Rate (tCO_2e/yr)	**4 643**	–	**–97**	–	**177**	=	**4 563**
of which CO_2	1 537	–	–97		n/a	=	1 634
of which CH_4	3 106	–	0	–	177	=	2 929
Emission Rate (gCO_2e/m^2yr)	**354**	–	**–7**	–	**14**	=	**348**
of which CO_2	117	–	–7		n/a	=	125
of which CH_4	237	–	0	–	14	=	224

Percentile of Net GHG emissions within the database 56%

Relative contribution to CH_4 Post-Impoundment Emissions

Percentile of each CH_4 contribution within the database

		Percentile
Fraction of CH_4 diffusive flux from Total Reservoir CH_4 Emission (%)	46%	59%
Fraction of Degassing of CH_4 from Total Reservoir CH_4 Emission (%)	48%	10%
Fraction of Bubbling of CH_4 from Total Reservoir CH_4 Emission (%)	7%	20%

User Notice
WARNING Deep Water Intake. Likely Important Contribution of Degassing.

Unrelated Anthropogenic Sources
Potential amount of UAS as % of post-Impoundment emissions 6%
Weighted sum total model risk result 66

To Total GHG Summary Page

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Printable Reports

Reservoir Name Trung Son

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Import Saved Parameters

Technical Support

Introduction | Catchment | Reservoir | Reservoir services | Construction GHG | UAS | Reservoir GHG | **Total GHG footprint** | Emission Factors | Earth Engine

Predicted Emissions

Online Technical Document for Total GHG footprint

Net Predicted Annual CO_2e Emission

	Post-Impoundment	–	Pre-Impoundment	–	Unrelated Anthropogenic Sources	+	Construction (Reservoir)	=	Net GHG Footprint
Areal Emission ($gCO_2e/m^2/yr$)	354	–	–7	–	14	+	n/a	=	348
Reservoir Wide Emissions (tCO_2e/yr)	4 643	–	–97	–	177	+	3 983	=	8 546
Total Lifetime Emission (tCO_2e)	464 339	–	–9 683	–	17 706	+	398 332	=	854 648

Net GHG Emissions Contribution for Each Reservoir Services

Reservoir Service	GHG Emissions from Reservoir (tCO_2e/yr)	GHG Emissions from Construction (tCO_2e/yr)	GHG Footprint (tCO_2e/yr)	Percentage Allocation (%)
Flood Control	228	199	427	5
Fisheries	0	0	0	0
Irrigation	0	0	0	0
Navigation	0	0	0	0
Environmental Flow	0	0	0	0
Recreation	0	0	0	0
Water Supply	0	0	0	0
Hydroelectricity	4335	3784	8119	95

Allocation Method Used:

Operating Rule Curve

Emission Factor Used:

Default Emission Factors Used

Construction Comments:

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G-res Tool

GHG Results Report

Name of reservoir: Trung Son

Back to G-REs Tool

Back to Reports

Reservoir GHG Information

Net Predicted Annual CO_2e Emission

	Post-Impoundment	–	Pre-Impoundment	–	Unrelated Anthropogenic Sources	=	Net GHG Footprint
Emission Rate (tCO_2e/yr)	4 643	–	–97	–	177	=	4 563
of which CO_2	1 537	–	–97		n/a	=	1 634
of which CH_4	3 106	–	0	–	177	=	2 929
Emission Rate ($gCO_2e/m^2/yr$)	354	–	–7	–	14	=	348
of which CO_2	117	–	–7		n/a	=	125
of which CH_4	237	–	0	–	14	=	224

Percentile of Net GHG emissions within the database	56%
Relative contribution to CH_4 Post-Impoundment Emissions	
Fraction of CH_4 diffusive flux from Total Reservoir CH_4 Emission (%)	46%
Fraction of Degassing of CH_4 from Total Reservoir CH_4 Emission (%)	48%
Note: WARNING Deep Water Intake. Likely Important Contribution of Degassing.	
Fraction of Bubbling of CH_4 from Total Reservoir CH_4 Emission (%)	7%
Unrelated Anthropogenic Sources	
Potential amount of UAS as % of post-impoundment emissions	6%
Weighted sum model risk result	66

Total GHG footprint information

	Post-Impoundment	–	Pre-Impoundment	–	Unrelated Anthropogenic Sources	+	Construction (Reservoir)	=	Net GHG Footprint
Areal Emissions ($gCO_2e/m^2/yr$)	354	–	–7	–	14	+	n/a	=	348
Reservoir Wide Emissions (tCO_2e/yr)	4 643	–	–97	–	177	+	3 983	=	8 546
Total Lifetime Emission (tCO_2e)	464 339	–	–9 683	–	17 706	+	398 332	=	854 648

Appendix C
Suggested Template for GHG Reporting

The following page shows an example of a template that can be included in appraisal documents for hydropower and dam infrastructure projects. By way of illustration, the template has been filled out based on the application of the *G-res* tool to Trung Son (see appendix B).

General Project Description		
Project name:		Trung Son, Vietnam
Purpose:		Main purpose: Hydropower. Project also has flood control benefits.
Reservoir Area (km^2):		13.1
Climate:		Tropical
Vegetation:		Mixed forest and shrubland
If hydropower	Installed capacity (MW)	260
	Annual energy (GWh)	1019
	Power Density (W/m^2)	19.8
Initial screening		
Likely counterfactual:		Because of the high growth in electricity demand in Vietnam, if Trung Son would not be built, it is likely that power would be produced through a mix of gas and coal powered plants. These would produce emissions in the order of 450–900 g CO_2/kWh
Gross emissions applying 25–75th percentile of global measurements (t CO_2eq/year):		6,000–46,000
If hydropower	Power density below 100 W/m^2?	Yes
	Global envelope for Power density (g CO_2/kWh):	1–40
Conclusion on screening:		Significant reservoir emissions cannot be dismissed
Comment:		Although it is clear this project is a mitigation project by replacing fossil fuel power generation, the reservoir emissions could be significant in absolute terms
Estimation of reservoir emission (leave empty if initial screening concluded negligible emissions)		
Catchment area (km^2):		14,660
Description of land cover in CA:		53% shrubland, 40% forest, 7% cropland
Reservoir volume (million m^3):		349

table continues next page

Average depth (m):		27	
Description of land cover in reservoir area:		91% shrubland, 5% forest, 4% cropland	
Type of soil and soil carbon content:		Mineral soil, 3.4 kg C/m^2	
Solar Radiation (kWh/m^2/day):		3.8	
Average temperature (^oC):		23	
Method used for estimation:		*G-res* (UNESCO/IHA 2017)	
Net reservoir emissions (t CO_2eq/year):			4,563
GHG from unrelated anthropogenic sources (t CO_2-eq/year)			177
Other comparative methods:		World Bank (2013): 15,300 t CO_2eq/year	
Confidence in results	Reliable	Yes	
	Explanation	The *G-res* shows specific emissions per m^2 (56th percentile) in the normal range where the tool is most reliable. The *G-res* and World Bank (2013) results indicate 5-15 g CO^2/kWh, which are both in the same order of magnitude (<3%) compared to the counterfactual.	
Further measures to be taken			
Further detailed measurements and/or modeling required:		No	
GHG management measures to consider:		Although not a major issue, the ESMP should consider reducing inflow of anthropogenic organic material and nutrients, which will improve water quality and reduce GHG as a result of UAS	

Sources: Project information from Supplementary Environmental and Social Impact Assessment 2009. Carbon content from FAO Harmonized Soil Database, Solar Radiation from NASA - SSE 2008, Land cover from ESA-CCI, Temperature from Global Climate Database (2005).

Glossary

Aerobic	Describes conditions or processes in water or sediments in which oxygen is present.
Anaerobic	Describes conditions or processes in water and sediments in which oxygen is absent.
Anoxic	Synonymous with anaerobic: describes conditions in water and sediments in which oxygen is absent.
Anthropogenic	Resulting from or produced by human beings.
Biomass	The total mass of living organisms in a given area, volume, or ecosystem at a given time; recently dead plant material is included in dead biomass. The quantity of biomass can be expressed as a dry weight or as the energy or carbon content.
Bubbling	See *ebullition*.
Carbon cycle	The process of carbon flow through the atmosphere, ocean, terrestrial biosphere (including freshwater systems), and sediments, as well as its transformation processes (chemical alteration, photosynthesis, respiration, decomposition, air-sea exchange, etc.).
Carbon dioxide (CO_2)	A naturally occurring GHG fixed by photosynthesis into organic matter and released during respiration. It is a by-product of fossil fuel combustion, biomass burning, land use changes, and other industrial processes.
CO_2 equivalent ($CO_2e(q)$)	The amount of CO_2 emission that would have the same GWP, over a given time horizon, as an emitted amount of a GHG or a mixture of GHGs. The CO_2equivalent emission is obtained by multiplying the emissions of a GHG by its GWP for the given time horizon. For a mix of GHGs it is obtained by adding up the CO_2equivalent emissions of each gas.
Carbon footprint	A form of carbon calculation that considers the net emissions of GHG throughout the life cycle of a project or investment.
Carbon mass flow	Carbon in a water body can be in particulate or dissolved form and can be organic or inorganic. The forms to be measured are: Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Dissolved Inorganic Carbon (DIC), and Particulate Organic Carbon (POC). Carbon inputs and outputs to be considered are: carbon brought in by macrophytes*, carbon exchanges with groundwater, carbon lost permanently to sediment, carbon exchanged with atmosphere in form of CO_2 and CH_4, and humic substance income and output.
Carbon sequestration	Buildup of GHG concentration in vegetation, water or sediments.
Carbon sink	See *sink*.

Carbon stock	In the context of this note, the quantity of carbon in a water body and its sediments. [In the context of forests, it refers to the amount of carbon stored in the world's forest ecosystem, mainly in living biomass and soil, but to a lesser extent also in dead wood and litter.]
Decomposition	Chemical processes by which organic matter in a water body is transformed into gaseous end products. Major processes are oxidative decomposition, methanogenesis, and denitrification and their end products: CO_2, CH_4, and N_2O.
Degassing	GHG flux induced by dramatic pressure change immediately after water discharge from reservoir outlets.
Denitrification	Denitrification describes the conversion of nitrate into nitrite, then to N_2O, and finally to nitrogen gas. This process happens in the slightly anoxic upper layer of sediment.
Diffusive flux	Discharge of GHG from the air-water interface of a water body.
Dissolved Oxygen (DO)	The oxygen in a water body in its dissolved form. Dissolved oxygen influences organic matter decomposition processes and serves fish and other aquatic organisms for respiration.
Ebullition (bubbling)	Discharge in form of bubbles of gaseous substances from a water body, which results from carbonation, evaporation, or fermentation.
Ecosystem	The interactive system formed from all living organisms and their abiotic (physical and chemical) environment within a given area. In the context of this note, a difference is made between aquatic and terrestrial ecosystems.
Epilimnion	The dense top-most layer of water in a thermally stratified water body.
Global Warming Potential (GWP)	An index, based on the radiative properties of GHGs, measuring the radiativeforcing of a unit mass of a given GHG in today's atmosphere integrated over a chosen time horizon, relative to that of CO_2. The GWP represents the combined effect of the differing lengths of time that these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The IPCC considers the GWP of GHG within a 100-year time frame.
Greenhouse gas (GHG)	GHGs are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. In the context of this note, the evaluation of net emissions from water bodies includes the three GHG species CO_2, CH_4, and N_2O.
Hypolimnion	The dense bottom layer of water in a thermally stratified water body.
Macrophyte	Rooted plant that grows in or near water.
Methane (CH_4)	A naturally occurring GHG, a main component of natural gas, and an end product of animal husbandry and agriculture.

Methane oxidation	Process by which CH_4 is oxidized to CO_2 and that occurs in aerobic conditions.
Methanogenesis	Production of CH_4 by anaerobic bacteria and microbes present in the anoxic layers of a water body, which feed on the detritus of organic matter and respire CH_4.
Nitrification	An aerobic process in which bacteria change the ammonia and organic nitrogen in water and decomposed matter into oxidized nitrogen (nitrate).
Nitrous oxide (N_2O)	A naturally occurring GHG which is produced through bacterial nitrification and denitrification processes.
Oxic	Synonymous with aerobic: describes conditions in water and its sediments in which oxygen is present.
Photosynthesis	Process driven by solar energy by which atmospheric CO_2 is fixed by plants and algae for the primary production of organic matter and oxygen as a by-product.
Residence time	Average time a water molecule spends in a reservoir; used to describe the flow rate of the water through the reservoir. Its value can vary inside one reservoir.
Respiration	*Heterotrophic* respiration is the process whereby micro-organisms grow by converting organic matter to sugars; *autotrophic* (or maintenance) respiration is the process through which plants and animals burn sugars to give energy. Both reactions produce CO_2.
Sink	A natural or artificial reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period.
Stratification	A water body can be stratified in layers of temperature, salinity, or chemical compositions, which can act as barriers to water mixing.
Water retention time	A calculated quantity expressing the mean time that water spends in a particular water body.

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