Greenhouse Gases from Reservoirs Caused by Biogeochemical Processes

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World Bank Group
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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 (CO₂), methane (CH₄), and nitrous oxide (N₂O) 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 CO₂ 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 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 km³ and was corrected to exclude regulated natural lakes. The global estimate of GHG emissions was also corrected to include emissions from small impoundments.

Reference

Abbreviations

CH$_4$ methane
CO$_2$ carbon dioxide
CO$_2$(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$_2$O 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), “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.\textsuperscript{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


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.
Reduction of greenhouse gas (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. 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, 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.


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 CO₂ 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 (CO₂), methane (CH₄), and nitrous oxide (N₂O). CH₄ and N₂O have stronger warming effects than CO₂ 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 CO₂, CH₄, and N₂O are expressed as CO₂ equivalents (CO₂eq). 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 CO₂eq emissions for a 100-year period, the quantities of CH₄ produced should be multiplied by 34 and those of N₂O by 298.

To understand the impact of reservoirs on GHG emissions, it is essential to understand the main processes in the cycle of CO₂ and other GHGs in a river basin (figure 2.1).

- Atmospheric CO₂ 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 CO₂ 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 CO₂.

- 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 CO₂ can be lost to the atmosphere at the surface. As part of the aquatic ecosystem, CO₂ 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.

- CH₄ 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
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$_2$O 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$_2$O 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.
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 CO₂ - 198 reservoirs; diffusive CH₄ - 137 reservoirs; bubbling CH₄ - 39 reservoirs; and degassing CH₄ - 35 reservoirs. Deemer et al. (2016) used GHG emission data from a total of 267 reservoirs, of which 229 yielded data on CO₂, 142 on diffusive CH₄, 50 on bubbling CH₄, and 58 on N₂O (maps 2.2-2.4) (figure 2.4). This shows that data on N₂O and on CH₄ bubbling and degassing are still relatively rare.
**FIGURE 2.3.** Analysis of Scientific Papers Published Related to Measured GHG Data from Reservoirs

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**MAP 2.1.** Location of Reservoirs with Measured Diffusive Flux of CO₂
MAP 2.2. Location of Reservoirs with Measured Diffusive Flux of CH₄

Source: Based on data from UNESCO/IHA.

MAP 2.3. Location of Reservoirs with Measured Ebullition (Bubbling) Flux of CH₄

Legend
• CH₄ Diffusive emissions
• CH₄ Bubbling emissions
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 Tucurui 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 CO₂ 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 CH₄ is produced in anoxic conditions and can be oxidized to CO₂ in aerobic conditions. If anoxic conditions exist in most of the water column, it allows fluxes of CH₄ to the atmosphere. The greater the thickness of the overlying epilimnion layer in the water column, the less likely it is that diffuse CH₄ emissions will be produced. This is because the production area and volume become smaller while the oxidizing area and volume (where CH₄ can transform to CO₂) 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 CO₂ and CH₄ 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 CH₄ 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 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.

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 material 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

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* Methanogenesis is the process by which methane is produced.
being registered in the first 5–15 years after inundation (figure 2.6).

$\text{N}_2\text{O}$ emissions have been studied in a limited number of reservoirs so far. The results indicate that, similar to methane, $\text{N}_2\text{O}$ creation and emission vary greatly (table 2.1). In general, $\text{N}_2\text{O}$ contributes less to GHG emissions from reservoirs than $\text{CO}_2$ and $\text{CH}_4$, even when expressed in $\text{CO}_2\text{eq}$ 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 $\text{CO}_2\text{eq}$ 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).
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 CO₂ 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 CO₂ 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).
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 CO₂ flux, diffusive CH₄ flux, bubbling of CH₄, and degassing of CH₄. 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 CH₄ emissions are attributed to the new reservoir, while attributable CO₂ 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 CO₂ emissions.

The annual net emissions of both CO₂ and CH₄ 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. 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 CO₂ when a Dam is Constructed in a River

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 Agreements 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 CO₂ and CH₄ 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 CO₂ emissions (Kim et al. 2016), and modeling is ongoing in Petit Saut, in French Guiana.

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). 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 m² 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
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 km² (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 km³ 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 km², or 36 percent of the total area of 452,000 km² 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 km³ storage capacity). By statistically extrapolating the distribution of dams, Lehner et al. (2011) estimated the missing net additional water surface created by these dams to be 306,723 km².

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, 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 are not included. This resulted in a lower net carbon dioxide emissions from

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

<table>
<thead>
<tr>
<th>Importance</th>
<th>Explicit prioritization</th>
<th>Operating rule curve</th>
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<tr>
<td>Primary</td>
<td>Ranked 1 to 3 in operational hierarchy.</td>
<td>Operating rules are designed to maximize these service benefits for part or all of the year.</td>
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<tr>
<td>Secondary</td>
<td>Ranked lower than 3 in operational hierarchy, or places constraints on operation.</td>
<td>The service places operational constraints on the operating level of the reservoir for part or all of the year.</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Provides benefits, but does not alter the operation of the reservoir.</td>
<td>The service provides benefits but has little impact on the operation of the reservoir.</td>
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<table>
<thead>
<tr>
<th>Importance</th>
<th>Apportionment (%)</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Primary</td>
<td>80</td>
<td>If there is more than one service in the level, split equally.</td>
</tr>
<tr>
<td>Secondary</td>
<td>15</td>
<td>Where there are no secondary services, the apportionment (15%) is split between the primary services.</td>
</tr>
<tr>
<td>Tertiary</td>
<td>5</td>
<td>Where there are no tertiary services, the apportionment (5%) is split between the secondary services.</td>
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Note: G-res = GHG Reservoir.
reservoirs than previously estimated (figure 3.3). Secondly, using site-specific factors to govern CH₄ 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 CH₄ emissions is highly skewed,
FIGURE 3.3. Illustration of Changing Distribution of $\text{CO}_2$ Emissions for All Reservoirs over the World When Considering Net Rather than Gross Values

Source: IHA/UNESCO.

Note: $\text{CO}_2$ = carbon dioxide. Previous global estimates $\text{CO}_2$ 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 $\text{CO}_2$ and $\text{CH}_4$, but ignores $\text{N}_2\text{O}$, for which data are still scarce. The limited research on $\text{N}_2\text{O}$ has, however, indicated that nitrous oxide emissions are generally small compared to the emissions of $\text{CO}_2$ and $\text{CH}_4$. Deemer et al. (2016) estimated that $\text{N}_2\text{O}$ 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 $\text{CH}_4$ 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 km². The resulting GHG emissions from the G-res tool are plotted against the power density (W/m²) in figure 3.4.

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

![Map 3.2](image-url)
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; gCO₂/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/m² still have emission profiles below 100 g CO₂eq/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.


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

<table>
<thead>
<tr>
<th>Factor to retrieve</th>
<th>Proposed methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size and shape of inundated area and volume of reservoir</td>
<td>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 (<a href="https://www2.jpl.nasa.gov/srtm/">https://www2.jpl.nasa.gov/srtm/</a>), to delineate inundated area up to planned full supply level. 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.</td>
</tr>
<tr>
<td>Climate, temperature, and rainfall in reservoir area</td>
<td>These data are normally available from the first phases of the ESIA. If not available, use global databases such as the WorldClim (<a href="http://www.worldclim.org">www.worldclim.org</a>).</td>
</tr>
<tr>
<td>River inflow to the reservoir and water retention time</td>
<td>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., <a href="http://www.bafg.de/GRDC/EN/01_GRDC/grdc_node.html">www.bafg.de/GRDC/EN/01_GRDC/grdc_node.html</a>). Divide average annual inflows by the reservoir volume to get the average retention time.</td>
</tr>
<tr>
<td>Type and extent of flooded vegetation</td>
<td>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 <a href="http://www.esa-landcover-cci.org">www.esa-landcover-cci.org</a>).</td>
</tr>
<tr>
<td>Type of flooded soil and extent of soil carbon</td>
<td>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, IIAAS, ISRIC, ISSCAS, and JRC (<a href="http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML">http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML</a>).</td>
</tr>
</tbody>
</table>
### TABLE 4.1. Basic Information to Assess Future Potential GHG from a Reservoir (continued)

<table>
<thead>
<tr>
<th>Factor to retrieve</th>
<th>Proposed methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land cover and use in catchment area and water quality of inflowing rivers</td>
<td>This information is normally available from the first phases of the ESIA. If not available, use population density (<a href="http://sedac.ciesin.columbia.edu/data/collection/gpw-v4">http://sedac.ciesin.columbia.edu/data/collection/gpw-v4</a>) together with global land cover maps (see above) to conduct an overall assessment of land use and potential sources of organic matter and nutrients.</td>
</tr>
<tr>
<td>Characteristics of dam and construction methods</td>
<td>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/m²). 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.</td>
</tr>
</tbody>
</table>

**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

**Ability to supply carbon stock**
- Yes

**Ability to create GHG**
- Yes
  - E.g.
    - Large reservoir area
    - High percentage of forests
    - High density of vegetation
    - High carbon content in soil

**Ability to release GHG**
- Yes
  - E.g.
    - High temperature
    - Long retention time
    - Stratification of reservoir
    - Large inflow of nutrients from upstream areas

**Potentially significant GHG emissions**
- E.g.
  - Shallow reservoir
  - Anoxic conditions in most of the water column
  - Intake for downstream releases in anoxic zone
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/m², which would be the case in most run-of-river projects, the global data indicate that reservoir emissions are normally below 1 g CO₂/kWh, and even in extreme cases below 10 g CO₂/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 CO₂/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/m² indicates a median reservoir emission of about 5 g CO₂/kWh.

- Should the counterfactual have negligible emissions and the power density lie below 100 W/m², it is suggested that the threshold be set by the size of the reservoir. Using a threshold of 100,000 tons CO₂eq (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 km² during median conditions, and from 0.5-0.7 km² 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 CO₂eq. It is thus suggested that 100,000 tons CO₂eq be used as the threshold when reservoir emissions may be negligible. This threshold corresponds to 1,000 tons CO₂eq 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 CO₂ and CH₄ emissions (~3,500 tons/km² and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 0.3 km².

- If factors seem to favor low specific emissions, use the 25th percentile for total CO₂ and CH₄ emissions (~500 tons/km² and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 2 km².

- If factors affecting specific emissions are mixed, use the median for total CO₂ and CH₄ emissions (~1,000 tons/km² and year). A threshold of 100,000 tons for the lifetime emissions would correspond to a surface area of 1 km².

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). 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 CH₄ 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. 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 CO₂ and CH₄ 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.

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 CH₄ 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 CH₄ 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 CH₄ 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 CO₂ and CH₄ as measured by surface floating chambers;
- Covers the reservoir along its longitudinal axis as well as the immediate river stretch downstream of the reservoir;
- Includes sampling of CH₄ 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 m²) 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).


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. 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
Appendix A
Conversion of GHG Units and CO₂ Equivalents

Conversion from Moles to G

In chemistry, a mole is considered Avogadro’s number \((6.02 \times 10^{23})\) 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.

\[
\text{Number of moles} = \frac{\text{(# of grams)}}{\text{(molar mass)}}
\]

\[
\text{Number of grams} = \text{(# of moles)} \times \text{(molar mass)}
\]

Conversion table for the most common GHGs in reservoirs:

<table>
<thead>
<tr>
<th>GHG</th>
<th>Molar mass (g/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>44.0095</td>
</tr>
<tr>
<td>CH₄</td>
<td>16.0107</td>
</tr>
<tr>
<td>N₂O</td>
<td>44.0128</td>
</tr>
</tbody>
</table>

CO₂ Equivalents

The international practice is to express GHG emissions in CO₂ equivalents (CO₂eq or CO₂e). Emissions of gases other than CO₂ are converted into CO₂eq by multiplying their respective volumes by their respective Global Warming Potentials (GWPs). From the 2013 IPCC Report:

GWP relative to CO₂ at different time horizons for the most common GHGs in reservoirs:

<table>
<thead>
<tr>
<th>Gas name</th>
<th>Chemical formula</th>
<th>GWP for given time horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20-yr</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>86</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O</td>
<td>268</td>
</tr>
</tbody>
</table>

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 CO₂ molecule to the atomic mass of a carbon atom is 44:12.

- To convert from “g of C” to “g of CO₂,” multiply by 44/12.
- To convert from “g of CO₂” to “g of C,” multiply by 12/44.
Sometimes you find this noted as gC-CO₂ or tC-CO₂ (to make clear that these “g of C” refer to carbon in a CO₂ molecule).

For **methane**, the ratio of the atomic mass of a CH₄ molecule to the atomic mass of a carbon atom is 16:12.

- To convert from “g of C” to “g of CH₄” multiply by 16/12.
- To convert from “g of CH₄” to “g of C” multiply by 12/16.
- It is important to make clear that these grams of C refer to carbon in a CH₄ molecule (i.e., NOT CO₂eq—in other words, not taking into account GWP). It is common to use gC-CH₄ or tC-CH₄.

### Carbon Dioxide Equivalents Vs. Carbon Equivalents

While the international standard is to express emissions in CO₂ equivalents (CO₂eq), 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 CO₂ equivalent (Tg CO₂eq). One teragram is equal to 10¹² grams, or 1 million tons.

- To convert from CE to CO₂eq, multiply by 44/12.
- To convert from CO₂eq to CE, multiply by 12/44.
### Appendix B

**Example of G-res Application**

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Trung Son</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Vietnam</td>
</tr>
<tr>
<td>Installed Capacity</td>
<td>260 MW</td>
</tr>
<tr>
<td>Yearly Generation</td>
<td>1,019 GWh/year</td>
</tr>
<tr>
<td>Climate</td>
<td>Tropical</td>
</tr>
<tr>
<td>Reservoir area</td>
<td>13.1 km²</td>
</tr>
</tbody>
</table>

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)
### Introduction

**Catchment Data**

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

<table>
<thead>
<tr>
<th>Land Cover Type</th>
<th>Pre-Impoundment</th>
<th>Post-Impoundment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Croplands</td>
<td>3.6 %</td>
<td>3.6 %</td>
</tr>
<tr>
<td>Bare Areas</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Wetlands</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Forest</td>
<td>53 %</td>
<td>91 %</td>
</tr>
<tr>
<td>Grassland/Shrubland</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Permanent Snow/Ice</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Settlements</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Water Bodies</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Drained Peatlands</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>No Data</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

**Current Totals**

- **Post-Impoundment**: 4643 tCO2e/yr
- **Pre-Impoundment**: -97 tCO2e/yr
- **UAS**: 177 tCO2e/yr

---

### 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.

### User Notices

**WARNING**—Please be sure to add 0% to all land cover with no value.
### Input Page 2/4—Reservoir Data

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

<table>
<thead>
<tr>
<th>Country</th>
<th>Vietnam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude of Dam (DD)</td>
<td>104.76</td>
</tr>
<tr>
<td>Latitude of Dam (DD)</td>
<td>20.59</td>
</tr>
<tr>
<td>Climate Zone (Reservoir Area)</td>
<td>Tropical</td>
</tr>
<tr>
<td>Impoundment Year</td>
<td>2016</td>
</tr>
<tr>
<td>Reservoir Area (km²)</td>
<td>13.1</td>
</tr>
<tr>
<td>Reservoir Volume (km³)</td>
<td>0.345</td>
</tr>
<tr>
<td>Mean/Normal Operating Level (m above sea level)</td>
<td>159</td>
</tr>
<tr>
<td>Maximum Depth (m)</td>
<td>50.0</td>
</tr>
<tr>
<td>Mean Depth (m)</td>
<td>28.336</td>
</tr>
<tr>
<td>Littoral Area (%)</td>
<td>5.408</td>
</tr>
<tr>
<td>Thermocline Depth (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Water Intake Depth (m)</td>
<td>14.0</td>
</tr>
<tr>
<td>Water Intake Elevation (m above sea level)</td>
<td>145</td>
</tr>
<tr>
<td>Soil Carbon Content Under Impounded Area (gC/m²)</td>
<td>3.4</td>
</tr>
<tr>
<td>Annual Wind Speed at 10 m (m/s)</td>
<td>1.7</td>
</tr>
<tr>
<td>Water Residence Time (WRT, yrs)</td>
<td>0.0427</td>
</tr>
<tr>
<td>Annual Discharge from the Reservoir (m³/s)</td>
<td>256.1</td>
</tr>
<tr>
<td>Phosphorus Concentration (µg/L)</td>
<td>26.4</td>
</tr>
<tr>
<td>Trophic Level</td>
<td>Mesotrophic</td>
</tr>
<tr>
<td>Reservoir Mean Global Horizontal Radiance (Wh/m²/d)</td>
<td>3.8</td>
</tr>
<tr>
<td>Mean Temperature per Month (°C)</td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>16.4</td>
</tr>
<tr>
<td>February</td>
<td>18.1</td>
</tr>
<tr>
<td>March</td>
<td>20.4</td>
</tr>
<tr>
<td>April</td>
<td>23.9</td>
</tr>
<tr>
<td>May</td>
<td>26.9</td>
</tr>
<tr>
<td>June</td>
<td>28.0</td>
</tr>
<tr>
<td>July</td>
<td>27.6</td>
</tr>
<tr>
<td>August</td>
<td>27.5</td>
</tr>
<tr>
<td>September</td>
<td>28.5</td>
</tr>
<tr>
<td>October</td>
<td>24.2</td>
</tr>
<tr>
<td>November</td>
<td>21.5</td>
</tr>
<tr>
<td>December</td>
<td>18.0</td>
</tr>
<tr>
<td>Mean Annual Air Temperature (°C)</td>
<td>23.3</td>
</tr>
</tbody>
</table>

**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.
### Allocation of Reservoir Purposes

<table>
<thead>
<tr>
<th>Purposes</th>
<th>Percentage Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Control</td>
<td>Tertiary 5%</td>
</tr>
<tr>
<td>Fisheries</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Navigation</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Environmental Flow</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Recreation</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Water Supply</td>
<td>Tertiary 0%</td>
</tr>
<tr>
<td>Hydroelectricity</td>
<td>Primary 95%</td>
</tr>
</tbody>
</table>

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.

#### Importance

<table>
<thead>
<tr>
<th>Importance</th>
<th>Explicit Prioritisation</th>
<th>Operating Rule Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Ranked 1 to 3 in operational hierarchy.</td>
<td>Operating rules are designed to maximize the benefits of this service for part or all of the year.</td>
</tr>
<tr>
<td>Secondary</td>
<td>Ranked lower than 3 in operational hierarchy, or places constraints on operation.</td>
<td>The service places operational constraints on the operating level of the reservoir for part or the whole of the year.</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Does not alter the operation of the reservoir.</td>
<td>The service has little impact on the operation of the reservoir.</td>
</tr>
</tbody>
</table>
### Input Page 4/4—Construction Data

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.

#### 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.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Description</th>
<th>Quantity</th>
<th>ﺕonne (km distance)</th>
<th>Emission (kgCO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth and Rockfill</td>
<td>Material excavated and/or used for construction</td>
<td>470000 m³ 2 km moved</td>
<td>1068967</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>All concrete brought to site for the dam, tunnels, foundations</td>
<td>960000 m³ 50 km delivery distance</td>
<td>35770440</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>All steel brought to site for reinforcement, pipelines, mechanical and electrical equipments</td>
<td>11100 tonne 80 km delivery distance</td>
<td>2993622</td>
<td></td>
</tr>
</tbody>
</table>

#### 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.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Description</th>
<th>Quantity</th>
<th>𝑚 (km delivery)</th>
<th>Emission (kgCO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthworks</td>
<td>Soft Excavation</td>
<td>m³</td>
<td>km moved</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rock Excavation</td>
<td>m³</td>
<td>km moved</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Clearance and Removals</td>
<td>ha</td>
<td>km moved</td>
<td>0</td>
</tr>
<tr>
<td>Fill</td>
<td>Granular Fill</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rock Armour</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Zoned Rockfill</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rock bolts</td>
<td>number</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td>Concrete Works</td>
<td>Formwork</td>
<td>m²</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Facing Concrete</td>
<td>m²</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Mass Concrete</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Reinforced Concrete</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Shotcrete</td>
<td>m³</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Reinforcement</td>
<td>tonne</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td>Steelworks</td>
<td>Steel Penstocks</td>
<td>tonne</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Steel Liner</td>
<td>tonne</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous Steelwork</td>
<td>tonne</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td>Roads and Bridges</td>
<td>New Roads</td>
<td>km</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Refurbishment of Existing Roads</td>
<td>km</td>
<td>km delivery</td>
<td>0</td>
</tr>
<tr>
<td>Equipment</td>
<td>Power Generation</td>
<td>MW</td>
<td>km length</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Power Connection</td>
<td>kV</td>
<td>km length</td>
<td>0</td>
</tr>
</tbody>
</table>

Please record any assumptions, limitations and data sources here:

---

**Reservoir Name**: Trung Son

---

**Introduction**

- Catchment
- Reservoir
- Reservoir services
- Construction
- GHG
- UAS
- Reservoir GHG
- Total GHG footprint
- Emission Factors
- Earth Engine

---

**Online Technical Document for Construction**

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

---

**Technical Support**

- Export to .txt file
- Restart Analysis with a New Reservoir
- Printable Reports
### UNICEF/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.

<table>
<thead>
<tr>
<th>Reservoir Name</th>
<th>Trung Son</th>
</tr>
</thead>
</table>

**Introduction**

- Catchment
- Reservoir
- Reservoir services
- Construction
- GHG
- UAS
- Reservoir GHG
- Total GHG footprint
- Emission Factors
- Earth Engine

#### Calculations of Phosphorus Loads

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total P in the reservoir</td>
<td>26.4</td>
</tr>
<tr>
<td>Reference Level of P</td>
<td>25.7</td>
</tr>
<tr>
<td>P from industrial sewage</td>
<td>0.0</td>
</tr>
<tr>
<td>P from human sewage</td>
<td>0.0</td>
</tr>
<tr>
<td>P from human land use</td>
<td>1.5</td>
</tr>
<tr>
<td>P over Reference Land</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Share of UAS of the P in reservoir, evaluated as P (µg/L)**

- **1.5**

#### Estimated Contribution of UAS to the GHG Emissions from the Reservoir

- **Calculated CH₄ emissions from the reservoir (gCO₂e/m³/yr)**: 108.5
- **Amount of CH₄ of total estimates due to UAS (%)**: 6%
- **Estimated CH₄ release due to UAS (gCO₂e/m³/yr)**: 13.5

#### Weighted sum model risk

- **66**

**User Notices**

- **Trophic state:**
- If the reservoir is oligotrophic, no UAS contribution is identified

**Comment on Risk Factor for the GHG Emissions:**

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

**Share of Anthropogenic Impact**

- **% of total UAS emissions**
- **100%**

<table>
<thead>
<tr>
<th>Source</th>
<th>Emissions (gCO₂e/m³/yr)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAS emissions from Land Use</td>
<td>13.5</td>
<td>100%</td>
</tr>
<tr>
<td>UAS Emissions from Sewage</td>
<td>0.0</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Cropland:** Low to Moderate Risk

**Forestry:** Low to Moderate Risk

**Grasslands/Pasture:** Low to Moderate Risk

**Settlements:** Low to Moderate Risk

**Community sewage:** Low to Moderate Risk

**Industrial sewage:** Low to Moderate Risk
### Predicted Emissions

#### Net Predicted Annual CO$_2$e Emission

<table>
<thead>
<tr>
<th>Source</th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropogenic Sources</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>4 643</td>
<td>-97</td>
<td>177</td>
<td>4 563</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>3 106</td>
<td>0</td>
<td>177</td>
<td>2 929</td>
</tr>
</tbody>
</table>

**Emission Rate (gCO$_2$e/yr)**

- Post-Impoundment: 354
- Pre-Impoundment: -7
- Unrelated Anthropogenic Sources: 14
- Net GHG Footprint: 348

<table>
<thead>
<tr>
<th>Source</th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropogenic Sources</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>117</td>
<td>-7</td>
<td>n/a</td>
<td>125</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>237</td>
<td>0</td>
<td>14</td>
<td>224</td>
</tr>
</tbody>
</table>

**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%
- Fraction of Bubbling of CH$_4$ from Total Reservoir CH$_4$ Emission (%): 7%

**User Notice**


**Percentile of Net GHG emissions within the database**

- 56% 0 25 50 75 100
- 0 25 50 75 100

**Unrelated Anthropogenic Sources**

- Potential amount of UAS as % of post-impoundment emissions: 6%
- Weighted sum total model risk result: 66
UNESCO/IHA GHG RESEARCH PROJECT

G-res Tool

Warning: Please never refresh the page with the Reload Page button of the browser. This webpage 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.

Reservoir Name

<table>
<thead>
<tr>
<th>Reservoir Name</th>
<th>Reservoir services</th>
<th>Construction GHG</th>
<th>Total GHG footprint</th>
<th>Emission Factors</th>
<th>Earth Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trung Son</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Predicted Emissions

Net Predicted Annual CO₂ Emission

<table>
<thead>
<tr>
<th></th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropic Sources</th>
<th>Construction (Reservoir)</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal Emission</td>
<td>354</td>
<td>-7</td>
<td>14</td>
<td>n/a</td>
<td>348</td>
</tr>
<tr>
<td>Reservoir Wide Emissions (tCO₂/yr)</td>
<td>4,643</td>
<td>-97</td>
<td>177</td>
<td>3,983</td>
<td>8,546</td>
</tr>
<tr>
<td>Total Lifetime Emission (tCO₂)</td>
<td>464,339</td>
<td>-9,683</td>
<td>17,706</td>
<td>398,332</td>
<td>854,648</td>
</tr>
</tbody>
</table>

Net GHG Emissions Contribution for Each Reservoir Services

<table>
<thead>
<tr>
<th>Reservoir Service</th>
<th>GHG Emissions from Reservoir (tCO₂/yr)</th>
<th>GHG Emissions from Construction (tCO₂/yr)</th>
<th>GHG Footprint (tCO₂/yr)</th>
<th>Percentage Allocation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Control</td>
<td>2,280</td>
<td>427</td>
<td>8119</td>
<td>95</td>
</tr>
<tr>
<td>Fisheries</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Navigation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Environmental Flow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recreation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Water Supply</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hydropower</td>
<td>4,335</td>
<td>3,784</td>
<td>8119</td>
<td>95</td>
</tr>
</tbody>
</table>

Allocation Method Used:

Operating Rule Curve

Emission Factor Used:

Default Emission Factors Used

Construction Comments:
**Reservoir GHG Information**

Net Predicted Annual CO₂e Emission

<table>
<thead>
<tr>
<th></th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropogenic Sources</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Rate (tCO₂e/yr)</td>
<td>4 643</td>
<td>-97</td>
<td>177</td>
<td>4 563</td>
</tr>
<tr>
<td>of which CO₂</td>
<td>1 537</td>
<td>-97</td>
<td>n/a</td>
<td>1 634</td>
</tr>
<tr>
<td>of which CH₄</td>
<td>3 106</td>
<td>0</td>
<td>177</td>
<td>2 929</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropogenic Sources</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Rate (gCO₂e/m²/yr)</td>
<td>354</td>
<td>-7</td>
<td>14</td>
<td>348</td>
</tr>
<tr>
<td>of which CO₂</td>
<td>117</td>
<td>-7</td>
<td>n/a</td>
<td>125</td>
</tr>
<tr>
<td>of which CH₄</td>
<td>237</td>
<td>0</td>
<td>14</td>
<td>224</td>
</tr>
</tbody>
</table>

Percentile of Net GHG emissions within the database 56%

Relative contribution to CH₄ Post-Impoundment Emissions

- Fraction of CH₄ diffusive flux from Total Reservoir CH₄ Emission (%) 46%
- Fraction of Degassing of CH₄ from Total Reservoir CH₄ Emission (%) 48%
  
  *Note: WARNING Deep Water Intake. Likely Important Contribution of Degassing.*
- Fraction of Bubbling of CH₄ from Total Reservoir CH₄ 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**

<table>
<thead>
<tr>
<th></th>
<th>Post-Impoundment</th>
<th>Pre-Impoundment</th>
<th>Unrelated Anthropogenic Sources</th>
<th>Construction (Reservoir)</th>
<th>Net GHG Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal Emissions (gCO₂e/m²/yr)</td>
<td>354</td>
<td>-7</td>
<td>14</td>
<td>n/a</td>
<td>348</td>
</tr>
</tbody>
</table>

Reservoir Wide Emissions (tCO₂e/yr) = 4 643 – 97 = 177 + 3 983 = 8 546

Total Lifetime Emission (tCO₂e) = 464 339 – 9 683 = 17 706 + 398 332 = 854 648
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

<table>
<thead>
<tr>
<th>Project name:</th>
<th>Trung Son, Vietnam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose:</td>
<td>Main purpose: Hydropower. Project also has flood control benefits.</td>
</tr>
<tr>
<td>Reservoir Area (km²):</td>
<td>13.1</td>
</tr>
<tr>
<td>Climate:</td>
<td>Tropical</td>
</tr>
<tr>
<td>Vegetation:</td>
<td>Mixed forest and shrubland</td>
</tr>
<tr>
<td>If hydropower</td>
<td>Installed capacity (MW) 260</td>
</tr>
<tr>
<td></td>
<td>Annual energy (GWh) 1019</td>
</tr>
<tr>
<td></td>
<td>Power Density (W/m²) 19.8</td>
</tr>
</tbody>
</table>

### 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 CO₂/kWh.

| Gross emissions applying 25−75th percentile of global measurements (t CO₂eq/year): | 6,000−46,000 |
| If hydropower Power density below 100 W/m²? | Yes |
| Global envelope for Power density (g CO₂/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 (km²): | 14,660 |
| Description of land cover in CA: | 53% shrubland, 40% forest, 7% cropland |
| Reservoir volume (million m³): | 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/m²

### Solar Radiation (kWh/m²/day):
3.8

### Average temperature (°C):
23

### Method used for estimation:
G-res (UNESCO/IHA 2017)

### Net reservoir emissions (t CO₂eq/year):
4,563

### GHG from unrelated anthropogenic sources (t CO₂eq/year)
177

### Other comparative methods:
World Bank (2013): 15,300 t CO₂eq/year

<table>
<thead>
<tr>
<th>Confidence in results</th>
<th>Reliable</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explanation</td>
<td>The G-res shows specific emissions per m² (56th percentile) in the normal range where the tool is most reliable. The G-res and World Bank (2013) results indicate 5-15 g CO₂/kWh, which are both in the same order of magnitude (&lt;3%) compared to the counterfactual.</td>
<td></td>
</tr>
</tbody>
</table>

### 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:
<table>
<thead>
<tr>
<th><strong>Glossary</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerobic</strong></td>
</tr>
<tr>
<td><strong>Anaerobic</strong></td>
</tr>
<tr>
<td><strong>Anoxic</strong></td>
</tr>
<tr>
<td><strong>Anthropogenic</strong></td>
</tr>
<tr>
<td><strong>Biomass</strong></td>
</tr>
<tr>
<td><strong>Bubbling</strong></td>
</tr>
<tr>
<td><strong>Carbon cycle</strong></td>
</tr>
<tr>
<td><strong>Carbon dioxide (CO₂)</strong></td>
</tr>
<tr>
<td><strong>CO₂ equivalent (CO₂e(q))</strong></td>
</tr>
<tr>
<td><strong>Carbon footprint</strong></td>
</tr>
<tr>
<td><strong>Carbon mass flow</strong></td>
</tr>
<tr>
<td><strong>Carbon sequestration</strong></td>
</tr>
<tr>
<td><strong>Carbon sink</strong></td>
</tr>
<tr>
<td><strong>Carbon stock</strong></td>
</tr>
<tr>
<td><strong>Decomposition</strong></td>
</tr>
<tr>
<td><strong>Degassing</strong></td>
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<tr>
<td><strong>Denitrification</strong></td>
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<tr>
<td><strong>Diffusive flux</strong></td>
</tr>
<tr>
<td><strong>Dissolved Oxygen (DO)</strong></td>
</tr>
<tr>
<td><strong>Ebullition (bubbling)</strong></td>
</tr>
<tr>
<td><strong>Ecosystem</strong></td>
</tr>
<tr>
<td><strong>Epilimnion</strong></td>
</tr>
<tr>
<td><strong>Global Warming Potential (GWP)</strong></td>
</tr>
<tr>
<td><strong>Greenhouse gas (GHG)</strong></td>
</tr>
<tr>
<td><strong>Hypolimnion</strong></td>
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<tr>
<td><strong>Macrophyte</strong></td>
</tr>
<tr>
<td><strong>Methane (CH₄)</strong></td>
</tr>
<tr>
<td>Term</td>
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<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Methane oxidation</td>
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<tr>
<td>Methanogenesis</td>
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<tr>
<td>Nitrification</td>
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<tr>
<td>Nitrous oxide (N₂O)</td>
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<td>Oxic</td>
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<tr>
<td>Photosynthesis</td>
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<tr>
<td>Residence time</td>
</tr>
<tr>
<td>Respiration</td>
</tr>
<tr>
<td>Sink</td>
</tr>
<tr>
<td>Stratification</td>
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<tr>
<td>Water retention time</td>
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</tbody>
</table>
References


