GHG Reservoir Tool (G-res Tool)

Assessment of the net GHG footprint for the Cahora Bassa reservoir (Mozambique) using the G-res Tool methodology

Reservoir G-res # 2.102045
G-res Tool v2.1

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Table of contents

1. Summary

Compared to worldwide reservoirs, Cahora Bassa is a high emitting reservoir (847, CI :754-953 gCO2e/m2/yr), but remains in the same range as most tropical reservoirs. Half of the total predicted emissions is emitted through methane bubbling emissions. The reservoir has very little methane degassing emissions (i.e. emissions associated to the water transported through a dam into the downstream river) because mostly well oxygenated surface water is circulated through the turbines. The only methane degassing emissions is caused by the water flowing through the spillways. The interannual variation in water level (from 312 to 328, average 322 m) has no influence on the final emissions rate, though higher water levels lead to an increase in the emissions intensity. After allocation (i.e. attributing emissions to the different purposes of the reservoir), the emissions intensity is 105.9 gCO_2e/kWh (CI: 94-119), falling right above the recommended threshold (100 gCO_2e/kWh, IHA 2018).

2. Introduction

Greenhouse gas (GHG) emissions from natural inland waters (i.e. streams, rivers, and lakes) are important sources of atmospheric carbon, on the same order of magnitude as carbon uptake by land and sea, and thus play a significant role in the global carbon budget (Cole et al. 2007; Tranvik et al. 2009; Raymond et al. 2013; Borges et al. 2014). Research over the last few decades has shown that freshwater reservoirs can also emit substantial amounts of GHG. Estimates of GHG emissions are highly variable from one reservoir to another. The same is true for hydropower reservoirs for which, depending on their electricity generating potential, their GHG footprint can be as low as wind or solar power to as high as a coal-fired power plants. Such statements logically challenge the 'green' energy aspect of hydroelectric power. However, considering that natural water bodies also emit carbon (such as the rivers dammed to create reservoirs), it is important not only to measure the emissions, but also to understand the pathways and factors controlling them.

The carbon GHG, carbon dioxide (CO_2) and methane (CH_4), are produced from the decomposition of organic matter by bacteria in the sediments and water column of a water body. The organic matter is sourced both from internal primary production and input from the terrestrial zone in natural and man-made water bodies. An extra source in reservoirs is the organic matter of surrounding flooded

areas following reservoir construction. The resulting GHG evade to the atmosphere through various pathways (Figure 1).
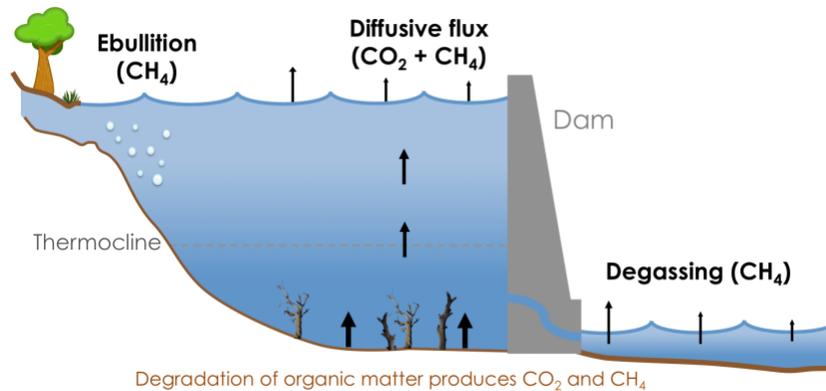

Figure 1: Schematic of the four pathways of GHG emissions in the G-res; CO_2 diffusive emissions, CH_4 diffusive, CH_4 bubbling and CH_4 degassing emissions

Firstly, in all water bodies, CO_2 and CH_4 will diffuse slowly from the sediment, up through the water column, and eventually be emitted to the atmosphere. Secondly, because of it lower solubility, CH_4 can also be liberated periodically as bubbles when CH_4 production rates in sediments are high enough, a feature commonly found in dammed river systems and reservoirs. A third emission pathway, unique to hydropower reservoirs, is the degassing of waters following transport through a dam into the downstream river. Many reservoirs exhibit a thermal stratification where warmer surface water and colder deep water create a strong physical barrier, called the thermocline, which substantially slows the diffusion of gases from the deeper part of the reservoir to the surface. GHG thus accumulate in reservoir bottom waters up to quite high concentrations and if the dam water intake for the turbines is situated within this layer, then a significant amount of GHG can be emitted at the exit of the outlet and further downstream.

Evidence suggests that the factors driving emissions vary between pathways, but fall into a four major categories: climatic, geographic, edaphic (i.e. soil properties), and hydrologic. For example, it has been shown that diffusive emissions decrease with increasing reservoir age as the newly flooded soil and vegetation have been degraded. Factors controlling freshwater GHG emissions that appear in the natural inland water literature are also relevant to understand mechanisms in man-made water bodies. For example, it has been shown that CH_4 bubbling predominantly occurs in the littoral zone of lakes.

The objective of the G-res Tool project is to use our existing knowledge base to create a new modelling framework to assess the net GHG footprint from freshwater reservoirs, which excludes emissions occurring pre-dam construction, as well as many other aspects of carbon dynamics in aquatic systems (Prairie et al 2017b).

The G-res Tool's operating principles include:

- The GHG footprint of the landscape prior to impoundment;

- The particular environmental setting of each reservoir (climatic, geographic, edaphic and hydrologic);

- The temporal evolution of the GHG emissions over the lifetime of the reservoir;

- Displaced GHG emissions, i.e. emissions that would have occurred somewhere else in the aquatic network regardless of the presence of a reservoir; and

- Emissions increasing the net GHG emission impact of the reservoir, but that are the result of release of nutrients and organic matter by human activity occurring upstream of or within the reservoir.

Within these principles, we can thus apply a simple conceptual equation to define the net GHG footprint as:

Net GHG Footprint = [Post-impoundment GHG balance after introduction of a reservoir] – [Pre-impoundment GHG balance before introduction of a reservoir] – [Emissions from the reservoir due to Unrelated anthropogenic sources]

3. Methods

3.1 G-res Tool methodology

Knowledge regarding the factors driving GHG emissions from reservoirs is distributed across scientific literature. As part of the G-res project, an extensive literature review was conducted to summarize all past GHG estimates available in the scientific literature. In addition, over 50 variables spanning the four potential driver categories were collected for 223 reservoirs in which over 550

field measurements were made and used in the study (Prairie et al 2017). Using state-of-the-art statistical analysis, we found the best model to predict each of the four emission pathways (Annex 1, Prairie et al 2017): CO_2 diffusive emissions and CH_4 diffusive, CH_4 bubbling and CH_4 degassing emissions (Figure 1).

The results of the following reservoir were obtained using version 2.1 of the G-res Tool models. The G-res Tool also provides 95 % confidence interval (CI) which are derived from the uncertainty inherent to the models developed. In the G-res Tool, this uncertainty is recalculated each time randomly, and will be slightly different from one analysis to the other.

3.2 Pre-Impoundment

The pre-impoundment emissions are obtained by applying pre-established emission factors from IPCC (IPCC 2006; 2014) to each of the land coverage categories present in the impounded area (ESA-CCI 2014-2017). Because the reservoir has been flooded since 1974, we do not have any information about the land coverage and the soil under the impounded area. As a result, we applied the buffer method (described in Prairie et al 2017, Figure 3). The specific emission factors for each land coverage category and for specific climate used in the buffer method are available in the Technical document of the G-res Tool (Prairie et al 2017).
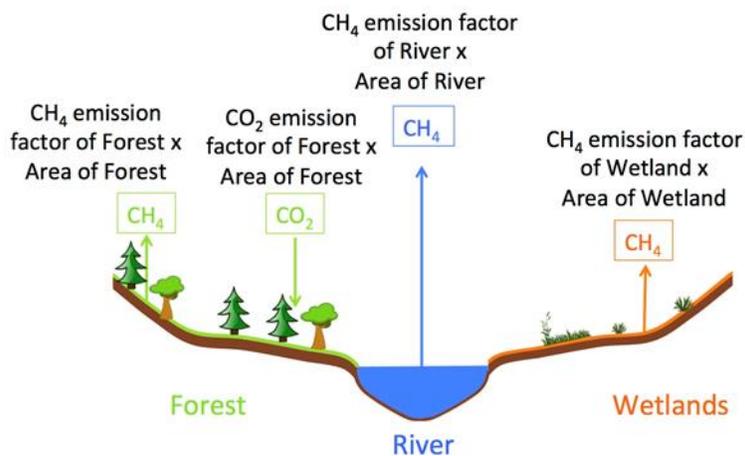

Figure 2: Schematic of an example of pre-impoundment landscape as a mosaic of ecological area with different GHG behaviors

3.3 Reservoir description

The Cahora Bassa reservoir, situated in Mozambique, has a surface area of 2,363 km² , with a mean depth and maximum depth of 23.2 m and 127.9 m, respectively. The reservoir is completely mixed from May to August and is stratified with a thermocline depth up to 40 m from September to April. The reservoir is characterized by a medium presence of littoral area (10.2 %). A total of 2,245 km² of land was impounded, constituted of 48 % of grassland/shrubland, 40 % of cropland and 6 % of forest (Figure 3), with low soil organic carbon content (5 kgC/m²).
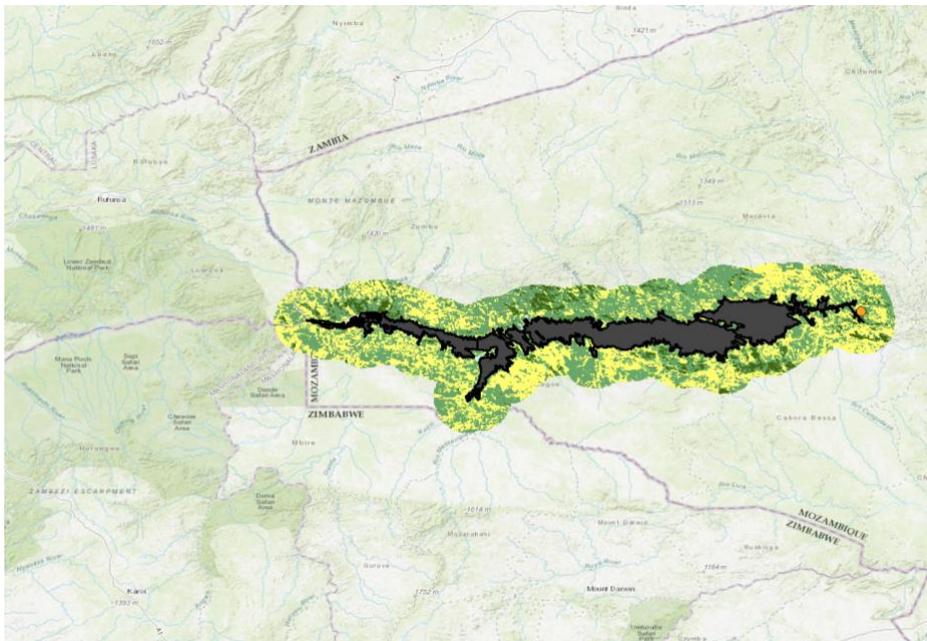
Figure 3: The Cahora Bassa reservoir (in black), its dam (orange point) and its buffer zone used to represent the land under the impounded area, showing the following land coverage categories: Grassland/Shrubland (pale green), Cropland (yellow), Forest (dark green), Bare Areas (pale grey), Water Bodies (dark blue) and Wetlands (pale blue)

This reservoir has a catchment area of 1,300,000 km² with 29 % of grassland/shrubland, 25 % of cropland and 44 % of forest. The catchment has high human presence of 3,693,331 persons, with a medium presence of intense human activities.

The Cahora Bassa reservoir experiences a tropical climate with a mean annual air temperature of 22.9 °C, a mean global horizontal radiance of 5.73 kWh/m²/d, an annual runoff of 75 mm/yr and average wind speed of 4.65 m/s.

Table 1: The Cahora Bassa reservoir data used in the G-res Tool to predict the net GHG footprint with the version 2.1 of the G-res models. The variables that are estimated from general equations are identified as *Estimated* and the equation used are presented in Annex 2.

Predicting variables		Units	Value	Data source
Catchment area		km^2	1,300,000	ESIA vol1 p7
Population in the catchment		persons	3,693,331	Extracted from CIESIN, 2005
Catchment annual runoff		mm yr^{-1}	75	ESIA vol2 p88
Catchment land cover	Forest	%	43.59	ESA-CCI 2014-2017
	Water Bodies	%	0.94	ESA-CCI 2014-2017
	Cropland	%	24.55	ESA-CCI 2014-2017
	Settlement	%	0.38	ESA-CCI 2014-2017
	Wetland	%	1.05	ESA-CCI 2014-2017
	Grassland/Shrubland	%	29.44	ESA-CCI 2014-2017
	Bare Area	%	0.01	ESA-CCI 2014-2017
	Permanent Snow/Ice	%	0	ESA-CCI 2014-2017
Reservoir area		km^2	2,363	SURVEY REPORT, 2017 (HCB)
Pre-Impoundment land cover	Forest	%	6.05	ESA-CCI 2014-2017, using a buffer around the reservoir
	Water Bodies	%	5	Estimated by G-res tool using River length (255km)
	Cropland	%	40.31	ESA-CCI 2014-2017, using a buffer around the reservoir
	Settlement	%	0	ESA-CCI 2014-2017, using a buffer around the reservoir
	Wetland	%	0.02	ESA-CCI 2014-2017, using a buffer around the reservoir
	Grassland/Shrubland	%	48.59	ESA-CCI 2014-2017, using a buffer around the reservoir
	Bare Area	%	0.03	ESA-CCI 2014-2017, using a buffer around the reservoir
	Permanent Snow/Ice	%	0	ESA-CCI 2014-2017, using a buffer around the reservoir
Country		-	Mozambique	
Climate zone		-	Tropical	
Maximum depth		m	127.8	SURVEY REPORT, 2017 (HCB)
Mean depth		m	23.2	SURVEY REPORT, 2017 (HCB)
Littoral area		%	10.2	Estimated by G-res tool
Thermocline depth		m	40	ESIA vol2 p108-109
Reservoir surface soil carbon content		kgC/m^2	5.02	SoilGrids (Hengl et al 2017)
Annual wind speed at 10 m		m/s	4.65	ESIA vol2 p81 (3.6 to 5.7 m/s range)
Phosphorus concentration		µg/L	35.86	Field mesurements

Reservoir mean global horizontal radiance	kWh m^{-2} d	5.73	SSE (NASA 2008)
Water residence time	yr	0.74	270 days, ESIA vol2 p106
Monthly mean air temperature	°C	22.9	ESIA vol2 p79

4.   Results

When applying the G-res model using the data found in Table 1 for the current project, we obtained a value of 223 gCO$_2$e/m^2/yr for the diffusive CO$_2$ emissions attributable to the reservoir, which is in the high range of reservoirs CO$_2$ emissions. In the case of CH$_4$ diffusive emissions, the Cahora Bassa reservoir is a medium emitter with emissions of 142 gCO$_2$e/m^2/yr. It also emits a high amount of methane as bubbles (418 gCO$_2$e/m^2/yr), but only sligthly contributes to atmosphere emissions through degassing (56 gCO$_2$e/m^2/yr) (see Annex 3, page 2).

From this total GHG footprint, we need to remove the pre-impoundment emissions (- 7 gCO$_2$e/m^2/yr), or in other words, the emissions from the landscape impouned, which account for around 10 % of the emissions predicted. The negative value for pre-impoundment represents a sink in GHG emissions, caused by an uptake from the forested area impouned (through primary production).

The G-res Tool can also normally provide an estimate of the emissions associated with other human activities, Unrelated Anthropogenic Sources emissions (UAS), observed at the reservoir surface area (Prairie et al 2017). For Cahora Bassa, the phosphorus concentration measured (35.86 µg/L) is much lower than the default value (201 µg/L) estimated using literature formula (Annex 2). This mismatch is mostly due to a problem estimating the input of phosphorus from the catchment in arid regions (runoff of 75mm/yr), as the current global formula to estimate those inputs do not capture the retention of phosphorus in the soil of those regions. Because of this mismatch, we were not able to estimate the share of UAS emissions.

The main purpose of this reservoir is the production of hydroelectric energy, though the reservoir is also used for flood control and water supply. Taking those different services into account, we allocated 80 % of the predicted net GHG footprint to the production of energy.

Cahora Bassa has an annual generation of 15,126 GWh/yr and an installed capacity of 2,075 MW. Considering a reservoir surface area of 2,363 km^2, such production of energy leads to a very low

Page 10   iha
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power density (0.9 W/m²) and a high GHG emissions intensity (105.9 , CI: 94 - 119 gCO₂e/kWh) (Annex 3, page 3).

5.   Discussion

Analysis of the emissions pathways

All four emission pathways (diffusive CO_2, diffusive, ebullitive and degassing CH_4) for the Cahora Bassa reservoir are predicted to be high. As temperature plays an important role in GHG production and emissions, high emissions can be linked to the monthly average temperatures, which are always above 19 °C. Temperature is directly involved in both the diffusive models (CO_2 and CH_4) and indirectly in the degassing pathway, as the predicted diffusive CH_4 emissions are also involved in the degassing model. For CH_4 bubbling emissions, the production of methane (68 % of methane emitted in this case) is estimated from solar irradiance, which can be used as a proxy for the amount of heat reaching the sediments. The Cahora Bassa reservoir, located in a tropical climate, receives an important amount of light from the sun all year long. This light warms up the shallow sediments and increases the production of methane. Furthermore, this reservoir has a non-negligible amount of littoral area (10 %), where CH_4 bubbling emissions is expected to happen due to the direct influence of solar radiation on sediments. As the model for predicting methane bubbling emissions is the most uncertain of the four pathways, it would be considered good practice to verify the adequacy of the prediction with field measurements.

Methane production in aquatic systems is a microbial process that generally requires anoxic conditions. For the surface water layer in contact with the atmosphere, anoxic conditions are normally confined to the sediments in the littoral zone. However, for the deeper water layer (below the thermocline), oxygen can quickly be consumed, making the layer become anoxic. Substantial amounts of CH_4 can accumulate in this layer and be channeled to the river dowstream of the dam when this water is transported through the turbines.

According to the G-res Tool methodology, the landscape present before impoundment was close to carbon neutral (-7 gCO₂e/m²/yr) and therefore has a low influence on the net total emissions. This value is explained by the fact that IPCC does not attribute any emissions to cropland and grassland/schrubland with mineral soil, which account together for 89 % of the impounded area. The only emissions considered are the low methane emissions from the water impounded (5.8 %) and

the uptake from the trees of the forested areas (6 %), which explains the negative emissions for the pre-impoundment.

Influence of degassing

If we predict that all the reservoir water circulating throught the turbines is emitting CH_4 through the degassing pathway, it would represent nearly a third of all the methane emissions for this reservoir. This is because the default emissions rate for CH_4 degassing in the G-res Tool assumes that the water intake of the turbines is located below the thermocline (where CH_4 can accumulated to high concentrations). In the case of Cahora Bassa, the turbines are actually drawing water from well oxygenated surface water all year long, so we do not expect any CH_4 degassing from this water. However, the spillways of Cahora Bassa are located much deeper (around 98 m) and this water, drawn deep in the reservoir, is expected to degass methane for most of the year. To assess the real situation in Cahora Bassa, we only predict degassing for the water flowing through the spillway. This leads to a CH_4 degassing emission rate of 56 $gCO_2e/m^2/yr$, representing only 9 % of total methane emissions.

Surface water level options

Over the period between 1997 and 2020, the average surface water level was 322 m. This is the value used for the main analysis of this report. Nonetheless, it is important to note that a change in the surface water level has an impact on reservoir area, reservoir volume, mean and maximum depth, and percent of littoral area. As such, a change in surface water level can have a major influence on the final net GHG footprint. To assess the impact of such a change on the final net GHG footprint, we consider two case scenarios using the maximum and minimum water surface levels observed in the past .

In the case of the Cahora Bassa reservoir, the lowest surface water level examined (312 m) causes the emissions to decrease to 821 $gCO_2e/m^2/yr$ when compared to the normal level (322 m). Increasing the surface water level to 328 m also causes a small decrease (825 $gCO_2e/m^2/yr$) (Table 2). Considering the uncertainty of the G-res results, it can be said that the natural water level variation of Cahora Bassa reservoir does not have a significant influence on the carbon footprint per m^2 of reservoir emissions.

When comparing the emissions to the energy produced (emissions intensity), changing only the surface water level (e.g. the total reservoir storage capacity) will result in a change in emissions intensity. Indeed, it causes a drop in the emissions intensity to 66 gCO_2e/kWh at the lower surface water level (312 m), but leads to an increase in the total emissions intensity to 126 gCO_2e/kWh at the higher level (328 m). These trends are directly linked to the changes in the flooded surface area. For example, a smaller area impounded, although having around the same emissions, will have a lower emissions intensity if the same amount of energy is produced (Table 2), simply due to the smaller surface area emitting to the atmosphere.

Table 2: Cahora Bassa reservoir water level effect on different variables and on net GHG footprint. 95 % confidence interval of emissions presented in parenthesis.

Impoundment level options	Average level	Minimum level	Maximum level
Surface water level (m)	322	312	328
Reservoir area (km^2)	2363	1521	2887
Mean depth (m)	23.2	23.3	24.5
Maximum depth (m)	127.8	117.9	133.9
% littoral area	10.2	9.9	9.6
Volume of water (km^3)	54.8	35.4	70.7
Net GHG emissions (gCO$_2$e/m^2/yr)	847 (754–953)	821 (727-927)	825 (736-926)
GHG emissions intensity (gCO$_2$e/kWh)	105.9 (94-119)	66 (58-75)	126 (112-141)

Reservoir GHG emissions intensity

According to many international standards, a reservoir emitting more than 100 gCO_2e/kWh is considered as a high GHG emitter (IHA 2018). The estimated emissions intensity of Cahora Bassa is high (105.9 gCO_2e/kWh), but remains around the acceptable limit considering the uncertainty of the results. This high value can be largely attributed to two different factors.

First, the predicted area emissions rate (847 gCO_2e/m^2/yr) is relatively high compared to global reservoirs, but is lower than the majority of reservoirs located in a similar climate. According to the G-res calculations, the Cahora Bassa reservoir emissions fall much lower than the median of tropical reservoir emissions (1295 gCO_2e/m^2/yr, n=468, Figure 4).
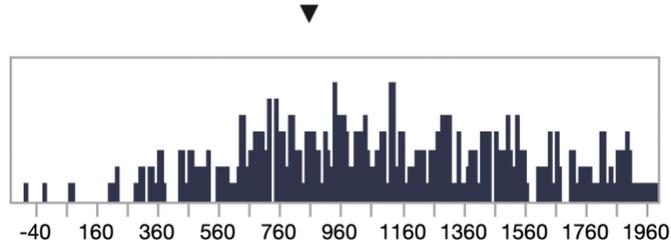
Figure 4: Cahora Bassa reservoir Net GHG footprint of (847 $gCO_2e/m^2/yr$ (Black triangle) location across a distribution of the Net GHG footprint of other tropical reservoir worldwide. Figure extracted from the G-res Tool - Reservoir GHG page.

The other main contributor is the production of energy per area impounded ratio. Cahora Bassa has a very low power density (0.9 W/m^2), implying that the energy produced per unit of land area flooded is low. In such cases, we need to go further than the international standards and look deeper at the local situation. Although the GHG footprint of Cahora Bassa is high relative to the average for hydropower projects (18.5 gCO_2e/kWh), it still remains better than any other non-renewable energy (Table 3).

Table 3: Cahora Bassa reservoir emissions intensity compared to median life-cycle carbon equivalent intensity (gCO2e/kWh) of other energy type (IPCC 2014, IHA 1018)

Energy type	Median life-cycle carbon equivalent intensity (gCO2e/kWh)
Coal	820
Gas	490
Cahora Bassa reservoir	105.9
Solar PV	48
Hydropower	18.5
Nuclear	12
Wind Onshore	11

6.   Conclusion

The Cahora Bassa reservoir net GHG emissions are estimated to reach 847 $gCO_2e/m^2/yr$ (confidence interval: 754 - 953) which is higher than most worldwide reservoirs, but within the typical range of tropical reservoirs. The major part of the emissions is CH_4 bubbling emissions, although all pathways contribute to the net footprint as follows:

Diffusive CO_2 emissions: 223 $gCO_2e/m^2/yr$

Diffusive CH_4 emissions: 142 $gCO_2e/m^2/yr$

Bubbling CH_4 emissions: 418 $gCO_2e/m^2/yr$

Degassing CH_4 emissions: 56 $gCO_2e/m^2/yr$

As half of the total emissions of the Cahora Bassa reservoir are estimated to be emitted through methane bubbling and considering that this emission pathway is more uncertain than the other pathways (being highly variable both spatially and temporally), it would be good practice to validate the current GHG assessment result by undertaking field measurements of methane bubbling.

When comparing the net GHG footprint to the energy production of the Cahora Bassa reservoir, the GHG emissions intensity reaches 105.9 gCO_2e/kWh (conf. int.: 94 - 119), which is high for a hydropower project GHG footprint, but remains at the proposed maximum limit for what is considered an acceptable emissions intensity.

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Annex A.1. Empirical models

Model equation

CH$_4$ diffusive emissions (in gCO2e/m^2/yr)[1]

$$= \frac{10^{\left(0.8804 + 0.6068 * log10\left(\frac{\% \, Littoral \, Area}{100}\right) + 0.04828 * Effective \, Temperature \, CH_4\right)} * \left(1 - 10^{(-(100 * 0.0117))}\right)}{(100 * 0.0117 * \ln(10))} * \frac{365}{1000} * \frac{16}{12} * 34$$

CH$_4$ bubbling emissions (in gCO2e/m^2/yr)

$$= 10^{\left(-0.98574 + 1.0075 * log10\left(\frac{\% \, Littoral \, Area}{100}\right) + 0.04928 * \left(\frac{Reservoir \, Cumulative \, Global \, Horizontal \, Radiance}{30.4}\right)\right)} * \frac{365}{1000} * \frac{16}{12} * 34$$

CH$_4$ degassing emissions (gCO2e/m^2/yr)

$$= \frac{10^{\left(-5.5029 + 2.2857 * log10(CH4 \, Diffusive \, Emissions \, Integrated \, on \, 100 \, yrs) + 0.9866 * log10(WRT)\right)} * 1000}{1000000000} * Catchment \, Area * 1000000$$
$$* \left(\frac{Annual \, Runoff \, (mm/yr)}{1000}\right) * 0.9 * \frac{16}{12} * 34 \, / \, Reservoir \, Area \, (km^2)$$

CO$_2$ diffusive emissions (in gCO2e/m^2/yr)[1]

$$= \left(\left(10^{(1.7892 + 0.0400 * Effective \, Temperature \, CO_2 + 0.06918 * log10(Reservoir \, Area) + 0.0216 * Reservoir \, Surface \, Soil \, C \, Content + 0,1472 * log10(TP))} * \frac{100^{(-0.3364 + 1)} - 0.5^{(-0.3364 + 1)}}{(-0.3364 + 1) * (100 - 0.5)}\right.\right.$$
$$\left. * \, 0.365 * \frac{44}{12} * \left(1 - \frac{\% \, River \, Area \, Before \, Impoundment}{100}\right)\right) -$$
$$10^{(1.7892 - 0.3364 * log10(100) + 0.0400 * Effective \, Temperature \, CO_2 + 0.06918 * log10(Reservoir \, Area) + 0.0216 * Reservoir \, Surface \, Soil \, C \, Content + 0,1472 * log10(TP))}$$
$$\left.* \frac{365}{1000} * \frac{44}{12} * \left(1 - \frac{\% River \, Area \, Before \, Impoundment}{100}\right)\right)$$

[1] The equation above uses the empirical model equation but also contains the operation necessary to integrate the emissions over 100 years (derived from calculus).

Annex A.2. Equations used for unavailable values

% Littoral Area

$$\% \text{ Littoral Area } = \left(1 - \left(1 - \frac{3}{Maximum\ Depth} \right)^{q\_bathymetric\ shape} \right) * 100$$

River Area Before Impoundment (km²)

$$River\ Area\ Before\ Impoundment\ = \frac{River\ Length\ Before\ Impoundment * 5.9 * Catchment\ area^{0.32}}{1000000}$$

Phosphorus Load Factor - Forest (kg/ha/yr)

$$Phosphorus\ Load\ factor\ -\ Forest\ = \frac{10^{\left(0.914 - log10\left(\left(\frac{Catchment\ Land\ Cover\ \% - Forest}{100} \right) * Catchment\ Area \right) * 0.014 \right)}}{100}$$

Phosphorus Load Factor- Croplands (kg/ha/yr)

$$Phosphorus\ Load\ factor\ -\ Croplands$$
$$= \frac{10^{\left(1.818 - log10\left(\left(\frac{Catchment\ Land\ Cover\ \% - Croplands}{100} \right) * Catchment\ Area \right) * 0.227 \right)}}{100}$$

P Input from catchment (kgP yr-1)

$P\ Input\ from\ catchment$

$$= \left(\begin{array}{l} Phosphorus\ Load\ factor - Croplands\ *\ Catchment\ Land\ Cover\ \% - Croplands \\ + Phosphorus\ Load\ factor - Forest\ *\ Catchment\ Land\ Cover\ \% - Forest \\ + Phosphorus\ Load\ factor - Wetlands\ *\ Catchment\ Land\ Cover\ \% - Wetlands \\ + Phosphorus\ Load\ factor - Settlements\ *\ Catchment\ Land\ Cover\ \% - Setttlements \\ + Phosphorus\ Load\ factor - Bare\ Areas\ *\ Catchment\ Land\ Cover\ \% - Bare\ Areas \\ + Phosphorus\ Load\ factor - Water\ Bodies\ *\ Catchment\ Land\ Cover\ \% - Water\ Bodies \\ + Phosphorus\ Load\ factor - Permanent\ Snow/Ice\ *\ Catchment\ Land\ Cover\ \% - Permanent\ Snow/Ice \end{array} \right)$$
$* Catchment\ Area$

**See table 12 for Load factor

P Human Input (kgP yr-1)

$$P\ Human\ input = Population\ in\ the\ catchment\ *\ 0,002\ * 365 * \%\ Removal\ Wastewater\ Treatment$$

***For more details about equations used, see the G-res Tool Technical Document (Prairie et al 2017)

Annex A.3. G-res pdf reports

PARTNERS:

Inputs Report

Name of reservoir: Cahora Bassa

Catchment Information

Catchment Area (km^2)	1300000
Population in the Catchment	3693331
Catchment Annual Runoff (mm/yr)	75
Release of phosphorus from community sewage in the catchment (kg P /yr)	0
Community Wastewater Treatment	None
Release of phosphorus from industrial sewage in the catchment (kg P /yr)	0
Industrial Wastewater Treatment	

	Land Cover in the Catchment Area		Land Use Intensity		Pre-Impoundment Land Cover in the Reservoir Area				% of Organic Soil that is Drained
	%	km^2	Past	Current	%	km^2	% Mineral Soil	% Organic Soil	Past Land Use Intensity
Croplands	24.6 %	319800			40 %	944.5	39.97 %	0 %	
Bare Areas	0 %	0			0 %	0.7	0.029 %	0 %	
Wetlands	1.1 %	14300			0 %	0.4	0.019 %	0 %	
Forest	43.6 %	566800			6 %	141.5	5.99 %	0 %	
Grassland/Shrubland	29.4 %	382200			48.2 %	1138.7	48.19 %	0 %	
Permanent Snow/Ice	0 %	0			0 %	0	0 %	0 %	
Settlements	0.4 %	5200			0 %	0	0 %	0 %	
Water Bodies	0.9 %	11700			5.8 %	137.05	5.8 %		
Drained Peatlands	0 %	0			0 %	0		0 %	
No Data	0 %	0			0.002 %	0.2	0.002 %		

Reservoir Information

Country	Mozambique	River Length before Impoundment (m)	255000
Longitude of Dam (DD)	32.71	Phosphorus Concentration (ug/L)	35.86
Latitude of Dam (DD)	-15.59	Trophic Level	Eutrophic
Climate Zone (Reservoir Area)	Tropical	Reservoir Mean Global Horizontal Radiance (kWh/m^2/d)	5.73
Impoundment Year	1974	Mean Temperature per Month (°C)	
Reservoir Area (km^2)	2363	January	24.5
Reservoir Volume (km^3)	54.8	February	24.1
Water Level (m above sea level)	322.1	March	24
Maximum Depth (m)	127.8	April	22.4
Mean Depth (m)	23.2	May	20.9
Littoral Area (%)	10.156	June	19.3
Thermocline Depth (m)	40	July	19.1
Water Intake Depth (m)	31	August	21.3
Water Intake Elevation (m above sea level)		September	23.5
Soil Carbon Content Under Impounded Area (kgC/m^2)	5.02	October	25.5
Annual Wind Speed at 10 m (m/s)	4.7	November	25.6
Water Residence Time (WRT, yrs)	1.1821	December	24.4
Annual Discharge from the Reservoir (m^3/s)	1470.6	Mean Annual Air Temperature (C°)	22.9

g-res tool
assessing ghg emissions from reservoirs

Reservoir GHG Results Report

PARTNERS: iha international hydropower association | UNESCO | uniTwin | UQÀM

Name of reservoir: Cahora Bassa

Reservoir GHG information

Net Predicted Annual CO_2e Emission

	Post-Impoundment	-	Pre-Impoundment	-	Unrelated Anthropogenic Sources	=	Net GHG Footprint	95% CI
Emission Rate (tCO_2e/yr)	**1 984 699**	-	**-17 589**	-	**0**	=	**2 002 288**	**(1 780 521 - 2 251 939)**
of which CO_2	527 815	-	-19 816		n/a	=	547 631	
of which CH_4	1 456 884	-	2 227	-	0	=	1 454 657	
Emission Rate (gCO_2e/m^2/yr)	**840**	-	**-7**	-	**0**	=	**847**	**(754 - 953)**
of which CO_2	223	-	-8		n/a	=	232	
of which CH_4	617	-	1	-	0	=	616	

*Using GWP100 of 34 to obtain CH_4 emissions as CO_2e (IPCC 2013)

Unrelated Anthropogenic Sources

Potential amount of UAS as % of post-impoundment emissions	0 %
Weighted sum model risk result	9

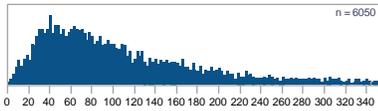### This reservoir compared to worldwide reservoirs

Net Reservoir Footprint (gCO_2e/m^2/yr) = 847

▼

n = 4783

-40 160 360 560 760 960 1160 1360 1560 1760 1960
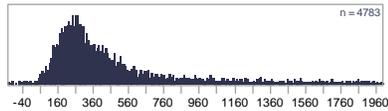
Detailed CH_4 Post-Impoundment Emissions

Relative contribution to CH_4 Post-Impoundment Emissions (%)

% CH4 diffusive
% CH4 Bubbling
% CH4 Degassing

% | 23 | 68 | 9

This reservoir CH_4 and CO_2 emissions compared to worldwide reservoirs

CH_4 Diffusive Emissions (gCO_2e/m^2/yr) = 142

▼

n = 6050

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340

CH_4 Bubbling Emissions (gCO_2e/m^2/yr) = 418
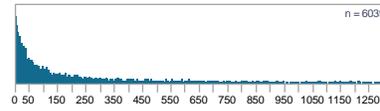
▼

n = 6039

0 50 150 250 350 450 550 650 750 850 950 1050 1150 1250

CH_4 Degassing Emissions (gCO_2e/m^2/yr) = 56

▼

n = 4923

40 80 120 160 200 240 280 320 360 400 440 480 520 560 600 640

CO_2 Diffusive Emissions (gCO_2e/m^2/yr) = 223

▼

n = 5408

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320

g-res tool
assessing ghg emissions from reservoirs
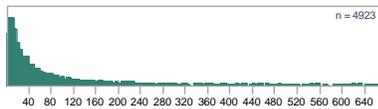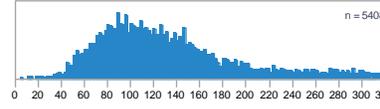
Total GHG Footprint Results Report

PARTNERS:
iha — international hydropower association
UNESCO | uni TWIN | UQÀM

Name of reservoir: Cahora Bassa

Total GHG footprint information

	Post-Impoundment		Pre-Impoundment		Unrelated Anthropogenic Sources		Construction (Reservoir)		Net GHG Footprint	95% CI
Areal Emissions (gCO$_2$e/m^2/yr)	840	-	-7	-	0	+	n/a	=	847	(754 – 953)
Reservoir Wide Emissions (tCO$_2$e/yr)	1 984 699	-	-17 589	-	0	+	0	=	2 002 288	(1 780 521 – 2 251 939)
Total Lifetime Emission (tCO$_2$e)	198 469 880	-	-1 758 872	-	0	+	0	=	200 228 752	(178 052 050 – 225 193 900)

*Using GWP100 of 34 to obtain CH$_4$ emissions as CO$_2$e (IPCC 2013)

Allocation information

Net GHG Emissions Contribution for Each Reservoir Services

Reservoir Service	GHG Emissions from Reservoir (tCO$_2$e/yr)	GHG Emissions from Construction (tCO$_2$e/yr)	GHG Footprint (tCO$_2$e/yr)	Percentage Allocation (%)
Flood Control	300343	0	300343	15
Fisheries	0	0	0	0
Irrigation	0	0	0	0
Navigation	0	0	0	0
Environmental Flow	0	0	0	0
Recreation	0	0	0	0
Water Supply	100114	0	100114	5
Hydroelectricity	1601830	0	1601830	80

Hydroelectricity and Net GHG footprint

Allocation Method Used:

Power Density (W/m^2) = 0.9
▼

n = 498

0 2 4 6 8 10 14 18 22 26 30 34 38 42 46 50
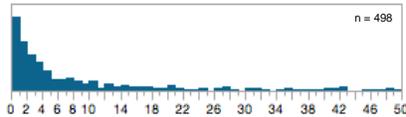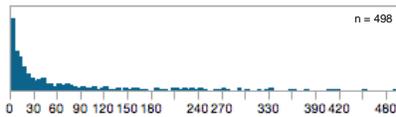
Emission Factor Used:
Default Emission Factors used

Allocated GHG emissions intensity (gCO$_2$e/kWh)=
105.9   (94 - 119)
▼

n = 498

0 30 60 90 120 150 180 240 270 330 390 420 480

Construction Comments: