Methane Emissions from Ecuadorian Hydropower Dams

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Abstract. Climate change is one of the most critical environmental problems nowadays. This change is caused by greenhouse effect, which is related to anthropogenic activities as gases production by fossil fuels and industrial production. Methane emission was evaluated in five Ecuadorian hydropower dams with the Intergovernmental Panel on Climate Change methodology. The average emission was 168,741 tCO₂eq per year in the five stations. The energy density of the Ecuadorian hydropower dams is higher than Brazilian with similar capacity; this result is due to the Ecuadorian's geography. Despite benefits of the hydropower, to mitigate methane emission is recommended to minimize the environmental impact.

1. Introduction

Energy generation is the main cause of greenhouse gas (GHG) emissions into the atmosphere, with fossil fuel combustion being the major source of these emissions. The most important activities are the use of fossil fuels in transport, energy production, and industrial sectors [1]. Since the beginning of the industrial age (1750) until 2013, dioxide carbon (CO₂) atmospheric global average concentrations have increased 41%. The same tendency is showed in methane (CH₄) concentration (160% higher) and nitrous oxide (N₂O) concentration (20% higher) [2].

CH₄ is a long-lived GHG because it persists in the atmosphere 21 times more than CO₂. About 40% of CH₄ global emission comes from natural sources and 60% of activities as rice cultivation, fossil fuels exploitation, landfills, biomass combustion and hydropower stations. Mainly of these activities are located in the tropical and middle latitudes of the northern hemisphere [2], [3]. CH₄ production in reservoirs has two origins: the decomposition of vegetation, which is accumulated at the bottom of the reservoirs (especially in tropical areas) and the high temperatures recorded in the regions where it belongs [4] [5]. Also, CH₄ emissions can be generated in aquatic ecosystems in three different ways: diffuse emission, bubble emission and degassing emission [6]. A part of the CH₄ is oxidized and converted to CO₂ when it rises to the surface of the reservoir mainly by bubbling. In tropical reservoirs, with little amount of water, the bubbles have less time to oxidize, that means they tend to produce higher CH₄ emission [7], [8]. These emissions occur exponentially in the early stages and cold water environments [9].
According to Organization for Economic Cooperation and Development (OECD), trophic status indicates a nutrient water enrichment, and this generally leads to symptomatic changes as increased aquatic plants production and water quality deterioration [10], [11]. Often, large and deep tropical reservoirs are thermally stratified. This thermal gradient is approximately 10 meters below the surface, which prevents diffusion of deep water and shallow waters [12]. This situation favours a CH$_4$ concentration profile that rapidly increases with depth until the local saturation level is reached. This profile follows a pattern that may differ between reservoirs or even in the same reservoir, and this depends on the amount of flooded organic matter, nonlocal inputs and water redox condition. These emissions account for about 1.6% of GHG worldwide emissions [6]. Also, CH$_4$ concentrations fluctuate over time with climatic variations as temperature and rainfall [11]. The northern reservoirs contribute CO$_2$ to global warming while tropical reservoirs add CH$_4$.

The IPCC has estimated that reservoirs and lakes are responsible for 22% of the total CH$_4$ worldwide emission [6]. The most significant CH$_4$ emission from reservoirs have been measured in warmer latitudes, and this is an argument against the use of hydropower. However, greenhouse gas emissions have been measured in only 18 of the 741 largest dams in the tropics.

Due to a large number of hydrographic basins in South America, hydropower stations have become the main source of electricity generation with a capacity of 161,793 MW [13]. In addition, 16% of the electricity consumed worldwide comes from hydropower [14]. Between 2005 and 2015 the total installed capacity has grown by 39%. This increase was primarily true in Latin American, Asian and African countries [15], and this trend will persist globally [16]. According to Department of Electricity and Renewable Energy (MEER) Ecuador had an installed hydraulic power (reservoir and run-of-river stations) of 2,219 MW by 2013. The most important project is Coca Codo Sinclair (Sucumbíos and Napo with 1,500 MW), which contributed to the National Interconnected System (SNI, acronym in Spanish) with a net energy of 3,605.41 GWh from April 2016 until January 2017. In Ecuador, 62.4% of the produced electricity comes from hydropower stations, followed by the 35.6% which is produced by thermal power stations [17], [18]. This study estimates the reservoirs impact of the hydropower dams in Ecuador have on the environment. CH$_4$ production was evaluated considering geography, weather, and water trophic status.

2. **Methodology**

To estimate CH$_4$ emissions, produced by Ecuadorian hydropower dams, IPCC methodology was used. This protocol classifies according to the types of emissions and depends on geography, climate, water quality and flooded characteristics areas [6]. The parameters required for the calculation are presented in Table 1, which includes daily average of diffuse emissions from the air-water interface (depending on weather of the area where the reservoir is located), and characteristics of CO$_2$ emissions in the environment. The calculation of these estimates depends on other factors that can alter the results, but these are not considered in this study.

| Reservoir | Province   | Flooded Area (km$^2$) | Year of commissioning | Dammed volume ($\times 10^6$ m$^3$) | Climate (kg CH$_4$/ha x day) | Water temperature ($^\circ$C) | Compensador      |
|-----------|------------|-----------------------|----------------------|-----------------------------------|-----------------------------|-----------------------------|------------------|
| Paute-Molino | Azuay      | 9                     | 2010                 | 410                               | Warm temperate wet (0.150) | 12.9                        | Cañar, Chimborazo, Azuay, Morona Santiago |
| Pisayambo-Pucará | Tungurahua | 5                     | 1977                 | 90                                | Temperate cold wet (0.061) | 13.4                        | Azuay            |
| Daule-Peripa | Los Ríos, Manabi, Santo Domingo, Guayas | 340                   | 1987                 | 6000                              | Tropical dry (0.295)       | 26                          | Morona Santiago |
| Amaluza     |            |                       |                      |                                   | Warm temperate wet (0.150) | 15.4                        | Napo             |
| Compensado  |            |                       |                      |                                   | Tropical very humid (0.630) | 20                          |                  |
Annual generation (GWh) | 816 | 230 | 980 | 4,700 | 8,743
Trophic state | Eutrophic | Eutrophic | Eutrophic | Eutrophic | Oligotrophic

The main sources of GHG emissions in hydropower stations are installations and decomposing biomass in reservoir floods [19]; the latter being the main source of uncertainty. Also, their rate of decomposition is highly dependent, not only in the climatic zone, also in specific aspects of flooded biome. During the first year, one tonne of CH$_4$ emission into the atmosphere has 72 times more effect in global warming potential against one tonne of CO$_2$ emission at the same time, this is because CH$_4$ cycles in the atmosphere are faster than CO$_2$ cycles over a period of 500 years [6]. The comparison between CO$_2$ and CH$_4$ emissions is made with the equivalent of CO$_2$ (CO$_2$eq), and it is a measure used to compare greenhouse gas emissions based on their Global Warming Potential (GWP).

2.1. **Diffuse Emission**

This emission is emitted by molecular diffusion through air-water interface and it is estimated by every $m^2$ (equation 1). This emission is called Level 1.

\[
CH_4\text{ emission} = (P_f) \left(E_{\text{diffuse}}(\text{CH}_4) \right) \text{reservoir surface} \times 10^{-6} = \frac{Gg}{\text{year}} \quad (1)
\]

In the equation, $P_f$ stands for ice-free period (year); $E_{\text{CH}_4\text{diffuse}}$ stands for daily period of diffuse emissions.

2.2. **Bubble Emission**

This gas emission comes from the sediment-water interface and sediment through the bubble water column. This emission pathway is essential, particularly in temperate and tropical regions, and in reservoirs that have been flooded for a short time (equation 2). This emission is called Level 2.

\[
CH_4\text{ emissions} = (P_f \times E_{\text{diffuse}}(\text{CH}_4) \times A) + (P_i \times E_{\text{bubble}}(\text{CH}_4) \times A) + \left(P_f \times E_{\text{diffuse}}(\text{CH}_4) + E_{\text{bubble}}(\text{CH}_4) \right) \times A = \frac{kg}{\text{year}} \quad (2)
\]

In the equation, $P_f$ stands for ice-free period (year); $P_i$ stands for period covered with ice (year); $A$ stands for flooded area. Equations 3, 4 and 5 should be used to calculate the other parameters.

\[
E_{\text{diffuse}}(\text{CH}_4) = \text{daily average of diffuse emissions from the air – water interface during the ice – free period} \quad (3)
\]

\[
E_{\text{bubble}}(\text{CH}_4) = \text{daily average emissions per bubble from air – water interface during the period} \quad (4)
\]

\[
E_{\text{bubble}}(\text{CH}_4) = \text{daily emissions per bubble related to the period covered by ice} \quad (5)
\]

For this calculation, a table of values for the average daily diffuse emissions from air-water interface is performed according to the weather in the area where the reservoirs are located (Table 2). The results of these estimates should be taken with caution as entirely dependent on other factors that can alter the results [6].

### Table 2. Average daily diffuse emission from air-water interface

| Weather                  | Diffuse emissions [free period of ice (kg CH$_4$/ha×day)] |
|--------------------------|-----------------------------------------------------------|
|                          | Half           | Minimum | Maximum |
| Polar/boreal very wet    | 0.086          | 0.011   | 0.300   |
| Temperate cold wet       | 0.061          | 0.001   | 0.200   |
| Temperate warm wet       | 0.150          | 0.050   | 1.100   |
| Temperate warm dry       | 0.044          | 0.032   | 0.090   |
| Tropical very wet        | 0.630          | 0.067   | 1.300   |
| Tropical dry             | 0.295          | 0.070   | 1.100   |

Comparing both methods, Level 2 is more accurate; however, it needs to carry a study with certain variables as sediments of reservoirs. To calculate gas flows from the sediments Fick diffusion formula can be used (equation 6). This is estimated with data obtained from reservoir sediments or lakes monitoring.

\[
J = -\varphi(D_v \theta^{-2}) \left(\frac{dC}{dz}\right) \quad (6)
\]
In the equation, J stands for diffuse gas flow from the sediment-water interface; φ stands for porosity; sediment; θ stands for tortuosity; D₀ stands for coefficient of gas diffusion in water.

2.3. Degassing Emission
This emission from reservoirs are due to a change in hydrostatic pressure, and the increasing variation of the air/water exchange surface after water passes through turbines or drain [4]. This is a fundamental channel of CH₄ emission from young tropical reservoirs, reaching 40% in a new-age reservoir [20]. This emission is called Level 3. To know the emissions of this level it is necessary to make a reservoirs classification, where can be known if their emissions are important or insignificant through certain characteristics. In addition, some conditions should be given as reservoir shape, circulating way and water movement inside, which directly influences GHG emissions. The age of the reservoir is also preponderant; for example, if reservoirs are newly flooded the carbon present in leaves and trash, can be decomposed quickly, whereas the decomposition of the trunks and little biodegradable organic matter is realized later and slowness. The entrance of organic matter and nutrients to the reservoirs accelerates the proliferation of aquatic plants.

3. Results and Discussion
CH₄ contributes more than CO₂ to global warming because it has higher thermal potential. The CO₂ equivalents normalized emission used as a global warming factor is 100-year 23 kgCO₂/kgCH₄.

3.1. Diffuse CH₄ Emission in Ecuadorian Reservoirs
Table 3 shows the results obtained by calculating the diffuse emissions of CH₄ from the reservoirs. The values obtained for the Daule-Peripa reservoir were significantly higher, compared to those obtained for the rest of the analysed reservoirs. It has significant diffuse emissions because it is located in a tropical humidity zone, and temperature plays an important role in the process of eutrophication of organic matter entering.

### Table 3. Diffuse emissions of CH₄ in Ecuadorian reservoirs.

| Reservoirs   | Gg CH₄/year | t CH₄/year | t CO₂ eq |  |
|--------------|-------------|------------|---------|---|
| Paute-Molino | 0.0876      | 87.6       | 1,839.6 |  |
| Mazar        | 0.0493      | 49.275     | 1,034.78|  |
| Pisayambo    | 0.0111      | 11.133     | 233.78  |  |
| Daule-Peripa | 7.8183      | 7,818.3    | 164,184.3|  |
| Compensador  | 0.0690      | 68.985     | 1,448.69|  |

3.2. Comparison of Diffuse CH₄ Emissions from Ecuadorian Reservoirs with Brazilian Reservoirs
Brazil has several investigations that provide relevant information about CH₄ emissions in hydropower dams [21]-[24]. For the estimation of diffuse emissions, between Brazilian and Ecuadorian reservoirs, the tropical zone, MW installed, and flood area (energy density) were considered.

A comparison was made with some Brazilian reservoirs (Tucuri, Samuel, Barra Bonita, Tres Marias, and Balbina), which are part of the First Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions [25]. Table 4 shows that hydropower stations with a higher energy density have smaller flooded areas. This analysis indicated Ecuadorian reservoirs have higher energy density and fewer flooded areas compared to Brazilian with similar capacity.

The CH₄ total amount estimated emitted by reservoirs is 8,035 tCH₄/year, which is equivalent to 168,741 tCO₂eq (table 4). According to the Inter-American Development Bank (IDB), in 2011 the recorded CH₄ emissions of the energy sector in Ecuador added up to a total of 3,433 tCO₂eq; this leads to the conclusion that the analysed reservoirs in this study account 5% of the total emissions made by this sector. In this study, the CH₄ emissions calculated using the IPCC methodology for diffuse emissions provide a general idea about the analysed reservoirs. Also, this reinforces the assertion that the analysed hydropower dams emit GHGs, especially CH₄, because of damming water in their reservoirs. Publications regarding CH₄ emissions in reservoirs have increased the interest in this subject and validate the obtained results [26].
Table 4. Energy density (ED) values for the Ecuadorian (e) and Brazilians (b) reservoirs.

| Reservoirs                  | MW   | km²  | Reservoir age | ED MW/km² |
|----------------------------|------|------|---------------|-----------|
| Paute-Molino (e)           | 1075 | 16   | 31            | 67.2      |
| Compensador (e)            | 1500 | 3    | 0             | 500       |
| Pisayambo (e)              | 74   | 8    | 37            | 9.3       |
| Daule-Peripa (e)           | 213  | 340  | 27            | 0.6       |
| Mazar (e)                  | 160  | 9    | 4             | 17.8      |
| Tucuri (b)                 | 8370 | 2875 | 17            | 2.9       |
| Samuel (b)                 | 216  | 560  | 14            | 0.4       |
| Barra Bonita (b)           | 140.76 | 334.3 | 38            | 0.4       |
| Tres Marias (b)            | 396  | 1155 | 39            | 0.3       |
| Balbina (b)                | 250  | 2360 | 19            | 0.1       |

In the medium term, it is expected that Ecuador can take measurements to reveal the real state of the existing reservoirs. Therefore, the GHGs that may be generated should not be dismissed, because they also contribute to global warming. The results obtained from this study show big differences between the energy density of Ecuadorian and Brazilian reservoirs. Even though, both countries are in the same tropical zone, their geography causes different flooded areas. Another important factor is the height of waterfall since they show whether the water requirements of hydropower projects are low or high.

4. Conclusion

According to the latest 2013 IPCC report, Latin America expects to experience significant impacts about climate change; for that reason, is essential that mitigation measures be implemented to reduce GHGs emissions. Based on hydropower, Ecuador has set policies for reducing these gases, which are aimed at using the existing water potential in the country to meet the projected medium-term demand. Today, hydropower stations are conceived as a clean source of electricity generation and are primarily implemented in emerging countries like Ecuador. Considering the existing research, this theory has weakened, since hydropower emits significant amounts of gases that can contribute to global warming. CH₄ emission from the reservoirs of the hydropower stations contribute significantly to global warming and this depends of station characteristics as geographic location, reservoir age, carbon and nutrients amount, water flow, rotation time, area, depth, water level fluctuations, turbines, and spillways location. For instance, in tropical areas, the emission is more than in temperate and boreal areas. Considering the Ecuadorian context, the creation of a model that allows estimating the emissions of any reservoir based on the station characteristics is recommended.

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