

## Article

# Evaluation of Greenhouse Gas Emissions from Reservoirs: A Review

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**Abstract:** In order to evaluate the greenhouse gas (GHG) emissions from a reservoir or from several reservoirs in a country or a climatic zone, simpler or more complex models based on measurements and analyses of emissions presented in the literature were developed, which take into account one or more reservoir-specific parameters. The application of the models in the assessment of GHG emissions from a multipurpose reservoir gave values that are more or less close to the average values reported in the literature for the temperate zone reservoirs. This is explained by the fact that some models only consider emissions caused by impoundment and not degassing, spillway emissions, and downstream emissions, or those that use different calculation periods. The only model that calculates GHG emissions over the life cycle that occur pre-impoundment, post-impoundment, from unrelated anthropogenic sources and due to the reservoir construction is the model used by the G-res tool. In addition, this tool is best suited for multipurpose reservoirs because it allocates GHG emissions for each use, thus facilitating the correct reporting of emissions. The G-res tool used to calculate GHG emissions from the Stânca-Costești Multipurpose Reservoir shows that this is a sink of GHG with a net emission of  $-5 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  (without taking into account the emissions due to dam construction).

**Keywords:** emissions; greenhouse gas; multipurpose reservoirs; temperate climate



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## 1. Introduction

Reservoirs are manmade lakes created by building dams on rivers for various purposes: flood control, electricity generation, irrigation, water supply, aquaculture, environmental services, recreational activities, navigation etc.

In freshwater ecosystems, several mechanisms are involved in the natural carbon cycle. They receive carbon from terrestrial ecosystems through drainage, capture the carbon through primary production, bury the carbon in sediments, emit GHG through biomass degradation and respiration, and transport the carbon downstream to the seas or oceans. GHG emissions can be increased by human activities around the ecosystem through sewage and agricultural pollution. Dams affect the natural carbon cycle in freshwater ecosystems through floods of terrestrial vegetation and soils. The flooded organic matter decomposes causing additional GHG emissions, especially in the first years after the reservoir creation. Flooding can also increase sedimentation and decomposition in the reservoir, due to longer water residence times, which can lead to higher GHG emissions [1]. In addition, reservoirs can have large fluctuations in the water level, especially hydroelectric reservoirs that store large volumes of water to be used during drought. It can, therefore, be said that artificial reservoirs differ from natural lakes by riverine nutrient inputs, the flooding of terrestrial organic carbon, and water-level fluctuations; they also may have different GHG emissions. Reservoirs present, from a social, economic and environmental point of view, not only advantages, but also disadvantages.

Reservoir use can serve single or multiple purposes. According to the International Commission on Large Dams (ICOLD), 70% of large reservoirs are designed for single-purpose usage. Around 11% of large reservoirs have been built only for hydropower generation and 14% for hydropower generation plus other uses. These high figures show why GHG emissions from reservoirs should be accounted for. In addition, the study of these emissions indicates ways to reduce them.

The main greenhouse gases emitted by a reservoir are CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. They have a different global warming potential (GWP). For the time period of 100 years, GWP for CO<sub>2</sub> is 1; for CH<sub>4</sub>, it is 34 times higher than that of CO<sub>2</sub>, and for N<sub>2</sub>O, it is 298 times that of CO<sub>2</sub> [2].

The CO<sub>2</sub> is generated by the decomposition of organic material and nutrients transported in the reservoir by affluent or by rainfall and overland flow, by the decomposition of dead organic matter stored in the soil of the reservoir, by the respiration of vegetation present in the reservoir, from CO<sub>2</sub> dissolved in water and from the oxidation of CH<sub>4</sub>. The sediments in drawdown areas are also a source of CO<sub>2</sub> emission, due to their exposure to air during water level fluctuations.

The emission of CH<sub>4</sub> comes from the decomposition of organic matter and vegetation under anaerobic conditions in the soil or sediment layer of the reservoir.

Nitrous oxide (N<sub>2</sub>O) arises as a by-product of the aerobic nitrification reaction or of the anaerobic denitrification that occurs in lake riparian areas. The few measurements of N<sub>2</sub>O emission from reservoirs showed a variation similar to that of CH<sub>4</sub> in terms of generation. The contribution of N<sub>2</sub>O to the total GHG emission expressed as an CO<sub>2</sub> equivalent is low, compared to CH<sub>4</sub> și CO<sub>2</sub> (N<sub>2</sub>O—17 mg CO<sub>2eq</sub>/m<sup>2</sup>/d; CH<sub>4</sub>—275 mg CO<sub>2eq</sub>/m<sup>2</sup>/d and CO<sub>2</sub>—1585 mg CO<sub>2</sub>/m<sup>2</sup>/d) [3].

GHG (CO<sub>2</sub> and CH<sub>4</sub>) reaches the atmosphere through the following channels: diffusive flow from the reservoir surface, through degassing when passing through the hydraulic turbine and spillway (due to pressure drop), through diffusive flow at the downstream river surface. Methane can also reach the surface of the reservoir through bubbling in shallow areas of reservoir.

The main factors influencing GHG emissions are the carbon stock in soil and flooded biomass or that transported by the upstream rivers in reservoirs; the concentration of dissolved oxygen in the reservoir; water quality and nutrient content; the inflow and shape of the reservoir; the water depth and extension of the littoral zone; the wind speed at the reservoir surface; and the water temperature and configuration of dam intake and outlets [3]. These factors influence the biochemical processes of organic matter formation, respiration, methanogenesis, CH<sub>4</sub> oxidation, gas exchange between the reservoir and the atmosphere. The GHG measurements showed a variation in time and space within a reservoir and also a seasonal variation and a decrease in general with the age of the reservoir.

There are many studies on the evaluation of GHG emissions from reservoirs, which differ by the methodologies used, the lifespan considered, and the size and type of reservoir [1,4–39].

Most studies have analyzed GHG emissions from hydropower reservoirs. The few studies performed on natural lakes have shown that there are no significant differences between reservoir surface emissions from hydropower reservoirs, compared to non-hydropower reservoirs [10]. At hydropower reservoirs, there are also degassing emissions, downstream emissions and emissions from drawdown zones.

From the analysis of GHG emissions from 85 different hydroelectric reservoirs with a global distribution, it was observed that all the reservoirs are sources of CH<sub>4</sub> to the atmosphere, the majority (88%) are also a source of CO<sub>2</sub> (only 12% of reservoirs are net sinks of CO<sub>2</sub>) and that there is a large variation in emissions [5].

Knowing the GHG emissions generated by reservoirs is an important factor in making decisions to finance future projects and discerning how environmentally friendly they are.

The purpose of this study is to review the main methodologies for assessing GHG emissions from a reservoir, find the most appropriate model to estimate GHG emissions from a multipurpose reservoir, and present the complete environmental performance of

a reservoir placed in the temperate zone of Eastern Romania, a country for which data are limited. On the Romanian territory, there are about 400 large reservoirs totaling 6300 million m<sup>3</sup>. The chosen Stâncă-Costești reservoir is one of the representative reservoirs, being the second largest in the country.

The models used both for reservoirs for any purposes other than power generation and for hydropower reservoirs are presented. The results obtained are presented comparatively to help stakeholders in identifying and choosing the calculation method.

## 2. Assessment of GHG Emissions from the Reservoirs

Because measuring GHG emissions from reservoirs is not an easy task due to the large variation in time and space, especially of CH<sub>4</sub> emissions, several methodologies for their evaluation were developed. All methodologies are based on measurements of emissions from reservoirs located in different climatic zones. The different emission values reported in the literature show the influence of specific reservoir factors, such as type, climate zone, age and depth of the reservoir, neighboring land cover types, land uses before flooding and others.

Table 1 shows the estimated GHG emissions from different types of reservoirs and freshwater ecosystems [10].

**Table 1.** GHG emissions from reservoirs and freshwater ecosystems [10].

System Type	GHG Areal Rate, (mg/m <sup>2</sup> /d)		CO <sub>2</sub> Equivalent Emissions, CO <sub>2eq</sub> , (g/m <sup>2</sup> /yr)
	CH <sub>4</sub>	CO <sub>2</sub>	
All reservoirs	160.8	1207.8	2436.38
Hydroelectric reservoirs	110–128	1822.68	2695.66–2253.76
Lakes	32.16–150	1412–2415	914.49–2742.98
Ponds	53.6	790.56	953.73
Rivers	36.18	1544.52	1012.74
Wetlands	8–131	29,111.64	10,725.03–12,251.46
	20–84	-	248.20–1042.44

In paper [16], an average global GHG emission is reported (reservoir surface plus drawdown area emissions and reservoir downstream emissions) from the hydropower reservoirs of 92 g CO<sub>2</sub>/kWh and 5.7 g CH<sub>4</sub>/kWh.

As stated in [32], the lifecycle GHG emissions from hydropower plants range from 1 g CO<sub>2eq</sub>/kWh to 2200 g CO<sub>2eq</sub>/kWh with an average value of 24 g CO<sub>2eq</sub>/kWh.

A distribution by the source of GHG emission from hydropower reservoirs from different climatic zones is presented in Table 2 [16,28]. The large variation from one climate zone to another can be seen as well as the higher contribution of emissions from drawdown areas and the contribution of CO<sub>2</sub> emissions to the total emissions.

**Table 2.** GHG emissions from hydroelectric reservoirs [16,28].

Climate Zone	Carbon Emission, (mg/m <sup>2</sup> /d)	
	CO <sub>2</sub>	CH <sub>4</sub>
	Reservoir surface	
Boreal	753	9.1
Temperate	1500 [16]	20 [16]
	386 [28]	2.8 [28]
Tropical	3097	91.3
	Drawdown area	
Temperate	2110	110
Tropical	3500 [16]	300 [16]
	13,000 [28]	235 [28]

The contribution to GHG emissions related to reservoir construction, meaning those from the activities related to dam construction (raw material extraction, equipment manufacturing, transportation, and building process of dam), is estimated to be (2.3–37.9) gCO<sub>2eq</sub>/kWh [27].

In paper [26], an average global emission of 173 kg CO<sub>2</sub>/MWh and 2.95 kg CH<sub>4</sub>/MWh was estimated after the emissions from over 1400 hydroelectric power plants were analyzed. The study emphasizes the importance of analyzing each hydropower plant and the need for standardized measurement procedures, taking into consideration carbon burial, drawdown areas and methane bubbles. Additionally, in this paper [26], the following models were developed using generalized linear models:

- CO<sub>2</sub> emission expressed in kg CO<sub>2</sub>/MWh as a function of the area-to-electricity ratio (ATER, km<sup>2</sup>/GWh) and reservoir area (S, km<sup>2</sup>):

$$\text{CO}_2 = -169.73 + 241.86 \times \text{ATER} + 120.34 \times \ln(S), \text{ kg CO}_2/\text{MWh} \quad (1)$$

- CH<sub>4</sub> emission expressed in kg CH<sub>4</sub>/MWh as a function of the reservoir age (A, years), area-to-electricity ratio (ATER, km<sup>2</sup>/GWh) and maximum temperature (T<sub>max</sub>, °C):

$$\ln(\text{CH}_4) = -9.81 - 0.75 \times \ln(A) + 1.18 \times \ln(\text{ATER}) + 4.5 \times \ln(T_{\text{max}}), \text{ kg CH}_4/\text{MWh} \quad (2)$$

GHG emission expressed in mg C/m<sup>2</sup>/d, which can also be used in the case of reservoirs with a use other than energy production, depending on the reservoir age (A, years), erosion rate (Er, t/ha/yr), reservoir area (S, km<sup>2</sup>) and maximum temperature (T<sub>max</sub>, °C):

$$\text{CO}_2 = 494.46 - 4.07 \times A + 8.09 \times \text{Er}, \text{ mg CO}_2/\text{m}^2/\text{d} \quad (3)$$

$$\ln(\text{CH}_4) = -12.84 - 0.03 \times A + 0.21 \times \ln(S) - 0.01 \times \text{Er} + 4.88 \times \ln(T_{\text{max}}), \text{ mg CH}_4/\text{m}^2/\text{d} \quad (4)$$

In [5], CO<sub>2</sub> and CH<sub>4</sub> emissions from 85 reservoirs between 68° N and 25° S were analyzed. The reservoir surface emissions were estimated, correlated to reservoir age (A, years) and latitude (L, °), dissolved organic carbon (DOC, mg/L) and mean reservoir depth (h, m). Based on the measured data, the CO<sub>2</sub> and CH<sub>4</sub> emissions were predicted, using the following multiple-regression equations:

$$\log(\text{CO}_2 + 400) = 3.06 - 0.16 \times \log(A) - 0.01 \times L + 0.41 \times \log(\text{DOC}), \text{ mg CO}_2/\text{m}^2/\text{d} \quad (5)$$

$$\log(\text{CH}_4) = 1.33 - 0.36 \times \log(A) - 0.32 \times \log(h) + 0.39 \times \log(\text{DOC}) - 0.01L, \text{ mg CH}_4/\text{m}^2/\text{d} \quad (6)$$

Ref. [38] presented a calculation tool called HydroCalculator, which, in addition to calculating financial indicators, also calculates greenhouse gas emissions. The biome carbon loss (BCL) model based on the initial carbon stock is used to calculate GHG emissions:

$$C_t = C_0 \left( \frac{e^{-0.3t}}{5} + \frac{e^{-0.03t}}{3} + \frac{1}{2} \right), \text{ tonne C/yr} \quad (7)$$

where C<sub>t</sub> is the amount of carbon (CO<sub>2</sub> and CH<sub>4</sub>) in tonnes in the year t, C<sub>0</sub> is the initial amount of organic carbon in soil and vegetation in tonnes, and t is the time in years.

This model calculates only GHG emissions from the decomposition of organic matter, not GHG emissions from turbines and spillway.

Paper [38] calculated the proportion of carbon emitted as CO<sub>2</sub> and CH<sub>4</sub>, observing that CO<sub>2</sub> emissions are 73% of carbon emissions and CH<sub>4</sub> emissions are 27%. Carbon emissions can be converted to CO<sub>2</sub> and CH<sub>4</sub> by multiplying the values by 44/12 and 16/12, respectively. CH<sub>4</sub> emissions are converted to CO<sub>2</sub> equivalents by multiplying the global warming potential of CH<sub>4</sub> specified in IPCC's Fifth Assessment Report [33].

Ref. [39] presented, in addition to Equation (7), two other calculation equations of CH<sub>4</sub> emissions, from the organic matter cycle (OMC model) (Equation (8)) and downstream emissions (from turbines and spillways) (downstream emission model) (Equation (9)):

$$E_{\text{OMCM}} = 10 \left( 15.5S^{0.841} + 1.73S^{0.927} + 35.2A^{0.649} \right), \text{ g CH}_4/\text{yr} \quad (8)$$

$$E_{\text{DEM}} = Q \times d \times c \times t, \text{ g CH}_4/\text{yr} \quad (9)$$

where  $S$  is the reservoir surface area ( $m^2$ );  $Q$  is the waterflow ( $m^3/d$ );  $d$  is the effective emission assumed to be 50% to 80%;  $c$  is the  $CH_4$  concentration in turbine/spillway water intakes ( $g/m^3$ ); and  $t$  is the annual operation of spillways (1/4 year) and turbines (3/4 year) (days).

In paper [6], their own measurements of methane emissions from reservoirs were analyzed together with the emissions from 49 other reservoirs from temperate and boreal zones in order to find the best mathematical relations for estimating emissions according to the characteristics of the reservoirs. The following regression equations for bubbling, diffusive and storage emissions were proposed:

- $CH_4$  bubbling emission:

$$(CH_4)_{bub} = 10^{0.838+0.934 \times \log(S)+0.881 \times \log(TP)}, \text{ g } CH_4/\text{yr} \quad (10)$$

- $CH_4$  diffusive emission:

$$(CH_4)_{diff} = 10^{0.234+0.927 \times \log(S)}, \text{ g } CH_4/\text{yr} \quad (11)$$

- $CH_4$  storage emission:

$$(CH_4)_{stor} = 10^{7.068+3.304 \times \log(TP)-1.904 \times \log(DOC)}, \text{ g } CH_4/\text{yr} \quad (12)$$

where  $S$  is the reservoir area ( $m^2$ ),  $TP$  is the concentration of total phosphorous ( $\mu\text{mol/L}$ ), and  $DOC$  is the concentration of dissolved organic carbon ( $\text{mg C/L}$ ).

The International Energy Agency Hydropower Implementing Agreement on Hydropower Technologies and Programs (IEA Hydro) developed a framework, which describes the steps for data collection and analysis and the modeling tools to estimate the GHG emissions from a reservoir on the principles of net emissions defined by the IPCC. The estimation of GHG emissions from reservoirs is based on the analysis of the collected data and four elements of the new reservoir projects (flooded area, reservoir, upstream catchment area, reservoir outflow facilities, downstream river) [35].

The International Government Panel on Climate Change guidelines [2] recommend estimating the diffusion emission of  $CO_2$  from reservoirs by using the following equation:

$$(CO_2)_{diff} = P \times E(CO_2)_{diff} \times S \times 10^{-3}, \text{ tonne } CO_2/\text{yr} \quad (13)$$

where  $(CO_2)_{diff}$  is the total  $CO_2$  emission from the reservoir, tonne  $CO_2/\text{yr}$ ;  $P$  is the number of days without ice cover during a year, days/yr; and  $E(CO_2)_{diff}$  is the average daily diffusive emissions, kg  $CO_2/\text{ha/d}$  (Table 3).

**Table 3.**  $CO_2$  measured emissions for flooded land [2].

Climate	Diffusive Emission (Ice-Free Period)
	$E(CO_2)_{diff}$ (kg $CO_2/\text{ha/d}$ ) Range and Median Values
Boreal wet	(0.8–34.5) 11.8
Cold temperate, moist	(4.5–86.3) 15.2
Warm temperate, moist	(−10.3–57.5) 8.1
Warm temperate, dry	(−12.0–31.0) 5.2
Tropical, wet	(11.5–90.9) 44.9
Tropical, dry	(11.7–58.7) 39.1

To these emissions must be added the degassing emissions, which represent up to 30% of the total  $CO_2$  emissions from reservoirs in a temperate moist region and less than 5% in cold temperate regions.

For a preliminary estimate of the total annual  $CH_4$  emissions (reservoir surface emissions plus emissions originating from reservoir but emitted downstream of dam) from reservoirs older than 20 years, the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use

(Chapter 7: Wetlands) [36] recommend the following equation with the emission factors derived from the G-Res model given in Table 2:

$$(\text{CH}_4)_{\text{tot}} = (\text{CH}_4)_{\text{res}} + (\text{CH}_4)_{\text{downstream}} = \alpha \times \text{EF}_{\text{CH}_4} \times S + \alpha \times \text{EF}_{\text{CH}_4} \times S \times R_d, \text{ kg CH}_4/\text{yr} \quad (14)$$

where  $(\text{CH}_4)_{\text{res}}$  is the annual reservoir surface emissions of  $\text{CH}_4$  from reservoirs > 20 years old,  $\text{kg CH}_4/\text{yr}$ ;  $(\text{CH}_4)_{\text{downstream}}$  is the annual emissions of  $\text{CH}_4$  emitted downstream of dam,  $\text{kg CH}_4/\text{yr}$ ;  $\text{EF}_{\text{CH}_4}$  is the emission factor for  $\text{CH}_4$  emitted from the reservoir surface,  $\text{kg CH}_4/\text{ha}/\text{yr}$  (Table 4);  $R_d$  is a constant equal to the ratio of total downstream emission of  $\text{CH}_4$  to the total flux of  $\text{CH}_4$  from the reservoir surface, (median value of  $R_d$  is 0.09);  $\alpha$  is the emission factor adjustment for the trophic state in the reservoir (it can be estimated from the trophic index (TI), total phosphorus (TP), total nitrogen (TN) and Secchi depth (SD), and mean annual chlorophyll-a concentration in the reservoir (Chl-a)) (Table 5).

**Table 4.**  $\text{CH}_4$  Emission factors  $\text{EF}_{\text{CH}_4}$  age > 20 [36].

Climate Zone	Average Values (kg $\text{CH}_4/\text{ha}/\text{yr}$ )
Cool temperate	54.00
Warm temperate/dry	150.90
Warm temperate/moist	80.30

**Table 5.** Relationship between TI, Chl-a, TP, TN, SD, trophic class and trophic state adjustment factor [36].

TI	Chl-a ( $\mu\text{g}/\text{L}$ )	TP ( $\mu\text{g}/\text{L}$ )	TN ( $\mu\text{g}/\text{L}$ )	SD (m)	Trophic Class	Trophic State Adjustment Factor, $\alpha$ Range and Recommended Values
<30–40	0–2.6	0–12	<350	>4	Oligotrophic	0.7 (0.7)
40–50	2.6–20	12–24	–350–650	2–4	Mesotrophic	0.7–5.3 (3)
50–70	20–56	24–96	650–1200	0.5–2	Eutrophic	5.3–14.5 (10)
70–100+	56–>155	96–>384	>1200	<0.5	Hypereutrophic	14.5–39.4 (25)

Paper [36] also recommends the use of the greenhouse gas reservoir (G-res) model as “currently the only easily and widely applicable model” that uses empirical relationships between environmental drivers and emissions to estimate reservoir GHG fluxes. The International Hydropower Association (IHA) in cooperation with the UNESCO Chair in Global Environmental Change has developed a detailed measurement guide for net GHG assessment [37] and the powerful and user-friendly G-res tool to assess GHG emissions [21]. Scientists from the University of Quebec at Montreal (UQAM), the Norwegian Foundation for Scientific and Industrial Research (SINTEF) and the Natural Resources Institute of Finland (LUKE) have also contributed to the development of the G-res tool [22]. The free online G-res tool (<https://g-res.hydropower.org/> accessed on 5 May 2021) estimates the GHG emissions resulting from the impoundment of an existing or planned reservoir and emissions related to human activities and infrastructure. The modeling of GHG emissions (diffusive  $\text{CO}_2$  flux, diffusive  $\text{CH}_4$  flux, bubbling of  $\text{CH}_4$  and  $\text{CH}_4$  degassing) is based on the statistical analysis of gross emissions from 223 reservoirs in all climatic zones considering the following key governing variables: temperature, reservoir age, littoral area, solar radiance, phosphorous concentration in the reservoirs, soil carbon content, operating regime of reservoir, climate zone, land cover, reservoir area and soil type. The user of the G-res tool should prepare the input data before accessing the tool. The estimated net annual GHG emissions from a hydropower reservoir result from subtracting the pre-impoundment emissions and emissions from the reservoir due to unrelated anthropogenic sources (activities within the catchment as sources of nutrients and carbon flowing into the reservoir) from the post-impoundment emissions. The total annual GHG emissions are calculated by adding to the net annual emissions the emissions related to reservoir construction.

### 3. Case Study: The Stâncă-Costești Multipurpose Reservoir

The Stâncă-Costești (Figure 1) multipurpose reservoir is located on the middle course of the Prut River, on the border between Romania and the Republic of Moldova. It was built between 1973 and 1978. It has an area of 6000 ha at normal retention level (NRL) and a maximum volume of 1400 million m<sup>3</sup>. In the Romanian Register of Large Dams, the Stâncă-Costești reservoir appears on the 49th place in order of height and on the second place, according to the useful volume of the reservoir (1290 million m<sup>3</sup>, after the Iron Gates I with 2100 million m<sup>3</sup>). The length of the reservoir, at normal retention level (NRL 90.80 m), is 70 km, and the length at maximum level (Nmax 99.50 m) is 90 km. The surface of the reservoir at normal retention level (NRL), is of 6000 ha and at maximum level (Nmax) is of 9200 ha. The reservoir has a reserve provided for flood control of 550 million cubic meters, which ensures the removal from flood risk of 100,000 ha of agricultural land, irrigation of 140,000 ha (70,000 on each shore), ensuring the necessary flows for water supply downstream (10–16 m<sup>3</sup>/s) and energy production with the help of two power plants with a hydro unit of 15 MW, at a flow rate of  $2 \times 65$  m<sup>3</sup>/s with an average annual energy supply of  $2 \times 65$  GWh [40,41].

To build the reservoir, eight villages were relocated on both banks of the Prut River. The surface of the river basin of the Prut River in the Stâncă-Costești section is about 12,000 km<sup>2</sup>, and the average multiannual flow is 81 m<sup>3</sup>/s.

The dam, made of concrete and local materials, uses the favorable morphological situation due to the presence of calcareous reefs, which reduce the average width of the major riverbed from 3–4 km to 400 m.

The GHG emission from the multipurpose reservoir Stâncă –Costești is estimated by using the above mentioned modeling methodologies and the powerful web-based tool G-res. The input data required by the G-res tool are given in Table 6, and the input data for the other models are the following: dissolved organic carbon concentration in reservoir water (DOC = 6.5 mg/L), maximum temperature ( $T_{\max} = 30$  °C); ice-free period (IFP = 319 days/yr); mean annual chlorophyll-a concentration in reservoir (Chl-a = 10 mg/L) [41] organic carbon in soil and vegetation ( $C_0 = 50$  tonne C/ha) [42]; erosion rate ( $Er = 0.5$  t/ha/yr) [43]; and concentration of total phosphorous in reservoir water (TP = 0.97 µmol/L).

To determine the average water volume of the Stâncă-Costești reservoir, the daily records made by the “Romanian Waters” National Administration (“Prut-Bârlad” Water Basin Administration) in the period 2002–2018 were used.

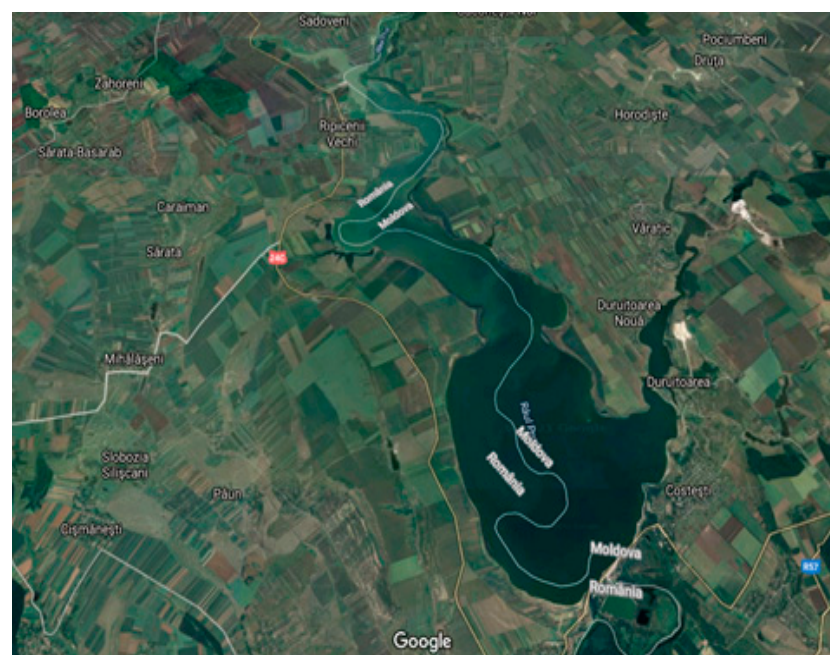
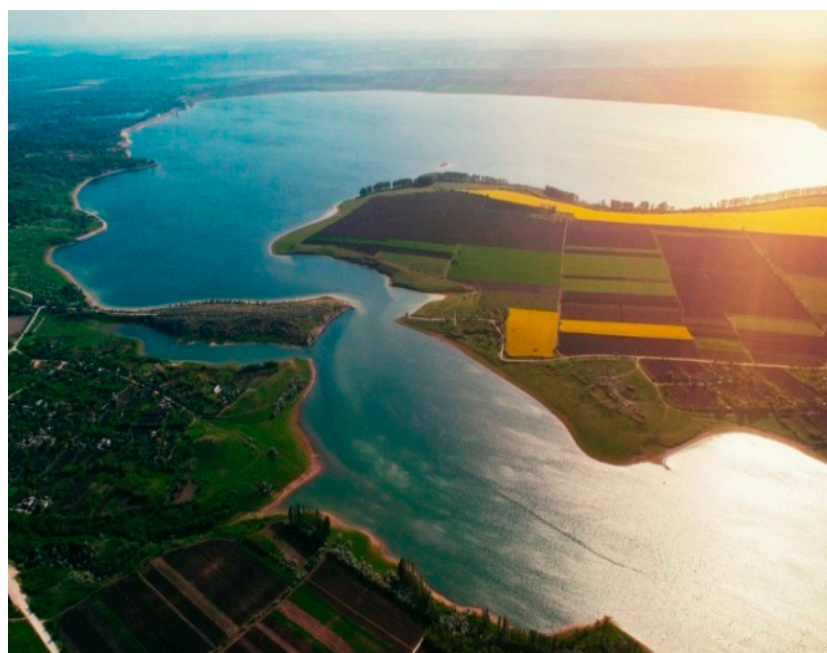


Figure 1. Cont.



**Figure 1.** Stânca-Costești multipurpose reservoir. Reprinted with permission from ref. [44]. Copyright 2021 [www.planiada.ro](http://www.planiada.ro) (accessed on 15 January 2021).

**Table 6.** Data on the multipurpose reservoir Stânca-Costești [45].

Catchment Information		Value	
Catchment area		12,000 km <sup>2</sup>	
Population in the catchment		150,000	
Precipitation		380 mm/yr	
Catchment annual runoff		10 m <sup>3</sup> /s [46]	
Community wastewater treatment		None	
Industrial wastewater treatment		None	
Land cover in the catchment area		Post-impoundment	Pre-impoundment
Croplands		64%	64%
Grassland		18%	19%
Forest		16%	16%
Water bodies		2%	1%
Reservoir Information			
Country		Romania	
Longitude of dam		27°14'00" E	
Latitude of dam		47°51'30" N	
Climate zone		Temperate	
Water uses		flood control, water supply (10 m <sup>3</sup> /s), irrigation (0.8 km <sup>3</sup> /yr), hydroenergy, aquaculture (2.9 m <sup>3</sup> /s)	
Impoundment year		1978	
Power generation		30 MW	
Power connection		110 V	
Yearly electricity generation		130 GWh	
Reservoir area		59 km <sup>2</sup>	
Reservoir volume (multiannual average)		1.4 km <sup>3</sup>	
Water Level (m above sea level)		126 m	
Maximum depth		32 m	
Mean depth		23.33 m (Calculated by the G-res Tool)	
Littoral area		3.59% (Calculated by the G-res Tool)	
Water intake depth		28 m	
Soil carbon content under impounded area		0.8 kg C/m <sup>2</sup>	
Annual wind speed at 10 m		6.6 m/s	
Water residence time		11.68 yr (Calculated by the G-res Tool)	
Annual discharge from the reservoir		3.8 m <sup>3</sup> /s (Calculated by the G-res Tool)	
River Length before Impoundment (m)		70,000 m	
Reservoir mean global horizontal radiance		3.24 kWh/m <sup>2</sup> /d	
Mean annual air temperature		13.3 °C	



Table 6. Cont.

Catchment Information	Value
Construction information	
Material excavated and/or used for construction	500,000 m <sup>3</sup>
All concrete brought to site for the dam, tunnels, foundations	4,000,000 m <sup>3</sup>
All steel brought to site for reinforcement, pipelines, mechanical and electrical equipment	5000 tonne

#### 4. Results and Discussions

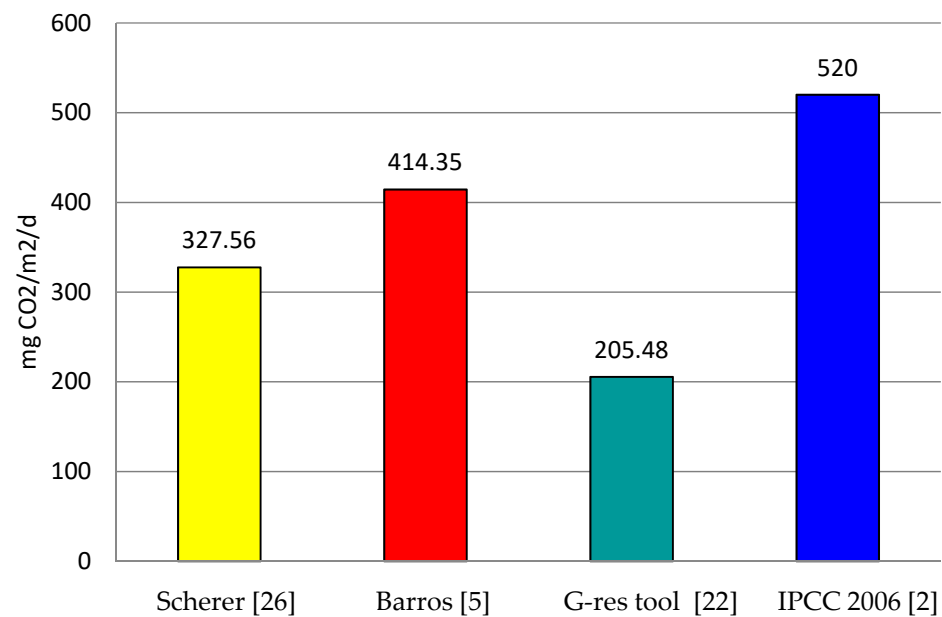
Using the models presented above and the G-res tool to evaluate the GHG emissions from the Stâncă-Costești multipurpose reservoir, we obtained the results given in Table 7.

Table 7. Comparison of different approaches to estimate reservoir emissions.

Model	Emissions								
	CO <sub>2</sub>			CH <sub>4</sub>			CO <sub>2eq</sub> (GWP <sub>100</sub> for CH <sub>4</sub> = 34)		
	mg/m <sup>2</sup> /d	kg/MWh	tonne/yr	mg/m <sup>2</sup> /d	kg/MWh	tonne/yr	mg/m <sup>2</sup> /d	kg/MWh	tonne/yr
Scherer 2016 [26]	327.56	155.88	-	28.57	5.93	-	1298.94	210.72	27,972.67
Barros 2011 [5]	414.35	-	-	1.15	-	-	453.65	73.59	9769.44
IPCC 2006 [2]	520	-	10,124.4	-	-	-	520	77.88	10,124.4
IPCC 2019 [36]	-	-	-	13.11	-	287.10	445.73	72.31	9761.40
Total	520	-	10,124.4	13.11	-	287.10	965.73	150.19	19,885.80
Bastviken 2004 [6]	Bubbling	-	-	-	2.46	-	53.88	83.65	1831.91
	Diffusion	-	-	-	1.27	-	27.82	7.01	945.86
	Storage	-	-	-	0.18	-	3.93	0.99	133.51
	Total	-	-	-	3.91	-	85.63	132.93	2911.27
Vilela 2017 [38]	-	-	1141.04	19.27	-	422.03	3497.3	567.34	15,490.06
Bergier 2007 [39]	OMCM	-	-	-	39.24	-	859.321	1334.11	29,216.91
	DEM	-	-	-	18.25	-	399.72	100.67	13,590.48
G-res tool [22]	Post-impoundment	205.48	-	4425.00	2.98	-	64.21	50.83	6608.00
	Pre-impoundment	216.44	-	4661.00	3.06	-	65.94	53.10	6903.00
	Unrelated Anthropogenic Source (UAS)	0.00	-	0.00	2.98	-	64.21	16.79	2183.00
	Net reservoir emission	-10.96	0.00	-236.00	-3.06	0.00	-65.94	-115.07	-2478.00

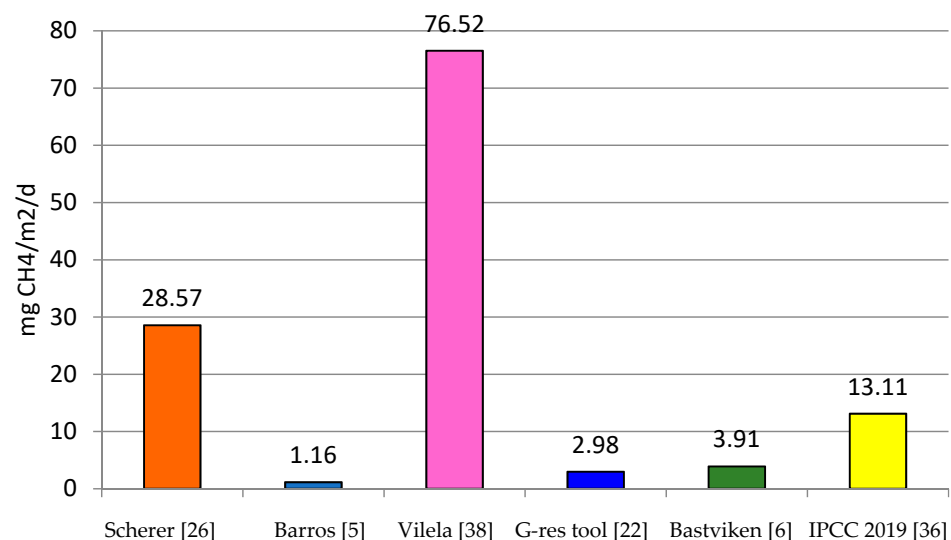
There are only three models (Scherer; Barros, Villela) and the G-res tool that calculates both CO<sub>2</sub> and CH<sub>4</sub> emissions. The only model that calculates the net GHG emission (post-impoundment emission minus pre-impoundment emission minus emissions from unrelated anthropogenic sources) is the G-res tool. It is also the only model that allows estimating GHG emissions related to reservoir construction, and which calculates the emissions related to each use of the reservoir (in the case of multipurpose reservoirs).

Regarding the CO<sub>2</sub> emission, the IPCC 2006 model (based on measured emissions) gave the largest emission (520 mg CO<sub>2</sub>/m<sup>2</sup>/d), followed by the Barros model (which takes into account the reservoir age and dissolved organic carbon (414.35 mg CO<sub>2</sub>/m<sup>2</sup>/d)), the Scherer model (which takes into account the reservoir age and erosion rate (327.56 mg CO<sub>2</sub>/m<sup>2</sup>/d)), and the G-res tool (which gave the lowest emission (205.48 mg CO<sub>2</sub>/m<sup>2</sup>/d)) (post-impoundment) (Figure 2).



**Figure 2.** Estimated CO<sub>2</sub> emission from the Stâncă-Costești multipurpose reservoir.

The values obtained for methane emission can be divided into two groups: a group of high values and a group of low values. The first group includes the Vilela plus Bergier model with 76.52 mg CH<sub>4</sub>/m<sup>2</sup>/d, the Scherer model with 28.57 mg CH<sub>4</sub>/m<sup>2</sup>/d and the IPCC 2019 model with 13.11 mg CH<sub>4</sub>/m<sup>2</sup>/d. The second group includes the Bastviken model with 3.91 mg CH<sub>4</sub>/m<sup>2</sup>/d, the G-res tool with 2.42 mg CH<sub>4</sub>/m<sup>2</sup>/d (post-impoundment) and the Barros model with 1.16 mg CH<sub>4</sub>/m<sup>2</sup>/d (Figure 3).



**Figure 3.** Estimated CH<sub>4</sub> emission from the Stâncă-Costești multipurpose reservoir.

The G-res tool indicates that the reservoir has a negative net GHG emission of  $-819$  mg CO<sub>2eq</sub>/m<sup>2</sup>/d, which means that the reservoir is a carbon sink, with a lower emission after impoundment ( $403$  mg CO<sub>2eq</sub>/m<sup>2</sup>/d) than before impoundment ( $1222$  mg CO<sub>2eq</sub>/m<sup>2</sup>/d).

Among the models that calculate the annual global GHG emission, the G-res tool gave the lowest emission ( $6608$  tonne CO<sub>2eq</sub>/yr) (post-impoundment), followed by the Barros model with  $9769.44$  tonne CO<sub>2eq</sub>/yr and the Scherer model with the highest emission of  $27,972.67$  tonne CO<sub>2eq</sub>/yr, more than four times higher than the lowest emission.

The calculation of GHG emission from a multipurpose reservoir as function of energy produced (expressed in kg CO<sub>2eq</sub>/MWh) is not conclusive, as energy generation is one of

multiple uses. For the studied multipurpose reservoir, given the reduced installed capacity of only 30 MW (and therefore the reduced amount of energy produced, 130 GWh/yr) the calculated amount of GHG emitted per unit of energy produced resulted in being two times higher than the IHA estimated emission of hydropower [47] (50.83 kg CO<sub>2eq</sub>/MWh versus of 23 kg CO<sub>2eq</sub>/MWh).

The G-res tool solves this shortcoming because it compares the GHG emissions obtained by using it with the emissions of reservoirs of the same type from the same climate zone.

The net reservoir footprint of  $-9 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  is placed at the base of the Gaussian distribution, which ranges from  $-90$  to  $+1960 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  and has a peak near  $+210 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$ . CH<sub>4</sub> diffusive emissions of  $+43 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  is very close to the value that gives the peak of the Gaussian distribution ( $+40 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$ ). CH<sub>4</sub> bubbling emissions of  $+3 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  is very close to the value that gives the peak of the Gaussian distribution ( $0 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$ ). CO<sub>2</sub> diffusive emissions of  $+75 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$  are very close to the value that gives the peak of the Gaussian distribution ( $+90 \text{ g CO}_{2\text{eq}}/\text{m}^2/\text{yr}$ ). CH<sub>4</sub> degassing emissions could not be calculated because the reservoir has a deep water intake. However, its contribution to the overall GHG footprint is relatively small (mean: 14%, median: 4%) [23]. The allocated GHG emissions intensity of  $4.1 \text{ g CO}_{2\text{eq}}/\text{kWh}$  is very close to the value that gives the peak of the Gaussian distribution ( $0 \text{ g CO}_{2\text{eq}}/\text{kWh}$ ). The CH<sub>4</sub> post-impoundment emissions have the following distribution: 93% CH<sub>4</sub> diffusive emissions and 7% CH<sub>4</sub> bubbling emissions. The contribution of each use of the reservoir is as follows: 26.7% flood control; 5% fisheries; 15% irrigation; 26.7% water supply; and 26.7% hydroelectricity.

Of course, for a preliminary and rapid estimate of GHG emissions from a reservoir, simple models can be used that require only a few reservoir-specific factors. For a more accurate assessment, it is necessary to use a more complex and complete model, such as the G-res tool. The G-res tool offers the possibility to find out the potential impact that the creation of a reservoir can have and also to find out if measures are needed to reduce GHG emissions from a certain reservoir (regardless of the reservoir purpose), or to find out that the emissions of a reservoir may be the result of human activity that is not related to the reservoir creation. When the necessary time and tools are available, it is most desirable to perform long-term measurements to report the actual values of emissions from all sources related to reservoirs (drawdown area, reservoir surface, turbines, spillway and downstream river).

Taking into account the lifecycle GHG emission intensity from Table 8, if the energy produced by the Stâncă-Costesti reservoir is produced by a coal-fired power plant, additional GHG emissions of 103,610 tonnes CO<sub>2eq</sub>/yr would be generated, and if it was produced by a natural gas-fired power plant, additional GHG emissions of 60,710 tonnes CO<sub>2eq</sub>/yr would be generated.

**Table 8.** Lifecycle GHG emissions for different electricity generation technologies [47].

Technology	Lifecycle GHG Emission Intensity kg CO <sub>2eq</sub> /MWh
Thermal-coal	820
Thermal-natural gas	490
Biomass	230
Solar-PV	48
Hydropower	23
Nuclear	12
Wind	12

## 5. Conclusions

Built to meet human needs, multipurpose reservoirs increase human well-being, but they cause changes in the water quality, ecosystem and flow regime of river networks. They are considered neutral in terms of GHG emissions, but they may become considerable sources of GHG depending, especially, on the climatic zone in which they are located and their uses. The

creation of a water reservoir on a river leads to the generation of GHG, due to biogeochemical processes in the reservoir. The calculation of GHG emissions of the studied reservoir, which is placed in a temperate zone and has multiple uses of water, shows that they are lower than those of a lake (306.85 g CO<sub>2eq</sub>/m<sup>2</sup>/yr versus 953.73 g CO<sub>2eq</sub>/m<sup>2</sup>/yr).

Knowing the GHG emissions from the reservoir is useful to accurately report the greenhouse gas (GHG) emissions. To calculate the CO<sub>2</sub> emission, four models were used; to calculate the CH<sub>4</sub> emission, six models were used. If the difference between the highest (520 mg CO<sub>2</sub>/m<sup>2</sup>/d) and the lowest CO<sub>2</sub> emission value (205.48 mg CO<sub>2</sub>/m<sup>2</sup>/d) is more than two-fold, the difference between the highest CH<sub>4</sub> emission (76.52 mg CH<sub>4</sub>/m<sup>2</sup>/d) and the lowest emission value (1.16 mg CH<sub>4</sub>/m<sup>2</sup>/d) is much larger, by about 65 times.

Because not all the methodologies reviewed make an overall assessment of GHG emissions and because some are used only for hydropower reservoirs—except the G-res tool, which estimates the GHG emissions from the reservoir surface, drawdown, turbines and spillway—it is difficult to compare the results obtained by applying the methodologies to the multipurpose reservoir, Stâncă-Costești.

In the absence of a standardized methodology for calculating GHG emissions from the reservoirs, the reviewed models can be used in correlation with the available data on reservoirs.

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