Water and carbon footprints for Vidraru hydropower development, Romania

Gabriela-Elena Dumitran[1], *Liana-Ioana* Vuta[1*], *Angela* Neagoe[1], *Eliza-Isabela* Tica[1]
Bogdan Popa[1], and *Ivaylo* Stoyanov[2]

[1]NUST POLITEHNICA Bucharest, Hydraulics, Hydraulic Machinery and Environmental Engineering Department, Bucharest, 060041, Romania
[2]University of Ruse, Department of Electrical Power Engineering, Ruse, 7017, Bulgaria

Abstract. Although the important positive effects that lakes have on development at the regional level and beyond, they also have a negative impact related to the large amounts of water that they can consume by evaporation. This paper quantifies the effects that one of the largest artificial lakes in Romania (with complex use) has on the environment by estimating the blue water footprint and the carbon footprint. Thus, an analysis is made of the evolution of the blue water footprint and carbon intensity (calculated for a 100-year life cycle) for 16 years and Pearson correlation coefficients for these indicators are investigated. During the 2008-2023 study period, the mean water footprint for the Vidraru hydropower plant was 5.07 m^3/GJ and the carbon intensity varies between 7.1 to 5.24 gCO_2/kWh, with a polynomial trend. Those results are in good agreement compared with the literature presenting results related to large reservoirs.

1 Introduction

By 2020, hydraulic energy has generated one-sixth of the world's electricity (4500 TWh), more than all other renewable energy sources combined [1]. Hydropower is a clean and sustainable energy source, that addresses humanity's expanding energy needs while minimizing global warming trends [2]. On the other hand, the environmental impact of hydropower projects, especially large-scale projects, cannot be neglected. Thus, we can recall the social effects, such as the problems related to the migration of the population but also to the occupation of land, and the most sensitive problem of the transformation of water courses into stagnant ecosystems with repercussions on the water quality but also the interruption of longitudinal and lateral connectivity [3, 4.]. Furthermore, due to the water evaporating from their surface, the reservoirs are more than just in-stream water users. Still, they can also be considered large water consumers which adds to the pressure on water resources on the regional scale [5].

A reservoir is typically used for various purposes, including hydroelectricity generation, water supply for residential and industrial use, irrigation water supply, river flow regulation

---

* Corresponding author: l_vuta@yahoo.com

to prevent flooding, inland navigation, and recreational and fishing. Many studies on the environmental impact of hydropower developments fail to account for evaporation, ignoring one of the most critical balance terms of water for energy.

The whole life cycle water footprint of hydropower plants (HPPs) consists of evaporation (greater than 99 %), construction stage, and operation stage [6]. This study only considers the water footprints of evaporation. Following a study of 1500 lakes worldwide, Scherer et al. in 2016 appreciate that about half of the study HPPs have negative water scarcity footprints (considering the monthly water stress and storage changes), which implies that they alleviate rather than worsen water scarcity. The hydro-energy causes impacts in terms of water scarcity on a global level, with a global production-weighted water scarcity footprint per unit of generated electricity between 8 to 11 m^3 H_2O_e/GJ, which means that the benefits are generally higher for smaller than for larger HPPs [7].

On the other hand, a lifecycle assessment of large hydropower developments must take into account three major sources of greenhouse gas (GHG) emissions: dam building and associated development components and decaying biomass from the water-covered land [8]. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and carbon tetrafluoride (CF_4) were the most commonly studied greenhouse gases [9]. Using regionally resolved evaluations of GHG fluxes and hydroelectric capacity datasets, M. Li and N. He estimated in 2022 that global GHG emissions from reservoirs are 0.38 10^{15} g CO_{2e}/year, accounting for 1% of total anthropogenic emissions. Hydropower has a median carbon intensity of around 63 kg CO_{2e}/MWh, which is lower than that of fossil fuels but higher than other renewable energy sources. High carbon intensity is typically associated with shallow (water storage depth <20 m) and eutrophic reservoirs. Furthermore, they discovered that the reservoir carbon intensity (CI) value would be significantly enhanced to 131.5 kg CO_{2e}/MWh when including the dams now under construction and planning [10]. To assess the impact of hydropower generation on GHG emissions are commonly used the carbon intensity or carbon footprint for reservoirs, which depends on net primary production, reservoir age, and the reservoir area. The average carbon intensity of CO_2 and CH_4 emissions from global reservoirs has been estimated to be 85 kg CO_2/MWh and 3 kg CH_4/MWh respectively [11].

This study aims to estimate the blue water footprint and carbon footprint of the Vidraru hydropower development, Romania, which is the fifth largest hydropower plant in Romania taking into account energy generation and the second anthropic storage considering the surface. Vidraru's development comes into the "A" category of extraordinary importance for Romania.

2 Materials and methods

2.1 Case study description

Vidraru hydropower development (HPD) is located in Arges County, central Romania, and was created in the 1950s and put into operation in 1965. Vidraru HPD uses Arges River's hydropower potential across a 28-kilometer length with a total head of 524 m, and its components include a large reservoir, a concrete double arch dam, a derivation, an underground hydropower plant (HPP), and a tailrace gallery. To generate significant energy, the water of a 745 km^2 river basin is captured. Vidraru HPP is located on the right bank of the Arges River in a cave 104 m below the river's level and has an installed capacity of 220 MW. The average flow collected to ensure the HPP's operation is 19.7 m^3/s.

The power station is equipped with four Francis turbines and produces an average energy of 400 GWh per year.

Characteristics related to the position, levels, and volumes of the Vidraru reservoir and characteristics related to Vidraru HPD are presented in Table 1.

Table 1. Characteristics of Vidraru HPD.

Parameter	**Value**	**Parameter**	**Value**
Longitude	45.22 DD	Total reservoir volume	496.93 m^3
Latitude	24.37 DD	Regulated storage capacity	462.20 m^3
Catchment area	745 km^2	Net head	280 m
Normal operating level	830 MASL	Installed flow	90 m^3/s
Maximum dam height	167 m	Installed capacity	220 MW
Top length of the dam	307 m	Mean annual generation	400 GWh/year

2.2 Methodologies for calculating water and carbon footprints

A reservoir's water footprint (WF) for electricity generated is calculated by dividing its evaporation rate at the reservoir's surface [mm^3/year] by annual energy production (GJ/year) [12]. Hogeboom et al. in 2018, proposed the determination of the WF related to evaporation from the reservoir surface (WF_{evap}) using the gross consumption approach [13], with the:

$$WF_{evap} = 10\,E\,A, \tag{1}$$

where E [mm/year] is the annual water evaporation from the reservoir surface, A [ha] is the maximum free surface reservoir area.

GHG can be released from hydropower reservoirs in a variety of ways, including ebullition, diffusion, plant-mediated emission, degassing from hydroelectric turbines and spillways, and emissions from downstream reaches [14,15]. While CO_2 and N_2O are usually released through diffusive emissions, CH_4 may also be released through ebullitive and diffusive emissions [16]. Where on-site measurements of GHG emissions of hydropower are not available, the G-res tool could be used to assess the potential environmental impact of this development, considering only the GHG emissions that are attributable to the tank being placed in a catchment. The G-res is a special instrument that uses factors and data that environmental specialists and project developers should already be aware of, rather than requiring measurements to be taken on-site. The following factors are explicitly taken into account by the G-res tool: the landscape's pre-impoundment GHG footprint, each reservoir's unique environmental setting, the temporal evolution of GHG emissions over the reservoir's lifetime, and the displaced GHG emissions that would have occurred elsewhere in the aquatic network regardless of the reservoir's presence [17]. Therefore, G-res software calculates the net carbon footprint by combining emissions from four stages of the hydropower station's lifespan using the following equation:

$$NCF = -PostImp_{CB} + PreImp_{CB} - Emission_{UAS} + GHG_{cons}\,, \tag{2}$$

where *NCF* represents the net carbon footprint, $PostImp_{CB}$ – the post-impoundment carbon balance of the reservoir, $PreImp_{CB}$ – the pre-impoundment carbon balance of the reservoir area before reservoir creation, $Emission_{UAS}$ – the emissions from the reservoir due to unrelated anthropogenic sources, and GHG_{cons} is GHG due to construction.

In 2023, a comprehensive study was carried out by the authors of this study to determine the carbon footprint of Vidraru HPD, the work being based on the use of G-res software [8]. The study showed that Vidraru HPD has a total carbon footprint of 120.884 tCO_{2e}, which includes 336.249 tCO_{2e} before the impoundment, 133.222 tCO_{2e} after the impoundment, 26.348 tCO_{2e} from unrelated human sources, and 350.294 tCO_{2e} during construction. More than that, the carbon intensity progression was calculated based on a 100-year lifespan, and it has an average value of around 3.02 gCO_2/kWh.

3 Results

3.1 Temporal variation of total WF and CF for Vidraru hydropower plants

According to the meteorological and hydropower data, the evaporation for the Vidraru reservoir for the study period averaged 788 mm/year, with the highest average monthly evaporation in July 2012, 148.53 mm, and the lowest one in December 2009, 11.5 mm. The mean energy for the 2008–2023 period was 402 GWh/year, with the highest average monthly energy in June 2021, 95.76 GWh, and the lowest in November 2019, 0.14 GWh (Figure 1). In Figure 1, the month number 1 represents the month January of the year 2008 - the start date of the study period, while the month with the number 192 represents December of 2023.

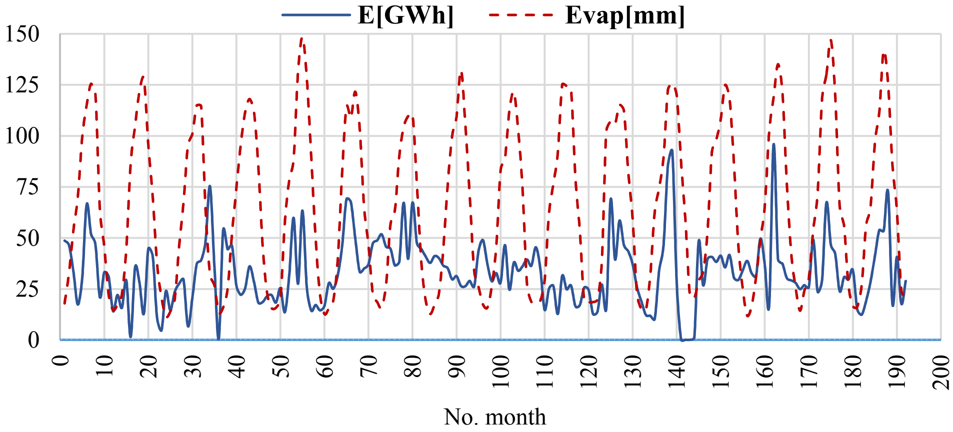

Fig. 1. Monthly values of evaporation and energy generation for Vidraru HPP in period 2008-2023.

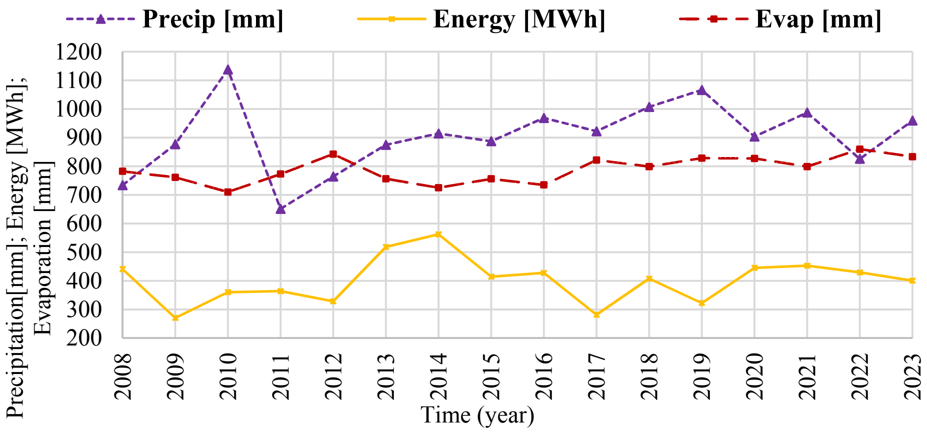

Fig. 2. Yearly values of energy, precipitation, evaporation, CI and WF for Vidraru HPP for 2008-2023.

Based on the values of the energies delivered in the system by Vidraru HPP and the weather variables in the area of Vidraru reservoir, available on https://open-meteo.com/ (Figure 2), it was determined WF for the 16 years analyzed. Thus, it is observed that the average value of the WF is 5.07 m^3/GJ with a variation between 3.62 m^3/GJ and 7.23 m^3/GJ (Figure 3).

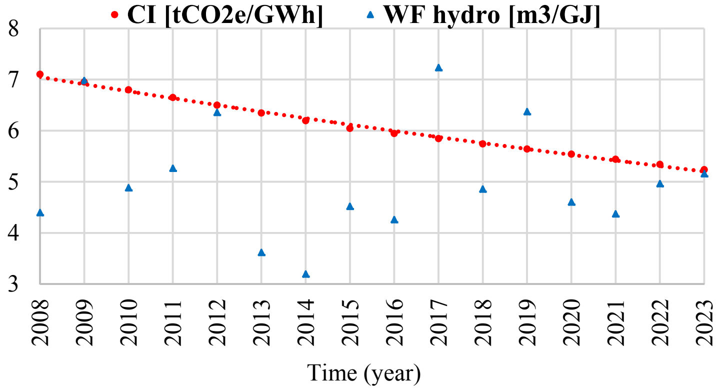

Fig. 3. CI and WF for Vidraru HPP.

The analysis of precipitation values in the 16 years (2008-2023) allowed us to classify them into three categories, as follows: dry years (2008, 2011 and 2012), normal years (2009, 2013 to 2017, 2020, 2022 and 2023) and rainy years (2010, 2018, 2019 and 2021). Pearson's correlation analysis of determined parameters was conducted to determine how the CI and WF indicators were correlated with the energy and meteorological data for Vidraru HPD. Pearson's correlation analysis revealed a strong relationship between WF and CI indicators and energy generated from Vidraru HPP (Table 2). The correlation between WF and energy was the best, with values of Pearson coefficients $r = 0.88 \div 0.97$. For the correlation between CI and energy, we obtained a correlation coefficient $r = 0.11 \div 0.99$, with maximum values for the dry years. CI is the best correlated with evaporation with values for the Pearson coefficient in the domain $r = 0.6 \div 0.93$, with the strongest correlation for wet years.

Table 2. Values for Pearson coefficient for Vidraru HPP.

Correlation between	**Values for Pearson coefficient**			
	Total	**Dry year**	**Normal year**	**Wet year**
CI – WP	0.11	0.94	0.13	0.1
CI - Precipitation	0.53	0.02	0.17	0.89
WF - Precipitation	0.18	0.32	0.04	0.33
CI - Evaporation	0.83	0.60	0.73	0.93
WF - Evaporation	0.42	0.83	0.41	0.44
CI - Energy	0.26	0.99	0.41	0.11
WF - Energy	0.93	0.96	0.97	0.88

[*] red – very strong, bleu – strong, yellow – moderate, orange – weak, red – very weak

3.2 Analysis of impact factors of WF and CI of Vidraru HPP

The Vidraru HPD has a vast reservoir with a large surface area that has high evaporative losses per unit of electricity generated [18]. Analyzing the values obtained for WF it is observed that: for dry years the average value is 5.34 m^3/GJ, for normal hydrological years WF has a mean value of 4.95 m^3/GJ, and for rainy years 5.12 m^3/GJ. On the other hand, it is observed that the WF values are better correlated with the energy produced by the Vidraru HPP than with the evaporation from the lake level (Figures 4÷6).

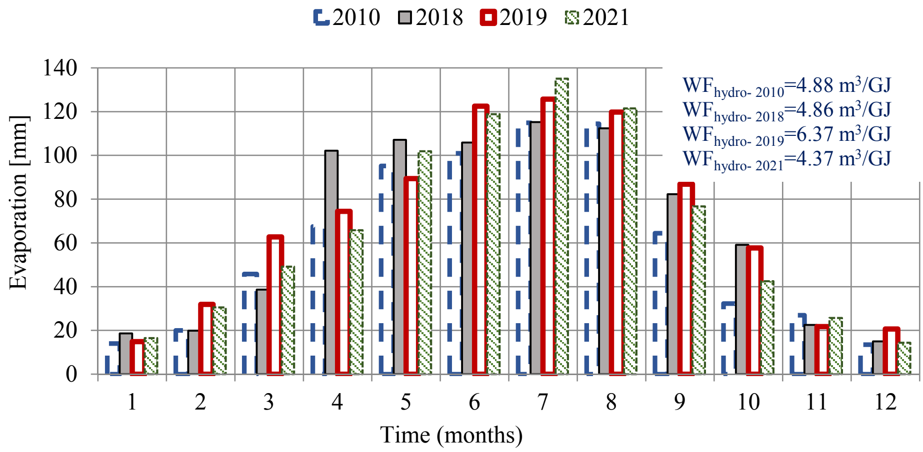

Fig. 4. Monthly evaporation values for Vidraru reservoir for rainy years.

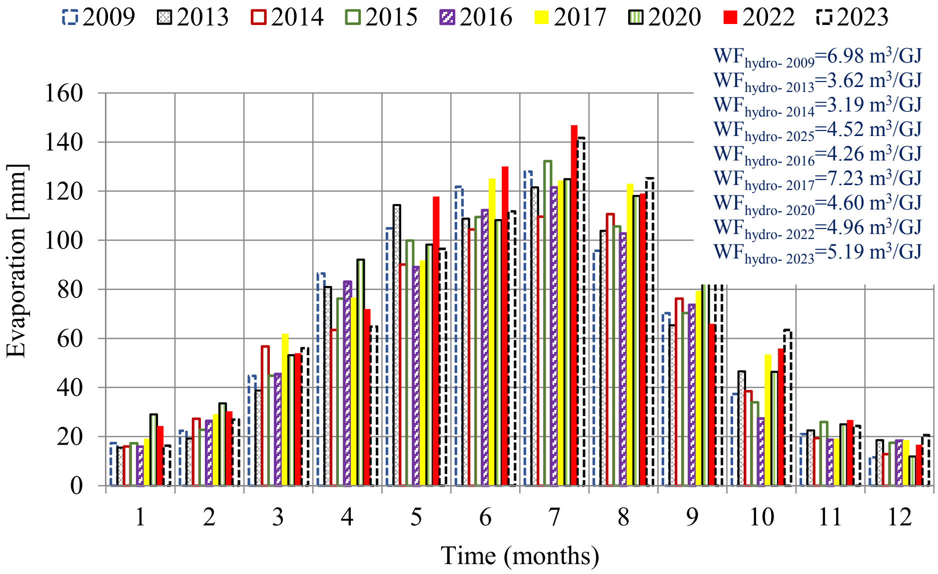

Fig. 5. Monthly evaporation values for Vidraru reservoir for normal years.

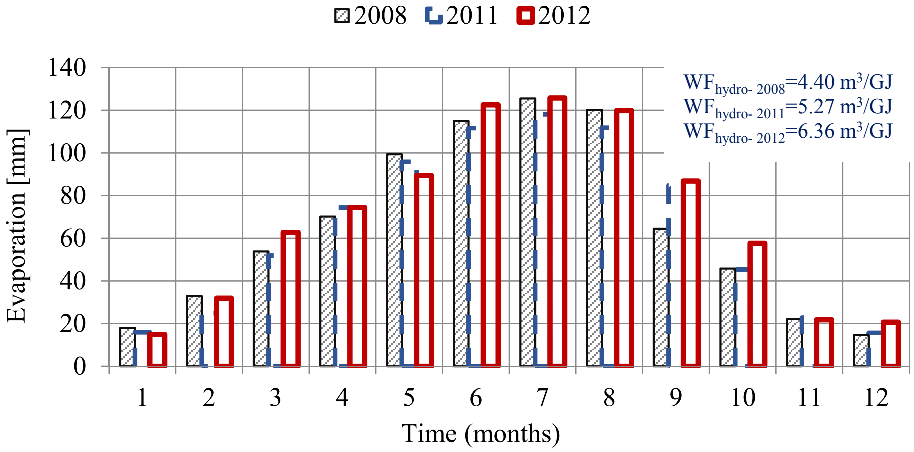

Fig. 6. Monthly evaporation values for Vidraru reservoir for dry years.

4 Conclusion

We found the WF for Vidraru HPP is 5.07 m^3/GJ compared with 14.6 m^3/GJ, the global average WF of hydroelectricity found by Hogeboom in 2018 [13], or 4 m^3/GJ for the same reservoir obtained by Robescu in 2018 [12]. This study's results are similar to those found by other writers. Furthermore in future research regarding WF, we must consider forVidraru reservoir for additional purposes such as flood control, recreation, irrigation, and water supply.

Also, this research used the G-res to calculate the carbon footprint of Romania's Vidraru reservoir. The acquired results, which demonstrate an exponential decrease in GHG intensity from 30 gCO$_{2e}$/kWh for a 10-year lifespan to 3.02 gCO$_{2e}$/kWh for a 100-year lifespan, are consistent with those obtained globally for HPP. In comparison to other traditional power plants that generate electricity, hydropower is the most environmentally friendly alternative.

This work was supported by a grant from the National Program for Research of the National Association of Technical Universities - GNAC ARUT 2023. The authors are greatly appreciative of NARW, which provided the data regarding Vidraru dam and reservoir.

References

1. A. Imburgia, Advantages and disadvantages of hydroelectric power, Advanced Journal of Environmental Science and Technology, **13,** 2, (2022)
2. I. Auestad, Y. Nilsen, K. Rydgren, Environmental Restoration in Hydropower Development—Lessons from Norway. Sustainability**10**, (2018)
3. A. Lindström, A. Ruud, Whose Hydropower? From Conflictual Management into an Era of Reconciling Environmental Concerns; A Retake of Hydropower Governance towards Win-Win Solutions?, Sustainability, **9**, 1262, (2017)
4. S. Pacca, A. Horvath, Greenhouse gas emissions from building and operating electric power plants in the upper Colorado River basin. Env. Sci. Technol. **36**, 3194–3200, (2002)
5. I.A. Shiklomanov, Appraisal and assessment of world water resources. Water Int. **25**, 11–32, (2000)
6. J. Wang, X. Chen, Z. Liu, V.F. Frans, Z. Xu, X. Qiu, et al. Assessing the water and carbon footprint of hydropower stations at a national scale. Sci Total Environ;**676**, 595–612, (2019)
7. L. Scherer, S. Pfister, Global water footprint assessment of hydropower, Renewable Energy **99**, 711e720, (2016)
8. L.I. Vuta, G.E.Dumitran, E.I. Tica, B. Popa, Carbon footprint of Vidraru hydropower development, IOP Conf. Ser.: Earth Environ. Sci. **1136**, 012061, (2023), 10.1088/1755-1315/1136/1/012061
9. M. Li, N. He, Carbon intensity of global existing and future hydropower reservoirs, Renewable and Sustainable Energy Reviews, **162**, 112433, (2022)
10. L.Gagnon, J.F. van de Vate, Greenhouse gas emissions from hydropower, Energy Policy **25,** 1, pp 7–13, (1997) https://doi.org/10.1016/S0301-4215(96)00125-5
11. E.G. Hertwich, Addressing biogenic greenhouse gas emissions from hydropower in LCA. Environ Sci Technol; **47**, 9604–11, (2013) https://doi.org/10.1021/es401820p
12. L.D. Robescu, A.D. Bondrea, The water footprint from hydroelectricity: a case study for a hydropower plant in Romania, E3S Web of Conferences **85**, 06012, (2019)
13. R.J. Hogeboom, L. Knook, A.Y. Hoekstra, The blue water footprint of the world's artificial reservoirs for hydroelectricity, irrigation, residential and industrial water supply, flood protection, fishing and recreation. Adv. Water Resour. **113**, 285–294, (2018) https://doi.org/10.1016/j.advwatres.2018.01.028.
14. C.R. Teodoru, J. Bastien, M. Bonneville, P.A. del Giorgio, M. Demarty, M. Garneau, et al. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem Cycles **26**, (2012)
15. T. DelSontro, J.J. Beaulieu, J.A. Downing. Greenhouse gas emissions from lakes and impoundments: upscaling in the face of global change. Limnol Oceanogr Lett; **3**, 64–75, (2018)

16. L. Scherer, S. Pfister, Hydropower's biogenic carbon footprint. PLoS One, **11**, e0161947, 2016
17. Y.T. Prairie, J. Alm, A. Harby, S. Mercier-Blais, R. Nahas, The GHG Reservoir Tool (G-res) Technical documentation. Updated version 3.0 (2021-10-27). UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association 73 pg. (2017)
18. S. Vaca-Jiménez, P.W. Gerbens-Leenes, S. Nonhebel, The monthly dynamics of blue water footprints and electricity generation of four types of hydropower plants in Ecuador Science of the Total Environment **713**, 136579, (2020)