ATTACHMENT 1: Highly Cited and Critical References

2025

Saunois, Marielle, Adrien Martinez, Benjamin Poulter, et al. **Global Methane Budget 2000–2020**. Preprint, ESSD – Atmosphere/Atmospheric chemistry and physics, June 6, 2024. https://doi.org/10.5194/essd-2024-115.

“New mean estimates of diffusive + ebullition CH4 emissions from reservoirs include 15 and 24 ± 8 (the median and mean ± CI 95 % from Rosentreter et al., 2021), 10 ± 4 (Johnson et al., 2021, mean ± 95 % CI), 10 (Harrison et al., 2021, low and high 95 % CI of 7 and 22 respectively), and 2.1 Tg CH4 yr−1 (Zhuang et al., 2023). We compile the first three estimates to a direct efflux of ∼ 14 Tg CH4 yr−1 (with ± CI 95 % of 9 and 23). We note the fourth estimate as a lower bound but exclude it from this budget given that it was generated via a model that only included data from six reservoir systems (Zhuang et al., 2023). We also add in an additional 12 Tg CH4 yr−1 (low and high 95 % CI of 7 and 37 respectively) that is estimated to degas in dam turbines (Harrison et al., 2021), which was not addressed in the studies by Rosentreter et al. (2021), Zhuang et al. (2023), or Johnson et al. (2021). Rocher-Ros et al. (2023) also excluded river observations below dams when executing their statistical model and so did not capture downstream dam emissions. Thus, we use a direct reservoir emission here of ∼ 13 [6–28] Tg CH4 yr−1 and estimate an additional ∼ 12 [7–37] Tg CH4 yr−1 from dam turbine degassing fluxes, giving a total of 25 [13–65] Tg CH4 yr−1 from reservoirs”

“We argue that all reservoirs should be categorised as a direct anthropogenic source of emissions. Most of the surface area of reservoirs are human-made, and reservoir construction leads to anoxic sediments and/or bottom \ waters with labile organic matter sourced from the watershed and to in situ nutrient augmented phytoplankton production (Deemer et al., 2016; Maavara et al., 2017; Prairie et al., 2018). It is also clear that the cultural eutrophication of natural lakes driven by run-off of agricultural nitrogen fertiliser and manure augments CH4 emissions (DelSontro et al., 2018; Li et al., 2021), with shallow lakes particularly likely to experience eutrophication (Qin et al., 2020). For instance, Beaulieu et al. (2019) modelled a 15 % reduction in lake CH4 with a 25 % reduction in lake phosphorus concentrations. Several recent studies have estimated that anywhere between 30 % and 50 % of lakes are eutrophic (Cael et al., 2022; Qin et al., 2020; Sayers et al., 2015; Wu et al., 2022).”

2024

Amani, Mabano, Biel Obrador, David Fandos, Andrea Butturini, and Daniel Von Schiller. **Exposed Sediments in a Temperate-Climate Reservoir under Dam Decommissioning Contain Large Stocks of Highly Bioreactive Organic Matter**. Limnetica 43, no. 1 (2023): 1. https://doi.org/10.23818/limn.43.11.

"We reported a high content of highly bioreactive sediment OM ("organic matter"), with the respiration efficiency of sediment WEOM ("water-extractable organic matter") being higher than that of bulk sediment OM. Sediment OM in exposed sediments during and after DD ("Dam Decommissioning") is susceptible to erosion and lateral transport downstream of the reservoir. Our results suggest that exposed sediments may be a great source of labile OM in downstream river reaches."

2023

Richardson, Katherine, Will Steffen, Wolfgang Lucht, et al. **Earth beyond Six of Nine Planetary Boundaries.** Science Advances 9, no. 37 (2023): eadh2458. https://doi.org/10.1126/sciadv.adh2458.

"Thus, in contrast to the earlier planetary boundary assessments (1, 2) where only blue water removal was considered, this new approach indicates substantial transgression of the freshwater change boundary. Transgressions of both the blue and green water boundaries occurred a century ago, in 1905 and 1929, respectively (46). Thus, with the revised definition of the control variables, fresh water would have been considered transgressed already at the time of the previous planetary boundary assessments."

"The 350-ppm boundary would lead to a lower level of anthropogenic global warming than the internationally agreed 1.5°C target in the United Nations Paris Climate Agreement but is consistent with recent studies (17, 18, 42) suggesting the possibility of extreme Earth system impacts even at 1.5o warming, with risks increasing already markedly above 1° warming."

Amani, Mabano, Biel Obrador, David Fandos, Andrea Butturini, and Daniel Von Schiller. **Exposed Sediments in a Temperate-Climate Reservoir under Dam Decommissioning Contain Large Stocks of Highly Bioreactive Organic Matter.** Limnetica 43, no. 1 (2023): 1. https://doi.org/10.23818/limn.43.11.

"Our results suggest that exposed sediments can be a source of labile organic matter and high carbon emissions in the river reach downstream of the reservoir after dam decommissioning."

2022

Delwiche, Kyle B., John A. Harrison, Joannes D. Maasakkers, et al. **Estimating Drivers and Pathways for Hydroelectric Reservoir Methane Emissions Using a New Mechanistic Model.** Journal of Geophysical Research: Biogeosciences 127, no. 8 (2022). https://doi.org/10.1029/2022JG006908.

“Turbines are potentially large point sources. For example, 24% of reservoirs have maximum potential downstream emissions higher than anthropogenic super-emitters, defined as sources exceeding 0.3 t CH4/hr by Subramanian et al., 2015 (estimated by averaging output from oligotrophic, mesotrophic, and eutrophic scenarios and assuming reservoirs stratify for a 5-month period).”

Amani, Mabano, Daniel Von Schiller, Isabel Suárez, et al. **The Drawdown Phase of Dam Decommissioning Is a Hot Moment of Gaseous Carbon Emissions from a Temperate Reservoir.** Inland Waters 12, no. 4 (2022): 451–62. https://doi.org/10.1080/20442041.2022.2096977.

“Total ecosystem carbon (CO2 + CH4) fluxes (kg CO2-eq d−1) were higher during and after than before reservoir drawdown because of higher CO2 fluxes from exposed sediment. The reservoir was a net sink of carbon before reservoir drawdown and became an important emitter of carbon during the first 10 months after reservoir drawdown.”

2021

Jervis, D, J McKeever, BOA Durak, et al. **“The GHGSat-D Imaging Spectrometer.”** *ATMOSPHERIC MEASUREMENT TECHNIQUES* 14, no. 3 (2021): 2127–40. WOS:000631085800001. https://doi.org/10.5194/amt-14-2127-2021.

“On 20 April 2017 we observed a methane plume over the dam vanes of the Lom Pangar hydro-electric reservoir (Fig. 5a) in eastern Cameroon that was flooded the previous year. Hydro-electric reservoirs are a known source of methane and carbon dioxide emissions.”

Bertassoli, D. J., Sawakuchi, H. O., de Araújo, K. R., de Camargo, M. G. P., Alem, V. A. T., Pereira, T. S., Krusche, A. V., Bastviken, D., Richey, J. E., & Sawakuchi, A. O. (2021). **How Green can Amazon Hydropower be? Net Carbon Emission from the largest Hydropower Plant in Amazonia**. *Science Advances*, *7*(26). https://doi.org/10.1126/sciadv.abe1470

“The current resurgence of hydropower expansion toward tropical areas has been largely based on run-of-the-river (ROR) dams, which are claimed to have lower environmental impacts due to their smaller reservoirs. The Belo Monte dam was built in Eastern Amazonia and holds the largest installed capacity among ROR power plants worldwide. Here, we show that postdamming greenhouse gas (GHG) emissions in the Belo Monte area are up to three times higher than preimpoundment fluxes and equivalent to about 15 to 55 kg CO2eq MWh−1. Since per-area emissions in Amazonian reservoirs are significantly higher than global averages, reducing flooded areas and prioritizing the power density of hydropower plants seem to effectively reduce their carbon footprints. Nevertheless, total GHG emissions are substantial even from this leading-edge ROR power plant. This argues in favor of avoiding hydropower expansion in Amazonia regardless of the reservoir type."

Harrison, John, Yves T. Prairie, Sara Mercier-Blais, Cynthia Soued. (2021) **Year-2020 Global Distribution and Pathways of Reservoir Methane and Carbon Dioxide Emissions According to the Greenhouse Gas from Reservoirs (G-res) Model.** *Global Biogeochemical Cycles*, doi: 10.1029/2020GB006888

"By damming rivers, humans have created millions of reservoirs, which, collectively, constitute an important greenhouse gas source, especially for methane, a particularly potent greenhouse gas. Using observed relationships between reservoir characteristics and greenhouse gas emissions, we show that much more methane either bubbles out of reservoirs or is emitted just downstream from reservoirs than was previously known. This is important because it may be possible to reduce methane emissions from downstream of reservoirs by selectively withdrawing water from near the surface of reservoirs, which tends to be methane-poor, rather than from greater depths, where methane often accumulates. We also found that on a per-area basis reservoirs are a more potent source of greenhouse gases than previously recognized, and that the highest rates of emissions occur in the tropics and subtropics. Finally, we show that estimates of reservoir greenhouse gas emissions are quite sensitive to climate-related factors like temperature."

Jane, S.F., Hansen, G.J.A., Kraemer, B.M. *et al.* (2021) **Widespread Deoxygenation of Temperate Lakes**. *Nature* 594, 66–70. https://doi.org/10.1038/s41586-021-03550-y

"The concentration of dissolved oxygen in aquatic systems helps to regulate biodiversity, nutrient biogeochemistry, greenhouse gas emissions, and the quality of drinking water. The long-term declines in dissolved oxygen concentrations in coastal and ocean waters have been linked to climate warming and human activity, but little is known about the changes in dissolved oxygen concentrations in lakes. Although the solubility of dissolved oxygen decreases with increasing water temperatures, long-term lake trajectories are difficult to predict. Oxygen losses in warming lakes may be amplified by enhanced decomposition and stronger thermal stratification or oxygen may increase as a result of enhanced primary production. Here we analyse a combined total of 45,148 dissolved oxygen and temperature profiles and calculate trends for 393 temperate lakes that span 1941 to 2017. We find that a decline in dissolved oxygen is widespread in surface and deep-water habitats. The decline in surface waters is primarily associated with reduced solubility under warmer water temperatures, although dissolved oxygen in surface waters increased in a subset of highly productive warming lakes, probably owing to increasing production of phytoplankton. By contrast, the decline in deep waters is associated with stronger thermal stratification and loss of water clarity, but not with changes in gas solubility. Our results suggest that climate change and declining water clarity have altered the physical and chemical environment of lakes. Declines in dissolved oxygen in freshwater are 2.75 to 9.3 times greater than observed in the world's oceans and could threaten essential lake ecosystem services."

Keller, P.S., Marcé, R., Obrador, B. *et al.* **Global carbon budget of reservoirs is overturned by the quantification of drawdown areas**. *Nat. Geosci.* **14**, 402–408 (2021). https://doi.org/10.1038/s41561-021-00734-z

"Reservoir drawdown areas—where sediment is exposed to the atmosphere due to water-level fluctuations—are hotspots for carbon dioxide (CO2) emissions. However, the global extent of drawdown areas is unknown, precluding an accurate assessment of the carbon budget of reservoirs. Here we show, on the basis of satellite observations of 6,794 reservoirs between 1985 and 2015, that 15% of the global reservoir area was dry. Exposure of drawdown areas was most pronounced in reservoirs close to the tropics and shows a complex dependence on climatic (precipitation, temperature) and anthropogenic (water use) drivers. We re-assessed the global carbon emissions from reservoirs by apportioning CO2 and methane emissions to water surfaces and drawdown areas using published areal emission rates. The new estimate assigns 26.2 (15–40) (95% confidence interval) TgCO2-C yr−1 to drawdown areas, and increases current global CO2 emissions from reservoirs by 53% (60.3 (43.2–79.5) TgCO2-C yr−1). Taking into account drawdown areas, the ratio between carbon emissions and carbon burial in sediments is 2.02 (1.04–4.26). This suggests that reservoirs emit more carbon than they bury, challenging the current understanding that reservoirs are net carbon sinks. Thus, consideration of drawdown areas overturns our conception of the role of reservoirs in the carbon cycle."

2020

Beaulieu, Jake J., Sarah Waldo, David A. Balz, et al. **"Methane and Carbon Dioxide Emissions From Reservoirs: Controls and Upscaling."** *Journal of Geophysical Research: Biogeosciences* 125, no. 12 (2020). https://doi.org/10.1029/2019JG005474.

"Estimating carbon dioxide (CO2) and methane (CH4) emission rates from reservoirs is important for regional and national greenhouse gas inventories. A lack of methodologically consistent data sets for many parts of the world, including agriculturally intensive areas of the United States, poses a major challenge to the development of models for predicting emission rates. In this study, we used a systematic approach to measure CO2 and CH4 diffusive and ebullitive emission rates from 32 reservoirs distributed across an agricultural to forested land use gradient in the United States. We found that all reservoirs were a source of CH4 to the atmosphere, with ebullition being the dominant emission pathway in 75% of the systems. Ebullition was a negligible emission pathway for CO2, and 65% of sampled reservoirs were a net CO2 sink. Boosted regression trees (BRTs), a type of machine learning algorithm, identified reservoir morphology and watershed agricultural land use as important predictors of emission rates. We used the BRT to predict CH4 emission rates for reservoirs in the U.S. state of Ohio and estimate they are the fourth largest anthropogenic CH4 source in the state. Our work demonstrates that CH4 emission rates for reservoirs in our study region can be predicted from information in readily available national geodatabases. Expanded sampling campaigns could generate the data needed to train models for upscaling in other U.S. regions or nationally."

Deemer, Bridget R. et al. (2020), Data from: **Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis,** Dryad, Dataset, https://doi.org/10.5061/dryad.d2kv0

"Collectively, reservoirs created by dams are thought to be an important source of greenhouse gases (GHGs) to the atmosphere. So far, efforts to quantify, model, and manage these emissions have been limited by data availability and inconsistencies in methodological approach. Here, we synthesize reservoir CH_4, CO_2, and N_2O emission data with three main objectives: (1) to generate a global estimate of GHG emissions from reservoirs, (2) to identify the best predictors of these emissions, and (3) to consider the effect of methodology on emission estimates. We estimate that GHG emissions from reservoir water surfaces account for 0.8 (0.5–1.2) Pg CO_2 equivalents per year, with the majority of this forcing due to CH_4. We then discuss the potential for several alternative pathways such as dam degassing and downstream emissions to contribute significantly to overall emissions. Although prior studies have linked reservoir GHG emissions to reservoir age and latitude, we find that factors related to reservoir productivity are better predictors of emission."

2019

Almeida, R.M., Shi, Q., Gomes-Selman, J.M. *et al.* (2019) **Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning**. *Nat Commun* 10, 4281. https://doi.org/10.1038/s41467-019-12179-5

"Hundreds of dams have been proposed throughout the Amazon basin, one of the world's largest untapped hydropower frontiers. While hydropower is a potentially clean source of renewable energy, some projects produce high greenhouse gas (GHG) emissions per unit electricity generated (carbon intensity). Here we show how carbon intensities of proposed Amazon upland dams (median = 39 kg CO_2eq MWh^{-1}, 100-year horizon) are often comparable with solar and wind energy, whereas some lowland dams (median = 133 kg CO_2eq MWh^{-1}) may exceed carbon intensities of fossil-fuel power plants. Based on 158 existing and 351 proposed dams, we present a multi-objective optimization framework showing that low-carbon expansion of Amazon hydropower relies on strategic planning, which is generally linked to placing dams in higher elevations and smaller streams. Ultimately, basin-scale dam planning that considers GHG emissions along with social and ecological externalities will be decisive for sustainable energy development where new hydropower is contemplated."

Beaulieu, J.J., DelSontro, T. & Downing, J.A. (2019) **Eutrophication will Increase Methane Emissions from Lakes and Impoundments during the 21st Century.** *Nat Commun* 10, 1375. https://doi.org/10.1038/s41467-019-09100-5

“Lakes and impoundments are an important source of methane (CH_4), a potent greenhouse gas, to the atmosphere. A recent analysis shows aquatic productivity (i.e., eutrophication) is an important driver of CH_4 emissions from lentic waters. Considering that aquatic productivity will increase over the next century due to climate change and a growing human population, a concomitant increase in aquatic CH_4 emissions may occur. We simulate the eutrophication of lentic waters under scenarios of future nutrient loading to inland waters and show that enhanced eutrophication of lakes and impoundments will substantially increase CH_4 emissions from these systems (+30–90%) over the next century. This increased CH_4 emission has an atmospheric impact of 1.7–2.6 Pg C-CO_2-eq y^{-1}, which is equivalent to 18–33% of annual CO_2 emissions from burning fossil fuels. Thus, it is not only important to limit eutrophication to preserve fragile water supplies, but also to avoid acceleration of climate change.”

Hager, PhD, Cecil Green and Ida Green Professor of Earth Sciences Department of Earth, Atmospheric and Planetary Sciences Massachusetts Institute of Technology
Documentation of the Carbon Footprint of Hydro Québec’s Hydropower
https://drive.google.com/file/d/1eq7QMjPx1X-Tzsl7vmtJpmfUJBMPkJ9r/view

“The purpose for building NECEC is to provide a conduit for ~ 10 TWh/yr of electricity to Massachusetts. The premise used to justify NECEC is that this power would result in much less net emission of greenhouse gases than what would be produced from electricity generated using modern natural gas power plants (~ 400 g CO_2/kWh). Yet despite claims that its power is “low-carbon,” Hydro Québec (HQ) has provided no formal documentation of this claim.”

“In this white paper I provide relevant references, as well as giving a road map through these references to finding values of CO_2e emissions of HQ reservoirs. The information in the peer reviewed literature demonstrates that a large fraction of HQ power is not low carbon.”

“A growing number of peer-reviewed articles in the scientific literature address the carbon footprint of hydro reservoirs worldwide. By studying these papers and the on-line supplementary materials accompanying them, I have assembled sufficient information to determine the greenhouse gas emissions of 18 of HQ’s major reservoirs – those that generate in excess of 1 TWh/yr of electricity each. There is a tremendous range in HQ emissions – from 5 g CO_2/kWh (half that produced by wind) to 2265 g CO_2/kWh (twice that produced by coal). About half of HQ generation is comparable in emissions to natural gas. These estimates are given in a table and illustrated in a figure in the final two pages of this document.”

Marcé, R. et al. (2019) **Emissions from Dry Inland Waters are a Blind Spot in the Global Carbon Cycle**. *Earth Sci. Rev*. 188, 240–248.
https://doi.org/10.1016/j.earscirev.2018.11.012

“A large part of the world's inland waters, including streams, rivers, ponds, lakes and reservoirs is subject to occasional, recurrent or even permanent drying. Moreover, the occurrence and intensity of drying events are increasing in many areas of the world because of climate change, water abstraction, and land use alteration. Yet, information on the gaseous carbon (C) fluxes from dry inland waters is scarce, thus precluding a comprehensive assessment of C emissions including all, also intermittently dry, inland waters. Here, we review current knowledge on gaseous C fluxes from lotic (streams and rivers) and lentic (ponds, lakes, and reservoirs) inland waters during dry phases and the response to rewetting, considering controls and sources as well as implications of including 'dry' fluxes for local and global scale estimates. Moreover, knowledge gaps and research needs are discussed. Our conservative estimates indicate that adding emissions from dry inland waters to current global estimates of CO2 emissions from inland waters could result in an increase of 0.22 Pg C year−1, or ~10% of total fluxes. We outline the necessary conceptual understanding to successfully include dry phases in a more complete picture of inland water C emissions and identify potential implications for global C cycle feedbacks."

Ocko, Ilissa B. and Steven P. Hamburg, (2019) **Climate Impacts of Hydropower: Enormous Differences among Facilities and over Time**, *Environmental Science & Technology* 2019 *53* (23), 14070-14082 DOI: 10.1021/acs.est.9b05083
https://www.eenews.net/assets/2019/11/15/document_ew_01.pdf

"To stabilize the climate, we must rapidly displace fossil fuels with clean energy technologies. Currently hydropower dominates renewable electricity generation, accounting for two-thirds globally, and is expected to grow by at least 45% by 2040. While it is broadly assumed that hydropower facilities emit greenhouse gases on par with wind, there is mounting evidence that emissions can be considerably greater, with some facilities even on par with fossil fuels. However, analyses of climate impacts of hydropower plants have been simplistic, emphasizing the aggregated 100-year impacts from a one-year pulse of emissions. Such analyses mask the near-term impacts of methane emissions central to many current policy regimes, have tended to omit carbon dioxide emissions associated with initial plant development, and have not considered the impact of the accumulation of gases in the atmosphere over time. We utilize an analytic approach that addresses these issues. By analyzing climate impacts of sustained hydropower emissions over time, we find that there are enormous differences in climate impacts among facilities and over time."

Félix-Faure, Jim, Christian Walter, Jerome Balesdent, et al. **"Soils Drowned in Water Impoundments: A New Frontier."** *Frontiers in Environmental Science* 7 (April 2019). https://doi.org/10.3389/fenvs.2019.00053.

"Assuming that carbon was lost as CO2 and CH4, the corresponding flux averaged over the reservoir's life is close to global areal estimates of CO2 emissions in temperate reservoirs and offsets a significant proportion of the carbon burial in reservoir sediments. Hence, flooded soils contribute significantly to the GHG budget of reservoirs, provide original long-term experimental sites to measure the effects of anoxia on soils and contain archives of past soil properties."

2018

Chow, M.F.; Bakhrojin, M.A.b.; Haris, H.; Dinesh, (2018), A.A.A. **Assessment of Greenhouse Gas (GHG) Emission from Hydropower Reservoirs in Malaysia**. *Proceedings* 2018, *2*, 1380. https://doi.org/10.3390/proceedings2221380

"This paper presents a preliminary assessment of greenhouse gas (GHG) emissions from all major hydropower reservoirs in Malaysia from the period of 1930–2017. The GHG emissions are calculated based on the Tier 1 method as recommended in International Government Panel on Climate Change (IPCC) guidelines. The results showed that approximately 151.64 Gg of annual methane emission released from hydropower dams in Peninsular Malaysia. While in East Malaysia, hydropower dams release 235.7 Gg of methane emission annually. Bakun dam contributes the most 41.26% of total annual methane emission from hydropower dams in Malaysia. Ulu Jelai hydroelectric dam with design power capacity of 372 MW contributes the least CH_4 emission of 0.02 Gg CH_4 yr^{-1}. It is seen that high head hydroelectric dam with small reservoir surface area is the most sustainable hydropower dam in reducing the GHG emission. However, long-term measurements must be made in order to clarify the net GHG emissions from reservoir surface, turbines, spillway and downstream river of hydropower dams in Malaysia."

DelSontro, T., J. Beaulieu, AND J. Downing. (2018), **Greenhouse Gas Emissions from Lakes and Impoundments: Upscaling in the Face of Global Change**. *Limnology and Oceanography Letters.* John Wiley & Sons, Inc., Hoboken, NJ, 3(3):64-75. https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/lol2.10073

"Lakes and impoundments are important sources of greenhouse gases (GHG: i.e., CO2, CH4, N2O), yet global emission estimates are based on regionally biased averages and elementary upscaling. We assembled the largest global dataset to date on emission rates of all three GHGs and found they covary with lake size and trophic state. Fitted models were upscaled to estimate global emission using global lake size inventories and a remotely sensed global lake productivity distribution. Traditional upscaling approaches overestimated CO2 and N2O emission but underestimated CH4 by half. Our upscaled size-productivity weighted estimates (1.25–2.30 Pg of CO2-equivalents annually) are nearly 20% of global CO2 fossil fuel emission with ~ 75% of the climate impact due to CH4. Moderate global increases in eutrophication could translate to 5–40% increases in the GHG effects in the atmosphere, adding the equivalent effect of another 13% of fossil fuel combustion or an effect equal to GHG emissions from current land use change."

Kosten, S. et al. (2018). **Extreme Drought Boosts CO2 and CH4 Emissions from Reservoir Drawdown Areas**. *Inland Waters* 8, 329–340. https://doi.org/10.1080/20442041.2018.1483126

“Although previous studies suggest that greenhouse gas (GHG) emissions from reservoir sediment exposed to the atmosphere during drought may be substantial, this process has not been rigorously quantified. Here we determined carbon dioxide (CO_2) and methane (CH_4) emissions from sediment cores exposed to a drying and rewetting cycle. We found a strong temporal variation in GHG emissions with peaks when the sediment was drained and then again during rewetting. To gain insight into the importance of these emissions at a regional scale, we used Landsat satellite imagery to upscale our results to all Brazilian reservoirs. We found that during the extreme drought of 2014–2015, an additional 1299 km2 of sediment was exposed, resulting in an estimated emission of 8.5 × 1011 g of CO_2-eq during the first 15 d after the overlying water disappeared and in the first 33 d after rewetting, the same order of magnitude as the year-round GHG emissions of large (~mean surface water area 454 km2) Brazilian reservoirs, excluding the emissions from the draw-down zone. Our estimate, however, has high uncertainty, with actual emissions likely higher. We therefore argue that the effects of drought on reservoir GHG emissions merits further study, especially because climate models indicate an increase in the frequency of severe droughts in the future. We recommend incorporation of emissions during drying and rewetting into GHG budgets of reservoirs to improve regional GHG emission estimates and to enable comparison between GHG emissions from hydroelectric and other electricity sources. We also emphasize that peak emissions at the onset of drought and the later rewetting should be quantified to obtain reliable emission estimates.”

Prairie YT, Alm J, Beaulieu J, et al. (2018). **Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?** *Ecosystems*; 21(5):1058-1071. https://doi.org/10.1007/s10021-017-0198-9

“Freshwater reservoirs are a known source of greenhouse gas (GHG) to the atmosphere, but their quantitative significance is still only loosely constrained. Although part of this uncertainty can be attributed to the difficulties in measuring highly variable fluxes, it is also the result of a lack of a clear accounting methodology, particularly about what constitutes new emissions and potential new sinks. In this paper, we review the main processes involved in the generation of GHG in reservoir systems and propose a simple approach to quantify the reservoir GHG footprint in terms of the net changes in GHG fluxes to the atmosphere induced by damming, that is, ‘what the atmosphere sees.’ The approach takes into account the pre-impoundment GHG balance of the landscape, the temporal evolution of reservoir GHG emission profile as well as the natural emissions that are displaced to or away from the reservoir site resulting from hydrological and other changes. It also clarifies the portion of the reservoir carbon burial that can potentially be considered an offset to GHG emissions.”

Räsänen, Timo A. et al. (2018). **Greenhouse Gas Emissions of Hydropower in the Mekong River Basin**, *Environ. Res. Lett.* 13 034030
https://iopscience.iop.org/article/10.1088/1748-9326/aaa817

“The Mekong River Basin in Southeast Asia is undergoing extensive hydropower development, but the magnitudes of related greenhouse gas emissions (GHG) are not well known. We provide the first screening of GHG emissions of 141 existing and planned reservoirs in the basin, with a focus on atmospheric gross emissions through the reservoir water surface. The emissions were estimated using statistical models that are based on global emission measurements. The hydropower reservoirs (119) were found to have an emission range of 0.2–1994 kg CO_2e MWh^{-1} over a 100 year lifetime with a median of 26 kg CO_2e MWh^{-1}. Hydropower reservoirs facilitating irrigation (22) had generally higher emissions reaching over 22 000 kg CO_2e MWh^{-1}. The emission fluxes for all reservoirs (141) had a range of 26–1813 000 t CO_2e yr^{-1} over a 100 year lifetime with a median of 28 000 t CO_2e yr^{-1}. Altogether, 82% of hydropower reservoirs (119) and 45% of reservoirs also facilitating irrigation (22) have emissions comparable to other renewable energy sources (<190 kg CO_2e MWh^{-1}), while the rest have higher emissions equaling even the emission from fossil fuel power plants (>380 kg CO_2e MWh^{-1}). These results are tentative and they suggest that hydropower in the Mekong Region cannot be considered categorically as low-emission energy. Instead, the GHG emissions of hydropower should be carefully considered case-by-case together with the other impacts on the natural and social environment."

Samiotis G, Pekridis G, Kaklidis N, Trikoilidou E, Taousanidis N, Amanatidou E. (2018). **Greenhouse Gas Emissions from two Hydroelectric Reservoirs in Mediterranean Region**. *Environ Monit Assess. May 26;190(6)*:363.
https://link.springer.com/article/10.1007/s10661-018-6721-4

"Water reservoirs are used for many purposes, such as water supply, irrigation, flood mitigation, and hydroelectric energy generation. Although hydroelectric energy is considered 'green,' many studies show that the construction of a reservoir enhances greenhouse gas (GHG) emissions at the transformed area. These emissions, mainly of CO_2, CH_4, and N_2O gases, depend on the age of the reservoir, landscape and soil composition, fauna and flora remnants of the impounded area, climatic conditions, and basin runoffs. Consequently, GHG emissions significantly vary between reservoirs and depending on local specificities. Several studies have investigated GHG emissions from reservoirs around the world, focusing mainly on reservoirs located in cold regions, temperate regions, and tropical regions. Research is lacking for reservoirs in Mediterranean countries, like Greece, and similar regions. This work initially assesses the net GHG emissions of a newly created reservoir (Ilarion est. 2012) in Western Macedonia, Greece. The methodology for net GHG emission calculation was based on the use of literature data concerning pre-impoundment emission factors and local specificities of the reservoir (terrain type, canopy cover), as well as on the 2-year measurement data that were collected using a 'static floating chamber.' Furthermore, in this work, the gross GHG emissions of an older, in-line reservoir (Polyfytos est. 1974) were also calculated, based on 2-year measurement data. The results show that the global warming potential (GWP) of the reservoirs is dictated by methane emissions; it minimizes during winter and spring and maximizes during summer and autumn. Hydroelectric energy production at Ilarion Reservoir results in 32 to 97 times less total CO_2 equivalent emissions in comparison to fossil fuels, while at Polyfytos Reservoir only 8 to 24 times less (based on gross emissions). It appears that the impact of a reservoir's morphology on GHG emissions is more significant than that of a reservoir's age."

Song, C. et al., (2018). **Cradle-to-Grave Greenhouse Gas Emissions from Dams in the United States of America,** *90 Renewable and Sustainable Energy Reviews 5*. https://www.researchgate.net/publication/324993878_Cradle-to-grave_greenhouse_gas_emissions_from_dams_in_the_United_States_of_America

"Several studies have investigated GHG emissions from reservoirs around the world, focusing mainly on reservoirs located in cold regions, temperate regions, and tropical regions. The methodology for net GHG emission calculation was based on the use of literature data concerning pre-impoundment emission factors and local specificities of the reservoir (terrain type, canopy cover), as well as on the 2-year measurement data that were collected using a 'static floating chamber.' Furthermore, in this work, the gross GHG emissions of an older, in-line reservoir (Polyfytos est. 1974) were also calculated, based on 2-year measurement data. The results show that the global warming potential (GWP) of the reservoirs is dictated by methane emissions; it minimizes during winter and spring and maximizes during summer and autumn. Hydroelectric energy production at Ilarion Reservoir results in 32 to 97 times less total CO2 equivalent emissions in comparison to fossil fuels, while at Polyfytos Reservoir only 8 to 24 times less (based on gross emissions). It appears that the impact of a reservoir's morphology on GHG emissions is more significant than that of a reservoir's age."

2017

Harrison, John A., Bridget R. Deemer, M. Keith Birchfield, and Maria T. O'Malley. **Reservoir Water-Level Drawdowns Accelerate and Amplify Methane Emission.** Environmental Science & Technology 51, no. 3 (2017): 1267–77. https://doi.org/10.1021/acs.est.6b03185.

"In these systems, we show that waterlevel drawdowns can, at least temporarily, greatly increase perarea reservoir CH4 fluxes to the atmosphere, and can account for more than 90% of annual reservoir CH4 flux in a period of just a few weeks. Reservoirs with higher epilimnetic [chlorophyll a] experienced larger increases in CH4 emission in response to drawdown ($R2 = 0.84$, $p < 0.01$), suggesting that eutrophication magnifies the effect of drawdown on CH4 emission. We show that drawdowns as small as 0.5 m can stimulate ebullition events. Given that drawdown events of this magnitude are quite common in reservoirs, our results suggest that this process must be considered in sampling strategies designed to characterize total CH4 fluxes from reservoirs."

Maavara, T., R. Lauerwald, P. Regnier, P.Van Cappellen. (2017) **Global perturbation of organic carbon cycling by river damming**. *Nature Communications*, 8: 15347 DOI: 10.1038/ncomms15347

The damming of rivers represents one of the most far-reaching human modifications of the flows of water and associated matter from land to sea. Dam reservoirs are hotspots of sediment accumulation, primary productivity (*P*) and carbon mineralization (*R*) along the river continuum. Here we show that for the period 1970–2030, global carbon mineralization in reservoirs exceeds carbon fixation ($P<R$); the global *P/R* ratio, however, varies significantly, from 0.20 to 0.58 because of the changing age distribution of dams. We further estimate that at the start of the twenty-first century, in-reservoir burial plus mineralization eliminated 4.0±0.9 Tmol per year (48±11 Tg C per year) or 13% of total organic carbon (OC) carried by rivers to the oceans. Because of the ongoing boom in dam building, in particular in emerging economies, this value could rise to 6.9±1.5 Tmol per year (83±18 Tg C per year) or 19% by 2030.

2016

Beaulieu, J.J., McManus, M.G. and Nietch, C.T. (2016), **Estimates of reservoir methane emissions based on a spatially balanced probabilistic-survey.** Limnol. Oceanogr., 61: S27-S40. https://doi.org/10.1002/lno.10284

"Global estimates of methane (CH_4) emissions from reservoirs are poorly constrained, partly due to the challenges of accounting for intra-reservoir spatial variability. Reservoir-scale emission rates are often estimated by extrapolating from measurement made at a few locations; however, error and bias associated with this approach can be large and difficult to quantify. Here, we use a generalized random tessellation survey (GRTS) design to generate unbiased estimates of reservoir-CH_4 emissions rates (±95% CI) for areas below tributary inflows, open-waters, and at the whole-reservoir scale. Total CH_4 emission rates (i.e., sum of ebullition and diffusive emissions) were 4.8 (±2.1), 33.0 (±10.7), and 8.3 (±2.2) mg CH_4 m^{-2} h^{-1} in open-waters, tributary-associated areas, and the whole-reservoir for the period in August 2014 during which 115 sites were sampled across an 7.98 km^2 reservoir in Southwestern, Ohio, U.S.A. Tributary areas occupy 12% of the reservoir surface, but were the source of 41% of total CH_4 emissions, highlighting the importance of riverine-lacustrine transition zones. Ebullition accounted for > 90% of CH_4 emission at all spatial scales. Overall, CH_4 emission rates were high for a temperate zone reservoir, possibly because earlier studies underestimated ebullition or did not include emission hot spots. Confidence interval estimates that incorporated spatial pattern in CH_4 emissions were up to 29% narrower than when spatial independence is assumed among sites. The use of GRTS, or other probabilistic survey designs, can improve the accuracy and precision of reservoir emission rate estimates, which is needed to better constrain uncertainty in global scale emission estimates."

Deemer, Bridget R., John A. Harrison, Siyue Li, Jake J. Beaulieu, Tonya DelSontro, Nathan Barros, José F. Bezerra-Neto, Stephen M. Powers, Marco A. dos Santos, J. Arie Vonk, (2016). **Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis,** *BioScience*, Volume 66, Issue 11, 1 November 2016, Pages 949–964, https://doi.org/10.1093/biosci/biw117

"Collectively, reservoirs created by dams are thought to be an important source of greenhouse gases (GHGs) to the atmosphere. So far, efforts to quantify, model, and manage these emissions have been limited by data availability and inconsistencies in methodological approach. Here, we synthesize reservoir CH_4, CO_2, and N_2O emission data with three main objectives: (1) to generate a global estimate of GHG emissions from reservoirs, (2) to identify the best predictors of these emissions, and (3) to consider the effect of methodology on emission estimates. We estimate that GHG emissions from reservoir water surfaces account for 0.8 (0.5–1.2) Pg CO_2 equivalents per year, with the majority of this forcing due to CH_4. We then discuss the potential for several alternative pathways such as dam degassing and downstream emissions to contribute significantly to overall emissions. Although prior studies have linked reservoir GHG emissions to reservoir age and latitude, we find that factors related to reservoir productivity are better predictors of emission."

Fearnside, P. (2016) **Greenhouse gas emissions from Brazil's Amazonian Hydroelectric Dams,** *Environ. Res. Lett.* 11 011002. doi**:** 10.1088/1748-9326/11/1/011002

"Tropical dams are often falsely portrayed as 'clean' emissions-free energy sources. The letter by de Faria *et al* (2015 *Environ. Res. Lett.* 10 124019) adds to evidence questioning this myth. Calculations are made for 18 dams that are planned or under construction in Brazilian Amazonia and show that emissions from storage hydroelectric dams would exceed those from electricity generation based on fossil fuels. Fossil fuels need not be the alternative, because Brazil has vast potential for wind and solar power as well as opportunities for energy conservation. Because dam-building is rapidly shifting to humid tropical areas, where emissions are higher than in other climatic zones, the impact of these emissions needs to be given proper weight in energy-policy decisions."

Scherer, Laura & Stephan Pfister, (2016). **Hydropower's Biogenic Carbon Footprint,** *PLOS ONE*, September 14, 2016. https://doi.org/10.1371/journal.pone.0161947

"Tropical dams are often falsely portrayed as 'clean' emissions-free energy sources. The letter by de Faria *et al* (2015 *Environ. Res. Lett.* 10 124019) adds to evidence questioning this myth. Calculations are made for 18 dams that are planned or under construction in Brazilian Amazonia and show that emissions from storage hydroelectric dams would exceed those from electricity generation based on fossil fuels. Fossil fuels need not be the alternative, because Brazil has vast potential for wind and solar power as well as opportunities for energy conservation. Because dam-building is rapidly shifting to humid tropical areas, where emissions are higher than in other climatic zones, the impact of these emissions needs to be given proper weight in energy-policy decisions."

2015

De Faria, Felipe A M, Jaramillo, Paulina, Sawakuchi, Henrique O, Richey, Jeffrey E, & Barros, Nathan (Dec 2015). **Estimating greenhouse gas**

emissions from future Amazonian hydroelectric reservoirs.
Environmental Research Letters, 10(12), 13.
https://iopscience.iop.org/article/10.1088/1748-9326/10/12/124019/pdf

“Brazil plans to meet the majority of its growing electricity demand with new hydropower plants located in the Amazon basin. However, large hydropower plants located in tropical forested regions may lead to significant carbon dioxide and methane emission. Currently, no predictive models exist to estimate the greenhouse gas emissions before the reservoir is built. This paper presents two different approaches to investigate the future carbon balance of eighteen new reservoirs in the Amazon. The first approach is based on a degradation model of flooded carbon stock, while the second approach is based on flux data measured in Amazonian rivers and reservoirs. The models rely on a Monte Carlo simulation framework to represent the balance of the greenhouse gases into the atmosphere that results when land and river are converted into a reservoir. Further, we investigate the role of the residence time/stratification in the carbon emissions estimate. Our results imply that two factors contribute to reducing overall emissions from these reservoirs: high energy densities reservoirs, i.e., the ratio between the installed capacity and flooded area, and vegetation clearing. While the models’ uncertainties are high, we show that a robust treatment of uncertainty can effectively indicate whether a reservoir in the Amazon will result in larger greenhouse gas emissions when compared to other electricity sources.”

Fearnside, Philip. 2015. **Emissions from Tropical Hydropower and the IPCC**. Environmental Science and Policy 50:225-229. doi: 10.1016/j.envsci.2015.03.002

“Tropical hydroelectric emissions are undercounted in national inventories of greenhouse gases under the United Nations Framework Convention on Climate Change (UNFCCC), giving them a role in undermining the effectiveness of as-yet undecided emission limits. These emissions are also largely left out of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation, and have been excluded from a revision of the IPCC guidelines on wetlands. The role of hydroelectric dams in emissions inventories and in mitigation has been systematically ignored.”

Fedorov, M.P., Elistratov, V.V., Maslikov, V.I. *et al.* 2015. **Reservoir Greenhouse Gas Emissions at Russian HPP.** Power Technol Eng 49, 33–39. https://doi.org/10.1007/s10749-015-0569-3

“Studies of greenhouse-gas emissions from the surfaces of the world’s reservoirs, which has demonstrated ambiguity of assessments of the effect of reservoirs on greenhouse-gas emissions to the atmosphere, is analyzed. It is recommended that greenhouse- gas emissions from various reservoirs be assessed by the procedure ‘GHG Measurement Guidelines for Fresh Water Reservoirs’ (2010) for the purpose of creating a data base with results of standardized measurements. A program for research into greenhouse-gas emissions is being developed at the St. Petersburg Polytechnic University in conformity with the IHA procedure at the reservoirs impounded by the Sayano-Shushenskaya and Mainskaya HPP operated by the RusHydro Co.”

2014

Maeck, A., Hofmann, H., and Lorke, A. (2014). **Pumping Methane out of Aquatic Sediments – Ebullition Forcing Mechanisms in an Impounded River**, Biogeosciences, 11, 2925–2938, https://doi.org/10.5194/bg-11-2925-2014

“Freshwater systems contribute significantly to the global atmospheric methane budget. A large fraction of the methane emitted from freshwaters is transported via ebullition. However, due to its strong variability in space and time, accurate measurements of ebullition rates are difficult; hence, the uncertainty regarding its contribution to global budgets is large. Here, we analyze measurements made by continuously recording automated bubble traps in an impounded river in central Europe and investigate the mechanisms affecting the temporal dynamics of bubble release from cohesive sediments. Our results show that the main triggers of bubble release were pressure changes, originating from the passage of ship lock-induced surges and ship passages. The response to physical forcing was also affected by previous outgassing. Ebullition rates varied strongly over all relevant timescales from minutes to days; therefore, representative ebullition estimates could only be inferred with continuous sampling over long periods. Since ebullition was found to be episodic, short-term measurement periods of a few hours or days will likely underestimate ebullition rates. Our results thus indicate that flux estimates could be grossly underestimated (by up to ~50%) if the correct temporal resolution is not used during data collection.”

2013

Andreas Maeck, Tonya DelSontro, Daniel F. McGinnis, Helmut Fischer, Sabine Flury, Mark Schmidt, Peer Fietzek, and Andreas Lorke, (2013) **Sediment Trapping by Dams Creates Methane Emission Hot Spots,** *Environmental Science & Technology 2013 47 (15),* 8130-8137 doi: 10.1021/es4003907

“Inland waters transport and transform substantial amounts of carbon and account for ~18% of global methane emissions. Large reservoirs with higher areal methane release rates than natural waters contribute significantly to freshwater emissions. However, there are millions of small dams worldwide that receive and trap high loads of organic carbon and can therefore potentially emit significant amounts of methane to the atmosphere. We evaluated the effect of damming on methane emissions in a central

European impounded river. Direct comparison of riverine and reservoir reaches, where sedimentation in the latter is increased due to trapping by dams, revealed that the reservoir reaches are the major source of methane emissions (∼0.23 mmol CH4 m–2 d–1 vs ∼19.7 mmol CH4 m–2 d–1, respectively) and that areal emission rates far exceed previous estimates for temperate reservoirs or rivers. We show that sediment accumulation correlates with methane production and subsequent ebullitive release rates and may therefore be an excellent proxy for estimating methane emissions from small reservoirs. Our results suggest that sedimentation-driven methane emissions from dammed river hot spot sites can potentially increase global freshwater emissions by up to 7%."

Hertwich EG.(2013) **Addressing biogenic greenhouse gas emissions from hydropower in LCA**. Environ Sci Technol. 2013 Sep 3;47(17):9604-11. doi: 10.1021/es401820p.

"The ability of hydropower to contribute to climate change mitigation is sometimes questioned, citing emissions of methane and carbon dioxide resulting from the degradation of biogenic carbon in hydropower reservoirs. These emissions are, however, not always addressed in life cycle assessment, leading to a bias in technology comparisons, and often misunderstood. The objective of this paper is to review and analyze the generation of greenhouse gas emissions from reservoirs for the purpose of technology assessment, relating established emission measurements to power generation. A literature review, data collection, and statistical analysis of methane and CO2 emissions are conducted. In a sample of 82 measurements, methane emissions per kWh hydropower generated are log-normally distributed, ranging from micrograms to 10s of kg. A multivariate regression analysis shows that the reservoir area per kWh electricity is the most important explanatory variable. Methane emissions flux per reservoir area are correlated with the natural net primary production of the area, the age of the power plant, and the inclusion of bubbling emissions in the measurement. Even together, these factors fail to explain most of the variation in the methane flux. The global average emissions from hydropower are estimated to be 85 gCO2/kWh and 3 gCH4/kWh, with a multiplicative uncertainty factor of 2. GHG emissions from hydropower can be largely avoided by ceasing to build hydropower plants with high land use per unit of electricity generated."

2012

Steinhurst, William, et al. (2012). **Hydropower Greenhouse Gas Emissions**, *Synapse Energy Econ.. 12.* https://www.synapse-energy.com/sites/default/files/SynapseReport.2012-02.CLF+PEW.GHG-from-Hydro.10-056.pdf

"This report reviews the state of information regarding one key policy consideration: how hydropower stacks up against other technologies with respect to greenhouse gas (GHG) emissions—including the life cycle emissions from the construction and operation of generating capacity. An important aspect of the analysis is a comparison of not only the ‘typical’ amount of GHG emissions from each technology, but a presentation of the range of values that may be observed. The report also discusses concerns about the way GHG emissions are measured, especially in the case of hydropower, and best practices for doing so. Finally, the report discusses a specific policy consideration: the relative trade-off (from a GHG emission perspective) of Canadian hydropower imports versus other energy options for New England.”

Life cycle analysis (LCA) is clearly the current best practice for comparing the GHG emissions of generating facilities. With respect to imported power, consideration of displaced emissions in the importing region, exporting region, and neighboring regions electrically interconnected with either may be necessary to form a true picture of GHG effects.

Teodoru, C. R., et al. (2012), **The net carbon footprint of a newly created boreal hydroelectric reservoir**, *Global Biogeochem. Cycles*, 26, GB2016, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GB004187

“We present here the first comprehensive assessment of the carbon (C) footprint associated with the creation of a boreal hydroelectric reservoir (Eastmain-1 in northern Québec, Canada). This is the result of a large-scale, interdisciplinary study that spanned over a 7-years period (2003–2009), where we quantified the major C gas (CO_2 and CH_4) sources and sinks of the terrestrial and aquatic components of the pre-flood landscape, and also for the reservoir following the impoundment in 2006. The pre-flood landscape was roughly neutral in terms of C, and the balance between pre- and post-flood C sources/sinks indicates that the reservoir was initially (first year post-flood in 2006) a large net source of CO_2 (2270 mg C m^{-2} d^{-1}) but a much smaller source of CH_4 (0.2 mg C m^{-2} d^{-1}). While net CO_2 emissions declined steeply in subsequent years (down to 835 mg C m^{-2} d^{-1} in 2009), net CH_4 emissions remained constant or increased slightly relative to pre-flood emissions. Our results also suggest that the reservoir will continue to emit carbon gas over the long-term at rates exceeding the carbon footprint of the pre-flood landscape, although the sources of C supporting these emissions have yet to be determined.”

West, W. E. et al. (2012). **Effects of Algal and Terrestrial Carbon on Methane Production Rates and Methanogen Community Structure in a Temperate Lake Sediment**. *Freshwater Biology* 57, 949-955. https://www3.nd.edu/~sjones20/ewExternalFiles/Westetal2012_FWB.pdf

“Ongoing changes in the catchment of lakes, including eutrophication and increased terrestrial organic carbon export, may affect CH_4 production rates as well as shape methanogen abundance and community structure. Therefore, inputs from catchments to lakes should be examined for their effects on CH_4 production. Our results indicate that

CH4 production rates were significantly elevated following the addition of algal biomass. Overall, anthropogenic impacts on aquatic ecosystems can influence methanogenesis rates and should be considered in models of global methane cycling and climate.”

2011

Barros, N., Cole, J., Tranvik, L. et al. (2011). **Carbon Emission from Hydroelectric Reservoirs Linked to Reservoir Age and Latitude**. *Nature Geosci 4, 593–596*.https://doi.org/10.1038/ngeo1211

“Hydroelectric reservoirs cover an area of 3.4×105 km2 and comprise about 20% of all reservoirs. In addition, they contain large stores of formerly terrestrial organic carbon. Significant amounts of greenhouse gases are emitted, especially in the early years following reservoir creation, but the global extent of these emissions is poorly known. Previous estimates of emissions from all types of reservoir indicate that these human-made systems emit 321 Tg of carbon per year. Here we assess the emissions of carbon dioxide and methane from hydroelectric reservoirs, on the basis of data from 85 globally distributed hydroelectric reservoirs that account for 20% of the global area of these systems. We relate the emissions to reservoir age, location biome, morphometric features and chemical status. We estimate that hydroelectric reservoirs emit about 48 Tg C as CO2 and 3 Tg C as CH4, corresponding to 4% of global carbon emissions from inland waters. Our estimates are smaller than previous estimates on the basis of more limited data. Carbon emissions are correlated to reservoir age and latitude, with the highest emission rates from the tropical Amazon region. We conclude that future emissions will be highly dependent on the geographic location of new hydroelectric reservoirs.”

2009

Gunkel, G. (2009), Hydropower – **A Green Energy? Tropical Reservoirs and Greenhouse Gas Emissions**. Clean Soil Air Water, 37: 726-734. https://doi.org/10.1002/clen.200900062

“Reservoirs are man-made lakes that severely impact on river ecosystems, and in addition, the new lake ecosystem can be damaged by several processes. Thus, the benefits of a reservoir, including energy production and flood control, must be measured against their impact on nature. New investigations point out that shallow and tropical reservoirs have high emission rates of the greenhouse gases CO2 and CH4. The methane emissions contribute strongly to climate change because CH4 has a 25 times higher global warming potential than CO2. The pathways for its production include ebullition, diffuse emission via the water-air interface, and degassing in turbines and downstream of the reservoir in the spillway and the initial river stretch. Greenhouse gas emissions are promoted by a eutrophic state of the reservoir, and, with higher trophic levels, anaerobic conditions occur with the emission of CH4. This means that a qualitative and quantitative jump in greenhouse gas emissions takes place. Available data from Petit Saut, French Guinea, provides a first quantification of these pathways. A simple evaluation of the global warming potential of a reservoir can be undertaken using the energy density, the ratio of the reservoir surface and the hydropower capacity; this parameter is mainly determined by the reservoir's morphometry but not by the hydropower capacity. Energy densities of some reservoirs are given and it is clearly seen that some reservoirs have a global warming potential higher than that of coal use for energy production."

2007

Walter, Katey, Laurence Smith, and Stuart Chapin. (2007) **Methane bubbling from northern lakes: present and future contributions to the global methane budget.** *Phil. Trans. R. Soc. A***.**3651657–1676. http://doi.org/10.1098/rsta.2007.2036

"Large uncertainties in the budget of atmospheric methane (CH4) limit the accuracy of climate change projections. Here we describe and quantify an important source of CH4—point-source ebullition (bubbling) from northern lakes—that has not been incorporated in previous regional or global methane budgets. Employing a method recently introduced to measure ebullition more accurately by taking into account its spatial patchiness in lakes, we estimate point-source ebullition for 16 lakes in Alaska and Siberia that represent several common northern lake types: glacial, alluvial floodplain, peatland and thermokarst (thaw) lakes. Extrapolation of measured fluxes from these 16 sites to all lakes north of 45° N using circumpolar databases of lake and permafrost distributions suggests that northern lakes are a globally significant source of atmospheric CH4, emitting approximately 24.2±10.5 Tg CH4 yr−1. Thermokarst lakes have particularly high emissions because they release CH4 produced from organic matter previously sequestered in permafrost. A carbon mass balance calculation of CH4 release from thermokarst lakes on the Siberian yedoma ice complex suggests that these lakes alone would emit as much as approximately 49 000 Tg CH4 if this ice complex was to thaw completely. Using a space-for-time substitution based on the current lake distributions in permafrost-dominated and permafrost-free terrains, we estimate that lake emissions would be reduced by approximately 12% in a more probable transitional permafrost scenario and by approximately 53% in a 'permafrost-free' Northern Hemisphere. Long-term decline in CH4 ebullition from lakes due to lake area loss and permafrost thaw would occur only after the large release of CH4 associated thermokarst lake development in the zone of continuous permafrost."

Pacca, Sergio. **Impacts from Decommissioning of Hydroelectric Dams: A Life Cycle Perspective**. Climatic Change 84, nos. 3–4 (2007): 281–94. https://doi.org/10.1007/s10584-007-9261-4.

"The amount of greenhouse gases emitted by the sediments upon dam decommissioning is a notable amount that should not be ignored and must be taken into account when considering construction and relicensing of hydroelectric dams."

2006

Intergovernmental Panel on Climate Change (IPCC) (2006), **Appendix 3 -- CH4 Emissions from Flooded Land: Basis for Future Methodological Development,** https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_p_Ap3_WetlandsCH4.pdf

"Flooded Land may emit CH4 in significant quantities, depending on a variety of characteristic such as age and depth of reservoirs, land-use prior to flooding, climate, and management practices. "

2005

Fearnside, P. (2005) **Do Hydroelectric Dams Mitigate Global Warming? The Case of Brazil's CuruÁ-una Dam.** *Mitig Adapt Strat Glob Change* 10, 675–691.. https://doi.org/10.1007/s11027-005-7303-7

"Hydroelectric dams in tropical forest areas emit greenhouse gases, as illustrated by the Curuá-Una Dam in the Amazonian portion of Brazil. Emissions include carbon dioxide from decay of the above-water portions of trees that are left standing in the reservoir and methane from soft vegetation that decays under anaerobic conditions on the bottom of the reservoir, especially macrophytes (water weeds) and vegetation that grows in the drawdown zone and is flooded when the reservoir water level rises. Some methane is released from the reservoir surface through bubbling and diffusion, but larger amounts are released from water passing through the turbines and spillway. Methane concentration in the water increases with depth, and the turbines and spillway draw water from sufficient depth to have substantial methane content. In 1990 (13 years after filling), the Curuá-Una Dam emitted 3.6 times more greenhouse gases than would have been emitted by generating the same amount of electricity from oil."

Tremblay et al. (2005). ***Greenhouse Gas Emissions - Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments****.* Germany: Springer, 2005. https://www.springer.com/gp/book/9783540234555

"In a time when an unquestionable link between anthropogenic emissions of greenhouse gases and climatic changes has finally been acknowledged and widely documented through IPCC reports, the need for precise estimates of greenhouse gas (GHG) production rates and emissions from natural as well as managed ecosystems has risen to a critical level. Future agreements between nations concerning the reduction of their GHG emissions will depend upon precise estimates of the present level of these emissions in both natural and managed terrestrial and aquatic environments. From this viewpoint, the present volume should prove to a benchmark contribution because it provides very carefully assessed values for GHG emissions or exchanges between critical climatic zones in aquatic environments and the atmosphere. It also provides unique information on the biases of different measurement methods that may account for some of the contradictory results that have been published recently in the literature on this subject. Not only has a large array of current measurement methods been tested concurrently here, but a few new approaches have also been developed, notably laser measurements of atmospheric CO concentration 2 gradients. Another highly useful feature of this book is the addition of - nitoring and process studies as well as modeling.”

2000

David M. Rosenberg, Patrick McCully, Catherine M. Pringle, (2000). **Global-Scale Environmental Effects of Hydrological Alterations: Introduction,** *BioScience*, *Volume 50, Issue 9, September 2000*, Pages 746–751, https://doi.org/10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2

“The study of the cumulative effects of hydrological alterations is a recent endeavor, compared with the study of individual dam and reservoir developments (e.g., Hall 1971, Hecky et al. 1984). The issue of greenhouse gas emissions from reservoirs, for example, is less than a decade old (Rudd et al. 1993). The global significance of reservoirs as sources of greenhouse gases depends on the total surface area of reservoirs and the flux rates from the major types of reservoirs in different geographical locations (Rosenberg et al. 1997). Neither of these quantities is well known, but flux rates have now been measured in 21 locations, enabling the first reasonable estimate of global greenhouse gas emissions from reservoirs (St. Louis et al. 2000).”

Vincent L. St. Louis, Carol A. Kelly, Éric Duchemin, John W. M. Rudd, David M. Rosenberg, (2000). **Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate**. *BioScience, Volume 50, Issue 9, September,* Pages 766–775, https://doi.org/10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2

“Reservoir creation is not greenhouse gas neutral with respect to production of electricity by hydroelectric generation, as has recently been suggested (Hoffert et al. 1998, Victor 1998). Although there is uncertainty in our estimates, they show that reservoir fluxes are of a similar magnitude to other fluxes already included in efforts to understand anthropogenic changes taking place in the global carbon”

1997

Fearnside, P. (1997). **Greenhouse-Gas Emissions from Amazonian Hydroelectric Reservoirs: The Example of Brazil's Tucuruí Dam as Compared to Fossil Fuel Alternatives.** *Environmental Conservation, 24*(1), 64-75. doi:10.1017/S0376892997000118

“Hydroelectric dams in tropical forest areas emit carbon dioxide and methane. How these emissions and their impacts should be calculated, and how comparisons should be made with global warming contributions of alternative energy sources such as fossil fuels, can lead to sharp differences in conclusions on the relative advantages of these options. The example of Brazil's Tucuruí Dam is examined to clarify these differences.

The present paper extends an earlier analysis to 100 years and explores the differences between these and comparable fossil fuel emissions."

1995

Fearnside, P. (1995). **Hydroelectric Dams in the Brazilian Amazon as Sources of 'Greenhouse' Gases.** *Environmental Conservation, 22*(1), 7-19. doi:10.1017/S0376892900034020

"Existing hydroelectric dams in Brazilian Amazonia emitted about 0.26 million tons of methane and 38 million tons of carbon dioxide in 1990. The methane emissions represent an essentially permanent addition to gas fluxes from the region, rather than a one-time release. The total area of reservoirs planned in the region is about 20 times the area existing in 1990, implying a potential annual methane release of about 5.2 million tons. About 40% of this estimated release is from underwater decay of forest biomass, which is the most uncertain of the components in the calculation. Methane is also released in significant quantities from open water, macrophyte beds, and above-water decay of forest biomass."