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Greenhouse gas emissions from hydropower reservoirs: emission processes and management approaches

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Abstract

Hydropower reservoirs, as vital inland waters bodies of anthropogenic origin, exhibit distinct characteristics from natural waters, thereby garnering research interest in the quantification and mapping of greenhouse gas (GHG) emissions. In this review, we systematically examine studies focusing on GHG emissions from hydropower reservoirs. We identify two key primary physical mechanisms resulting from river damming, namely water impoundment and water regulation, which can significantly influence GHG emissions in hydropower reservoirs. Reservoirs vary in size, with smaller reservoirs exhibiting higher CH_4 emissions per unit area. For instance, small reservoirs have an average flux rate of 327.54 mg C–CH_4/m^2/day, while medium-sized reservoirs emit 267.12 mg C–CH_4/m^2/day, and large ones emit 37.34 mg C–CH_4/m^2/day. This difference is potentially attributable to shorter water residence times in small reservoirs and increased susceptibility to littoral disturbance. In addition to reservoir scale, variations in GHG emissions between reservoirs are also influenced by the type of hydropower. Run-of-river and closed-loop pumped storage hydropower (PSH) systems are anticipated to exhibit lower GHG emissions (PSH: 4.2–46.5 mg C–CH_4/m^2/day) in comparison to conventional impoundment hydropower, owing to their operational characteristics, facilitating mixing and oxygenation within the reservoir water column and reducing sedimentation. Nonetheless, further field measurements are warranted. Through the integration of literature insights, we propose solutions aimed at managing emissions, considering both physical mechanisms and hydropower planning. Ultimately, these findings will advance our understanding of GHG emissions from hydropower reservoirs and facilitate sustainable carbon reduction management practices.

1. Introduction

Hydropower is generally regarded as a climate-friendly energy source and its installed capacity expanded at a rate of 2.1% per year from 2015 to 2019 (IPCC 2015, Muller 2019, IHA 2023). It is expected that the world's existing hydropower capacity will grow by 60% by 2050, to reach 2150 Gigawatts (GW), supporting efforts to reduce carbon usage (IRENA 2020). To achieve this growth, an estimated 3700 hydropower schemes generating more than 1 Megawatts (MW) are proposed or being constructed in developing countries, where only 22% of the hydropower potential has been exploited (Zarfl *et al* 2014). In the Net Zero Scenario, hydropower will remain the primary renewable energy source (IEA 2023). Additionally, combining pumped storage hydropower (PSH) with other renewable energy sources such as wind and solar power can enhance grid resilience against unpredictable climate changes. As a result, more reservoirs for renewable energy storage are expected (IHA 2024).

However, although hydropower is often considered a climate-friendly energy source, its reservoirs continue to impact carbon emissions due to the decomposition of organic matter in the water, which releases greenhouse gases (GHGs) (Barros *et al* 2011, IHA 2012, Deemer *et al* 2016, Prairie *et al* 2021). These projects will not only be used for hydroelectricity, where approximately 25% of reservoirs are mainly for hydropower, based on the GRanD database (Lehner *et al* 2011), but also serve other purposes, including irrigation (25%), recreation (4%), navigation (7%), and water supply (12%), are still being planned and implemented. Accurate assessments of the emissions resulting from increased water impoundment are crucial for creating realistic and effective climate change mitigation strategies. Without this focus, we risk underestimating the true environmental impact of hydropower.

Hydropower-associated GHG emissions are related to the construction and operation of a reservoir, which can require intense carbon processing (Li *et al* 2017a, Beaulieu *et al* 2020). During the operational phase, GHG emissions arise from the breakdown of organic material entering the reservoir through flooding, runoff, and river inputs, or they originate within the reservoir due to the growth of aquatic plants and algae (Deemer *et al* 2016). If the rivers are not dammed, these organic materials would be transported downstream. As carbon moves downstream, the relatively fast flow and well-oxygenated water allow it to react and be converted to CO_2, which is then released into the air. The remaining carbon will eventually reach the ocean. Conversely, when a water body is dammed, flow rates are reduced, allowing sediments containing carbon to settle at the bottom of the reservoir (i.e. carbon burial) and some of this will be degraded anaerobically by a variety of bacteria. In the final degradation stage, an anaerobic bacterium called methanogens uses suitable substrates, such as acetic acid and hydrogen, to produce CH_4 (Segers 1998, Duc *et al* 2010, West *et al* 2012) (figure 1). The produced GHG may dissolve in water or escape into the atmosphere.

CH_4 is emitted from reservoirs via one of the four pathways indicated in figure 1. First, CH_4 can be transported directly by molecular diffusion. The diffusive flux is the exchange of CH_4 between air and water, determined by the concentration of CH_4 in the atmosphere and water column (Wu *et al* 2019). Second, CH_4 can be released through ebullition, in which CH_4 becomes trapped in bubbles. If the water is shallow and the hydrostatic pressure is too low to keep the bubbles away from the surface, they will pass through the water column and burst, releasing CH_4 into the atmosphere (Bastviken *et al* 2004a). The third pathway is degassing, which occurs during hydropower operations when CH_4 is released through turbines or flood control spillways. Fourth, CH_4 can be advected through macrophytes. The emission of CO_2 is primarily through diffusion (figure 1) (King 1992, Jager *et al* 2022).

Environmental controls on GHG emission from inland waters include chlorophyll-a (Chl-a), temperature, latitude, oxygen level, water depth, soil redox, impoundment age, wind speed and stream flow (Bastviken *et al* 2004a, McGinnis *et al* 2006, Sobek *et al* 2009, 2012, West *et al* 2012, 2016, DelSontro *et al* 2016, Descloux *et al* 2017, Paranaíba *et al* 2018, Deemer and Harrison 2019, Huang and Li 2023). Current research has mostly focused on how these environmental factors affect GHG emissions, but there is a lack of consideration of the impacts of hydropower reservoir water regulation, which adjusts water levels for flood control, downstream water use, energy and food needs. Although hydropower reservoirs are a type of inland water body, they have distinct characteristics/mechanisms due to their anthropogenic nature and use, which can affect GHG emissions. Hydropower reservoirs vary in size (e.g. storage capacity, installed capacity) and operational type (e.g. run-of-river, reservoir-storage, and PSH). These differences can lead to significant variations in GHG emissions between hydropower reservoirs (Hunt *et al* 2018, Silverthorn *et al* 2018, Encinas Fernández *et al* 2020, Blakers *et al* 2021).

Given the potential significance of hydropower reservoirs to global GHG emissions, the expected increase in the number of hydropower reservoirs globally over the next two decades, and substantial knowledge gaps in our understanding of the controls on GHG emissions, this review aims to summarize the primary GHG production and emissions mechanisms. This will facilitate a better understanding of how GHG emissions originate from hydropower reservoirs and what potential solutions exist for mitigation, which has not yet been thoroughly reviewed. While some studies have explored emission, variations based on reservoir area size (Holgerson and Raymond 2016, Grinham *et al* 2018, Peacock *et al* 2021), the impact of varied storage capacity on emissions has not been adequately addressed in the literature. By highlighting these areas, we hope to draw attention to the importance of considering such factors in hydropower reservoir management to reduce carbon emissions.

Furthermore, there has been limited recognition in the literature of emissions differences between different types of hydropower projects. Particularly, there is a lack of GHG measurement data for run-of-river and PSH projects. This paper aims to fill this gap by initiating discussions based on existing literature and theoretical considerations. We hope this will encourage further research into GHG measurements from these types of hydropower projects, leading to more comprehensive discussions on emissions from different hydropower reservoir types and better-informed hydropower management strategies. Lastly, this paper proposes a range of solutions for mitigating

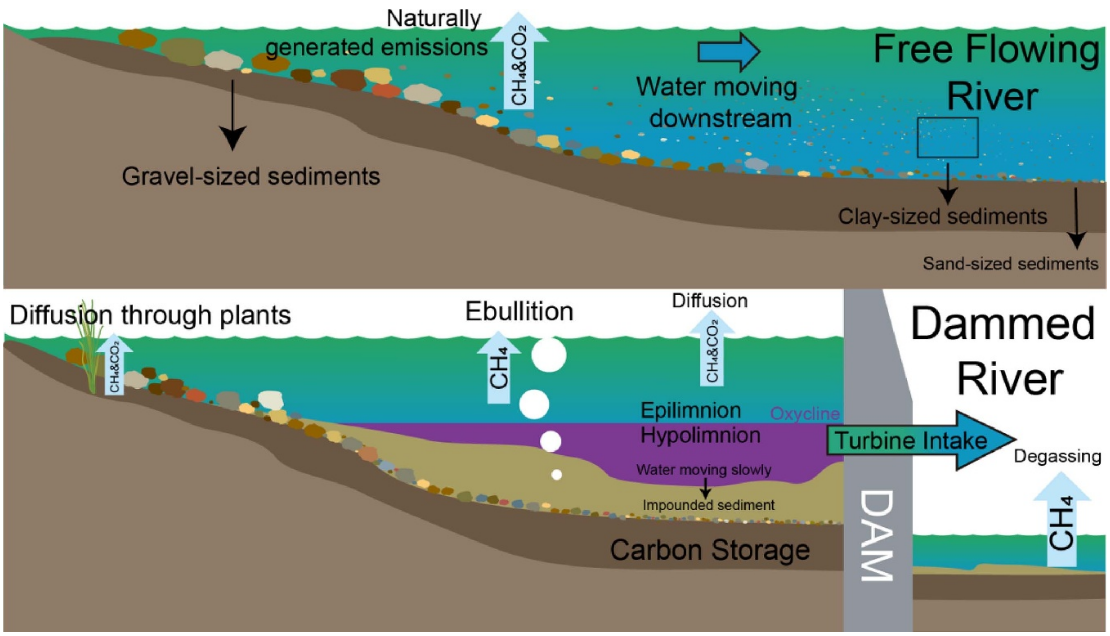

Figure 1. The main carbon emission pathways in a natural free-flowing river (top) and dammed river (bottom).

carbon emissions from hydropower reservoirs in its final sections, providing a level of comprehensive discussion not found in existing literature.

2. Method

Three research databases (Web of Science, Scopus, and Google Scholar) were systematically searched using an evidence-based approach. We queried these databases to identify relevant peer-reviewed articles in English published online from 2000 when St.Louis *et al* (2000) first highlighted the potential of reservoirs to emit high GHG, until 30 June 2023, employing a two-stage search method. The first search method focused on studies that addressed both 'hydropower reservoirs' (or related terms including reservoirs, hydroelectricity, dams, artificial water bodies, and lakes) and GHG emissions (or variants) within the title field. The initial search yielded 239 articles, mainly related to environmental science.

From this comprehensive list, we conducted a manual review of titles, abstracts, and article content to identify and exclude articles that fell outside the scope of our investigation, including only studies that focused on GHG emissions from hydropower reservoir water bodies. This process resulted in a final set of 43 studies. Since the majority of the articles focused primarily on conventional storage hydropower, to broaden the scope of the investigation we used the keywords 'GHG emissions' and 'PSH' or 'run-of-river' in the second search method to include the other two types of hydropower reservoirs. We applied the same systematic reduction strategy, leading to the identification of 7 relevant papers. Therefore, a total of 50 papers were identified for this review.

3. How altered characteristics of hydropower reservoirs influence GHG emissions

River damming modifies the hydraulic and sedimentological characteristics of rivers, leading to altered GHG emissions from hydropower reservoirs relative to the original river. This section summarizes two of the main waterbody characteristics that are altered in hydropower reservoirs and illustrates how they may affect GHG emissions (figure 2).

3.1. Water impoundment

Water impoundment by dams disrupts the downstream transport of sediment, leading to sediment and nutrient loads being retained within reservoirs. Human-induced changes to land use have brought about significant soil erosion, which is washed into river systems, elevating sediment and nutrient loads in rivers, globally (Mulholland *et al* 2008, Kreiling *et al* 2020). The water residence time (WRT), which is the time that a parcel of water is retained in the water body, is also increased due to river damming. It is estimated that dammed basins globally have an average WRT that is 58 d longer than undammed basins (Voeroesmarty *et al* 1997). Ultimately, it is the combination of elevated sediment and nutrient loads in rivers, their retention in reservoirs, and increased WRTs that create the conditions that enhance the biogeochemical and physical transformations leading to carbon burial (i.e. storage) and gaseous release into the atmosphere (Sobek *et al* 2009, 2012, Maavara *et al* 2020).

The balance between carbon burial and carbon emissions determines whether a reservoir is a net

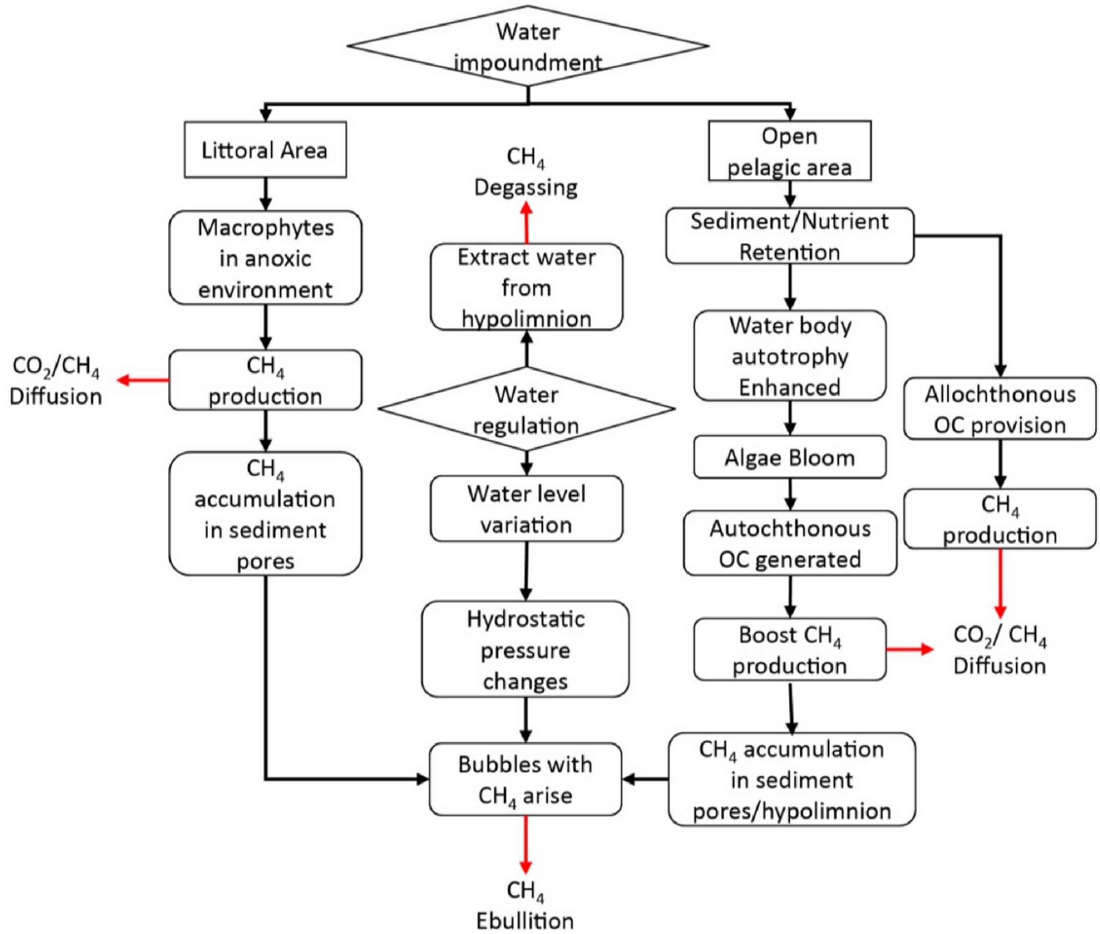

Figure 2. Characteristics altered by hydropower reservoir impoundment and how they can lead to GHG emissions from reservoirs.

carbon sink or a source. Anthropogenic changes in the landscape that typically increase soil erosion and nutrient inputs, can lead to algal blooms and increased net primary production (NPP) (Heathcote and Downing 2012). When the algal life cycle is completed, the decaying algae are converted into dissolved organic matter that typically enters the bottom water and is buried in sediments, which increases carbon burial in reservoirs (Zhou *et al* 2018). Mendonça *et al* (2017) found that anthropogenic sedimentation, eutrophication, and increased river damming are all attributable to a significant increase in carbon burial, which is estimated to be 0.05 Pg C yr^{-1} globally, accounting for nearly 33% of the total estimated global carbon burial rate.

Anthropogenic increases in aquatic productivity can also lead to increased GHG emissions by increasing NPP, leading to more carbon fixation through photosynthesis and increasing the autochthonous organic carbon (OC) in sediments (Sobek *et al* 2009, Maavara *et al* 2017). Increases in autochthonous OC can increase CH_4 emissions, with measurements indicating that CH_4 emissions from global reservoirs increase with system autotrophy (Deemer *et al* 2016). In oxygen-depleted environments, numerous bacterial communities' favor autochthonous OC over allochthonous OC, as the latter is typically older and has undergone extensive degradation and transformation processes during deposition. This results in the accumulation of complex molecules that are more resistant to methane-producing bacteria (Mollenhauer and Eglinton 2007, Sobek *et al* 2009). In aerobic conditions, the mineralization of allochthonous OC will be faster compared to anoxic environments (Bastviken *et al* 2004b) as only aerobic bacteria can break down structurally complex allochthonous OC (Sobek *et al* 2009). This recalcitrant OC slows down mineralization and prolongs methanogenic reactions (West *et al* 2012). On the contrary, autochthonous OC is more labile and can readily ferment leading to increased CH_4 production (West *et al* 2012). Thus, the increase in autochthonous OC brought about by eutrophication also enhances methanogenesis in bottom waters (Sobek *et al* 2009, Deemer and Harrison 2019). The CH_4 produced in the bottom waters dissolves in sediment porewater. Due to the low porosity of sediments, there is limited diffusion of CH_4, causing it to accumulate and become supersaturated in the sediment porewater. This excess CH_4 leads to the formation of gas bubbles, which are eventually released into the surrounding environment (Sobek *et al* 2012).

Hydropower reservoirs typically have a high average depth. Specifically, 27.1% of dams have an average depth between 0.1 m and 10 m, 28.52% between 10 m and 20 m, 16.72% between 20 m and 30 m, and 28.74% have an average depth above 30 m (according to the GranD database, Lehner *et al* 2011). As a result, they frequently exhibit thermal stratification driven by density gradients induced by solar surface heating, which hinders water mixing (Winton *et al* 2019, Cheng *et al* 2020). Where this stratification occurs, it separates reservoir waters into two distinct layers: a colder, oxygen-deprived bottom layer known as hypolimnion, and a warmer upper layer referred to as the epilimnion. The differing water densities of the hypolimnion and epilimnion impede the upward mixing of water from the bottom layer, thereby hindering nutrient exchange between the two layers (Elçi 2008). Under such circumstances, CH_4 produced in the hypolimnion can accumulate in the deeper portions of the water column. Also, thermal stratification leads to reduced oxygen levels in the colder bottom layer. This occurs because of limited water mixing to replenish oxygenated water from the surface and due to heterotrophic consumption. These conditions create an environment conducive to hypoxia, thereby promoting methanogenesis and facilitating the production and accumulation of CH_4 in the hypolimnion (Winton *et al* 2019).

3.2. Water regulation

Another mechanism through which hydropower reservoirs can influence GHG emissions is the water regulation process. Hydropower reservoirs store and release water to meet the hourly, daily, weekly, and seasonal demands for renewable energy, as well as to accommodate variations in hydrological regimes. One consequence of the water intake process is the degassing of CH_4 from the hypolimnion. When stratified, if the hydropower water intake depth is below the oxycline in the hypolimnion, accumulated CH_4 can escape into the atmosphere during the hydropower pumping process. Fearnside and Pueyo (2012) calculated that CH_4 emissions through this pathway can account for more than 50% of the total emissions in Amazonian reservoirs. Note that the water intake depth of high-head storage hydroelectric dams often ranges from 10 to 20 m below the water surface, typically aligning with or exceeding the thermocline depth (Winton *et al* 2019). Delwiche *et al* (2022) developed a new mechanistic model to predict CH_4 emissions from diffusion, ebullition and degassing. If all reservoirs had deep intakes with thermal stratification, maximum degassing emissions could reach 11 ± 4 Tg C yr^{-1}, with total emission from diffusion and ebullition pathways of 2.8 ± 0.2 Tg C yr^{-1}. In the future, elevating the water intake depth to avoid emissions from hypolimnion may help to constrain CH_4 emissions from hydropower.

Another related effect of water regulation from reservoirs on GHG emissions is the change in water level. Human-induced management of hydrological systems typically increases the amplitude of water level changes compared to unaltered hydrological systems. Cooley *et al* (2021) used satellite-measured water level data to calculate changes in water levels between October 2018 and July 2020 in 227 386 waterbodies globally, representing 3.9% of the total surface water reserves of the Earth. They found that the average seasonal water level variability was approximately 0.86 m in reservoirs, compared to about 0.22 m in natural rivers and lakes. In areas such as Colorado, Shatt Al Arab and Amazon basins, the water storage variability was 20 times higher than in natural water bodies (Cooley *et al* 2021). In the USA, 95% of reservoirs have endured at least one annual drawdown of 0.5 m and 70% have experienced multiple drawdowns of this magnitude (Harrison *et al* 2017).

The magnitude of water level changes may enhance GHG emissions by promoting more methanogenesis from the littoral zone (Tranvik *et al* 2009, Deemer *et al* 2016, Harrison *et al* 2017, Cooley *et al* 2021). Yang *et al* (2011) found that the average methane flux in the littoral zone of the Miyun Reservoir in China was 6.5 times higher than that in the methane flux in the open zone. Yang *et al* (2014) also showed that, in the littoral zone, the average CH_4 emission from seasonally inundated areas was 1120 times higher than that of the permanently unsubmerged areas. While this may be an extreme case, it suggests that during the drawdown the littoral zone becomes exposed allowing terrestrial vegetation to grow. Subsequently, the area is re-inundated when water levels rise, submerging vegetation and leading to GHG emissions as the newly submerged vegetation decomposes (Yang *et al* 2014, Deemer *et al* 2016). Under fluctuating water levels, not only is vegetation periodically submerged, but also the changing redox potential of the soil can lead to GHG emissions. When the water level is high, the soil transforms into an anoxic environment, which is more conducive to methanogenesis, producing CH_4 (Yang *et al* 2014, Deemer and Harrison 2019). Conversely, when the water level decreases, the soil becomes an aerobic environment, leading to lower CH_4 fluxes.

The ebullition emission pathway is also controlled by water level variation. Significant changes in hydrostatic pressure during drawdown can lead to a burst of ebullition events (Maeck *et al* 2014, Deemer and Harrison 2019), as lower water depths allow more bubbles to transfer CH_4 to the atmosphere. However, ebullition does not always correlate negatively with water depth. McGinnis *et al* (2006) tested an ebullition model at two sites; a shallow site (at a depth of 90 m) and a deeper site (230 m). The relationship between water depth and CH_4 emissions was not straightforward and only at shallow water depths

Table 1. Measured average CO_2, CH_4 flux rate, and carbon intensity of conventional, run-of-river, and PSH hydroelectric reservoirs.

Hydropower Reservoir Type	CO_2 (mg C m^{-2} d^{-1})	CH_4 (mg C m^{-2} d^{-1})	Carbon Intensity (gCO_2e/kWh)
Conventional	223 (−356–2636)[a]	40 (24–128)[a]	32.34 (1.2–547)[b,f]
Large	428.32[a]	37.34[a]	8.91 (2.06–32.63)[b,f]
Medium	458.01[a]	267.12[a]	119.53 (5.47–547)[b,f]
Small	241.86[a]	327.54[a]	22.43 (1.2–74.9)[b,f]
PSH		4.2–46.5[c]	5.6[d,f], 155[e,f], 609[e,f].
Run-of-River			1.2–55[b,f]

[a] Deemer *et al* (2020), Barros *et al* (2011).
[b] Gemechu and Kumar (2022), Li and He (2022).
[c] Encinas Fernández *et al* (2020).
[d] Denholm and Kulcinski (2004).
[e] Flury and Frischknecht (2012).
[f] Life Cycle Assessment values, with the carbon intensity column divided by ranges of large >100 MW, 10 < medium ⩽ 100, and small ⩽ 10 MW.

(i.e. less than 100 m) could significant amounts of CH_4 be transferred to the atmosphere, while at 230 m most of the CH_4 in the bubbles dissolved before it reached the water surface (McGinnis *et al* 2006). Additionally, the longer water column allows for a higher fraction of CH_4 to be oxidised. It also reduces the flux through vegetation, which can lead to CH_4 avoiding oxidation and thus being released into the atmosphere (Barros *et al* 2011). These findings suggest that a prudent reservoir management approach should include optimizing the trade-offs between water depth and surface area to reduce GHG emissions while achieving water supply and electricity production.

4. How hydropower size and type influence GHG emissions

The size and type of hydropower scheme can affect GHG emissions. First, the impact of the hydropower scale is discussed, necessarily considering the geographical region in which hydropower schemes are located. Second, hydropower type is discussed, with particular consideration given to two less-discussed types of hydropower; run-of-river and pump-storage hydropower. How the mode of operation can impact GHG emissions is detailed.

4.1. Hydropower scale

GHG emissions from reservoirs occur via four pathways, which are partially controlled by the type and size of hydropower. The size of a hydropower facility can be quantified in terms of storage capacity. Storage capacity denotes the volume of water that can be impounded when the water level reaches the top of the dam (SCDHEC 2023). To categorize hydropower by scale, we compiled the CO_2 and CH_4 flux data from 267 reservoirs, as reported in the literature and synthesized by Deemer *et al* (2020) (figure 3). Additionally, to accurately assess the impact of reservoir size, it is necessary to consider hydropower facilities in different climatic zones, as varying temperatures and weather conditions significantly affect GHG emissions (Barros *et al* 2011). Therefore, average emissions were calculated for four climate zones: boreal, temperate, Amazonian tropical and non-Amazonian tropical. The tropical zone was divided into Amazonian and non-Amazonian regions because the rich biodiversity and dense rainforests of the Amazon can accumulate significant amounts of organic matter in inundation areas, resulting in higher emissions compared to other tropical zones (Almeida *et al* 2019).

CH_4 emissions were higher per m^2 in small hydropower (table 1) than in large hydropower schemes in the majority of climatic zones (figure 3). However, for average CO_2 fluxes, this pattern is not universal, with a more consistent pattern emerging with scale in the non-Amazonian tropical and boreal regions. Therefore, there is a tendency for small hydropower reservoirs to have higher GHG emissions per unit area than larger ones. While larger reservoirs typically have higher total GHG emissions than smaller equivalents due to their larger area, cumulatively across the many millions of small reservoirs that exist globally, small reservoirs contribute significantly to GHG emissions from hydropower schemes (Downing *et al* 2006, Ollivier *et al* 2019, Webb *et al* 2019). This raises questions about the relative GHG emission impacts of many small schemes versus a few big schemes, discussed further below.

Few studies have considered the cumulative contributions of GHG emissions from small hydropower reservoirs (Grinham *et al* 2018, Ollivier *et al* 2019, Webb *et al* 2019). Several factors have been discussed as responsible for the large areal GHG emissions from small schemes (Wang *et al* 2017, Webb *et al* 2019, Beaulieu *et al* 2020). The first is the extensive use of small reservoirs for agricultural purposes. Agricultural land is often subject to intensive modification, including inputs of fertilizers, crop rotations, and mechanical disturbance of the soil, all of which can lead to increased sedimentation and nutrient runoff into reservoirs (Webb *et al* 2019). In addition,

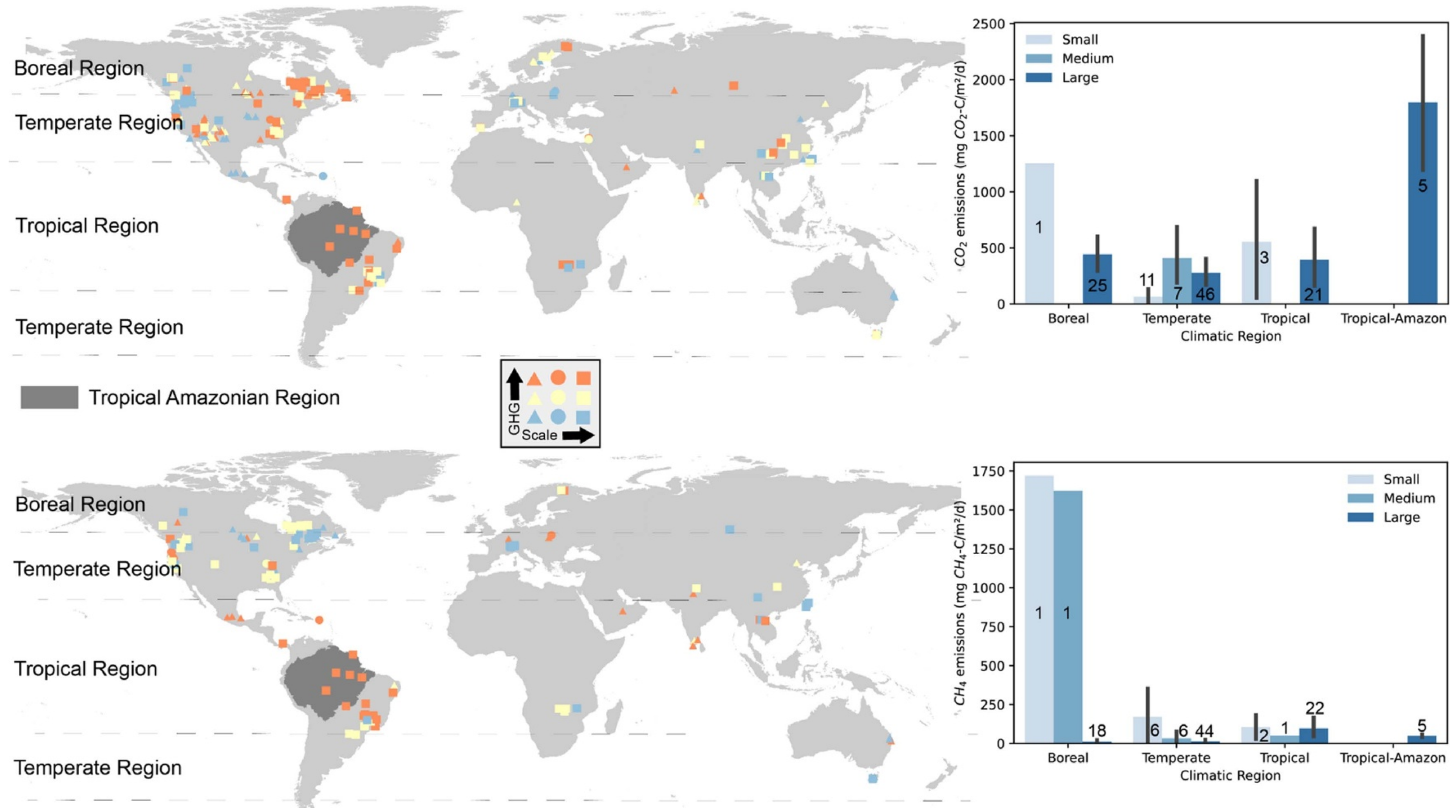

Figure 3. Comparisons of reservoir GHG emissions with a 20 year time horizon. According to the storage capacity, the reservoirs are classified into Small (Volume < 0.01 km^3), Medium (0.01 km^3 $<$ Volume < 0.1 km^3), and Large (Volume > 0.1 km^3). Data are from Deemer *et al* (2020). Average CO_2 and CH_4 emissions for the Boreal, Temperate, Tropical and Tropical-Amazon regions are shown as bar charts with the number of data points and 95% confidence intervals (CIs) indicated (black lines). Bars with only one data point lack 95% CIs.

small areas of inundation and the low buffering capacity of shallow, littoral zones make them vulnerable to external disturbances from the nearby environment (e.g. watershed land use types, wastewater discharge and agricultural practices) (Wang *et al* 2017). Hence, the large proportion of littoral zones may be partially responsible for higher GHG emissions from small reservoirs.

In larger reservoirs, the main source of biodegradation initially after construction is material originating from the original inundation. However, once the inundated area is fully decomposed, the influx of terrestrial and anthropogenic material becomes more important (Wang *et al* 2017). There is a negative correlation between water body size and sediment OC accumulation rates (Phyoe and Wang 2019). Grinham *et al* (2018) monitored 22 small ponds (surface area of 10^2–10^5 m^2) and found that smaller waterbodies had higher emissions than larger waterbodies, which was linked to greater variability in surface area in the smaller water bodies. Smaller reservoirs typically have a larger proportion of littoral habitats (areas less than 3 m deep) relative to their water volume when compared to large reservoirs, which can provide a significant source of degrading organic matter (Beaulieu *et al* 2020). Beaulieu *et al* (2020) used a machine learning algorithm to investigate the relationship between the three emission mechanisms of CH_4 and reservoir morphology and found a positive relation between littoral extent and CH_4 emission rates. This might be related to the relatively shallow water bodies offering little opportunity for the CH_4 released from littoral sediments to be oxidized and converted to CO_2 in the shallow water column, resulting in increased CH_4 emissions (Beaulieu *et al* 2020).

Another key factor influencing GHG emissions is the WRT. Webb *et al* (2019) revealed that CH_4 concentrations were at their lowest when WRT exceeded one year. Shorter WRTs have been linked to elevated internal CO_2 generation due to accelerated rates of allochthonous Dissolved OC decomposition (Vachon *et al* 2017). Longer WRTs typically occur in larger and deeper reservoirs, which take more time to exchange water within the reservoir itself. These larger reservoirs have a greater capacity for assimilating nutrients, leading to lower nutrient concentrations within the system and, therefore, a longer time before the detrimental effects of elevated nutrients are realised (Webb *et al* 2019). Deeper and larger reservoirs with longer WRTs normally have purer water (less turbid with higher clarity), which improves the passage of light through the water column and increases primary production, thereby facilitating CH_4 oxidation (Bastviken *et al* 2008, Webb *et al* 2019).

4.2. PSH

PSH plants use the force of gravity to generate electricity by releasing water previously pumped from lower water sources. Thus, it has two reservoirs at different altitudes located close to each other (figure 4). PSH has two main types, open-loop and closed-loop, where open-loop has an upper or lower reservoir connected to the river system and closed-loop is located away from the natural waterbodies (IHA 2024). The water in the upper reservoir is pumped up anthropogenically from the lower reservoir when generated renewable energy exceeds the demand (e.g. a windy or sunny day), and released from the upper reservoir to the lower one when the supply is lower than the demand (Blakers *et al* 2021). The types of pumping and generation cycles can be annual, seasonal, weekly or daily, and the larger the reservoir capacity, the more flexible its operating cycle. For example, an annual PSH has the largest upper reservoir storage capacity, which can store water for many years and release it during drought years or for daily use. However, a daily-running PSH cannot be run as a PSH for weekly, seasonal, or annual operating cycles due to its limited capacity (Hunt *et al* 2018).

Few studies have measured the GHG emissions of PSH during its operational phase. During the operation of PSH, the pumping and water release for power generation increases the aeration of the waterbodies, enhancing circulation and the mixing of water. Such processes will typically increase oxygen concentrations, as well as limit algal growth, promote the degradation of pollutants, and enhance the self-purification ability of the reservoir (Yang and Jackson 2011). As such, the operational programme of a PSH may be able to improve the nutrient status of the reservoir and lower the chance of eutrophication. This may indicate the potential for smaller GHG emissions from PSH reservoirs relative to similar-sized reservoirs used for more traditional hydropower operations. In support of this hypothesis, the most recent Global Synthesis of GHG Emissions report states that the average CH_4 emissions from reservoirs are approximately 98 mg CH_4 m^{-2} d^{-1} (Deemer *et al* 2020). In contrast, Encinas Fernández *et al* (2020) measured CH_4 extraction fluxes from a PSH located in Germany of around 5.6 and 62 CH_4 mg m^{-2} d^{-1} when the reservoir was executed as a daily or seasonal PSH.

Lower levels of sedimentation are another potential driver of lower carbon emission from closed-loop PSH than storage hydropower. The closed-loop PSH is likely to have a lower sediment load than reservoir hydropower as it is usually located in small watersheds or tributary rivers where the sediment load is significantly lower (Hunt *et al* 2018, 2021). Water from the upper reservoir is typically pumped via tunnels or pipes, reducing the exposed surface area where sediment can be deposited and, therefore, sedimentation does not as readily accumulate in upper reservoirs. Lower levels of sedimentation in the closed-loop PSH could lead to lower CH_4 production and storage, and

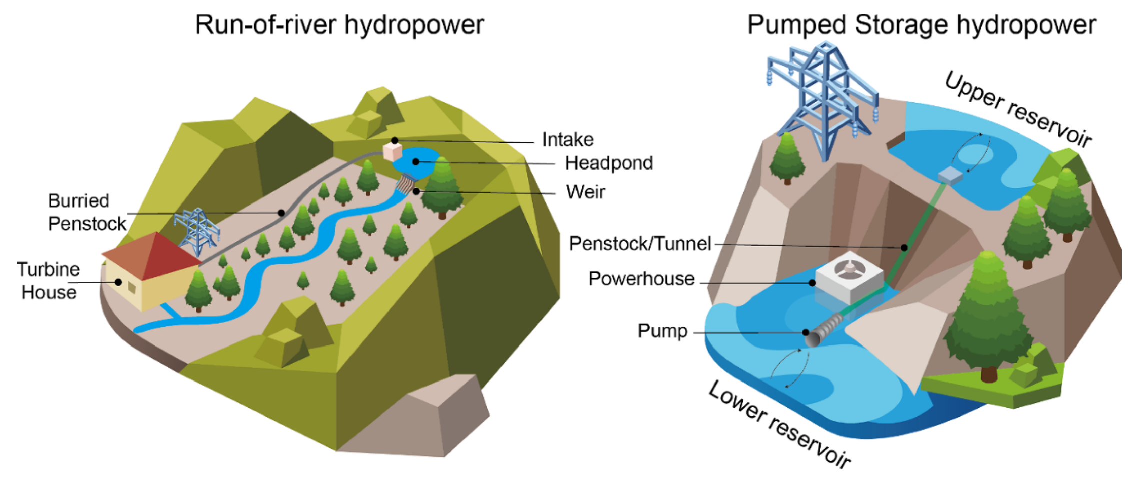

Figure 4. Diagram showing typical infrastructure associated with pumped storage hydropower and run-of-river hydropower.

lower GHG emissions in the closed-loop PSH might therefore be expected.

4.3. Run-of-river hydropower

Run-of-river hydropower generates electricity by harnessing the force of water with turbines, which capture the potential energy and kinetic energy from passing water without the need for a reservoir or pump action (figure 4). The amount of electricity that can be generated by the turbine depends on the discharge of water and the height of the waterfall (head) (Anderson *et al* 2015). Greater discharges and higher water heads can generate more hydroelectric power. Typically, the water head is created by a weir located at a relatively high point within a catchment to divert a proportion of the flow through a pipe leading to a downslope powerhouse (Gibeau *et al* 2016). Because run-of-river schemes typically have small or nearly zero water storage, they are associated with lower sedimentation and eutrophication.

Moreover, GHG emissions during operation are expected to be small (Silverthorn *et al* 2018, Blakers *et al* 2021), as the water in the run-of-river is constantly flowing. Sawakuchi *et al* (2021) evaluated the CH_4 dynamics of the Santo Antônio hydropower reservoir, a run-of-river reservoir in the Amazon River basin. Adequate mixing and oxygenation in the reservoir water column resulted in low methane emissions, possibly due to higher rates of methane oxidation during the falling water season (Sawakuchi *et al* (2021). In addition, such schemes reduce the chance of eutrophication and reduce the likelihood of sediment deposition relative to upstream storage hydropower dams. This makes run-of-river schemes unfavorable places for methanogenesis, hence they have lower GHG emissions during operation (Dones *et al* 2007).

5. Opportunities to lower GHG emissions from hydropower reservoirs

A major limitation in understanding GHG emissions from hydropower reservoirs and therefore our ability to manage GHG emissions effectively, is a lack of monitoring and measurements in reservoirs. A range of approaches for measurement approaches have been used to estimate these emissions (Barros *et al* 2011, IHA 2012, Deemer *et al* 2016, Harrison *et al* 2017, Prairie *et al* 2018). The most direct approach involves measuring emissions at multiple sampling sites across a reservoir over an extended period (Wik *et al* 2013, 2016). While this method can provide relatively accurate estimations, it requires substantial financial and labour support and may still miss spatial variability in GHG release across large reservoirs. Some studies employ a simplified approach to gauge carbon flux by measuring CO_2 and CH_4 concentrations in water and then deriving diffusive emissions (Wang *et al* 2017, Paranaíba *et al* 2018, Yang 2019). However, these methods are unable to fully capture emissions through ebullition and degassing pathways. The International Hydropower Association (IHA) has developed a G-res model, an empirical modeling approach that does not require on-site measurements (Prairie *et al* 2021). Practitioners enter values for a range of parameters to obtain estimations of diffusive, ebullitive, and degassing emissions (Prairie *et al* 2017). While this model can provide close estimates of reservoir emissions, the lack of available monitoring data impedes opportunities to test the model beyond a few key datasets.

Although techniques for measuring GHG emissions from reservoirs are evolving, there remains a lack of synthesis regarding solutions for reducing these emissions. In this section, we propose solutions to minimize emissions from two perspectives. One is by managing the physical mechanisms that lead

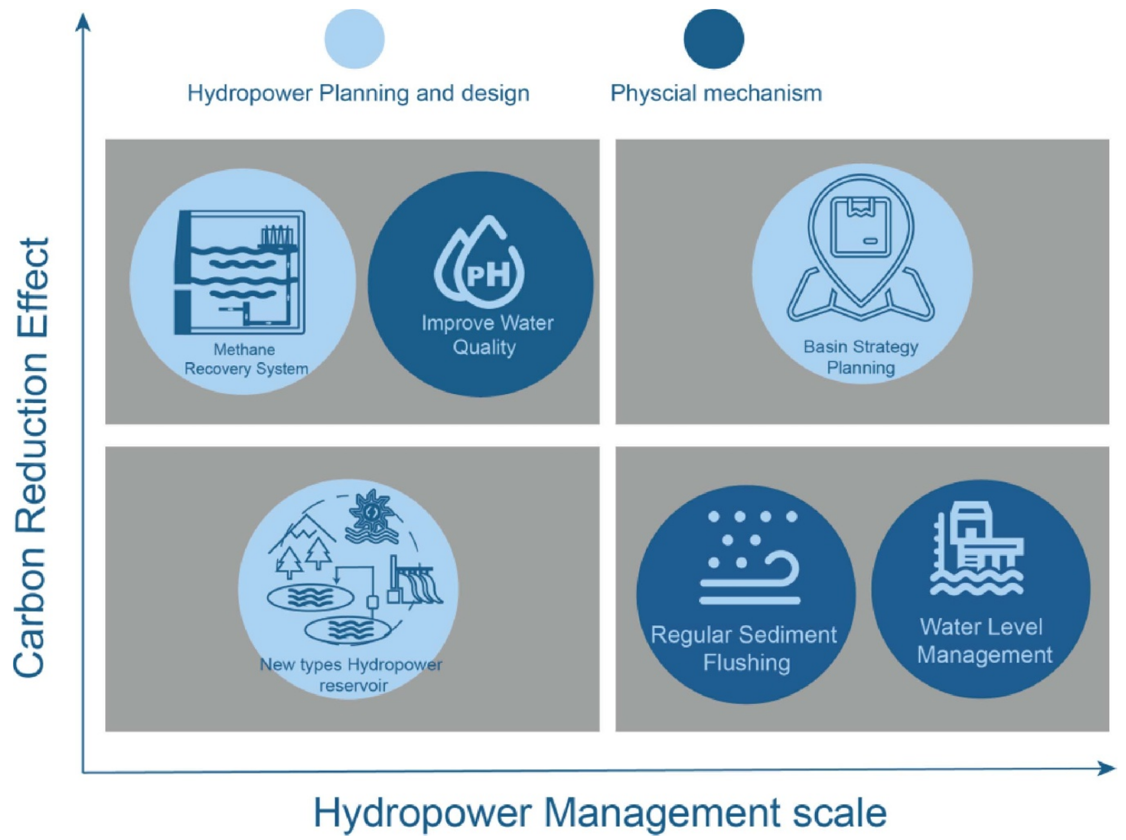

Figure 5. The proposed solutions are placed in a matrix, where the *x*-axis is the scale of hydropower management, indicating whether the management scale can be implemented at a larger (e.g. basin) or smaller (e.g. individual) scale. *y*-axis is the carbon reduction effect, i.e. how significantly the solution reduces carbon emissions from the reservoir.

to carbon production and emission and the other is by considering hydropower planning and design (figure 5). Every solution is not a one-size-fits-all and each has its advantages, challenges, and limitations. The appropriate one should be selected by considering the characteristics of the reservoirs and the solutions (table 2).

5.1. Solutions based on the management of physical mechanisms

5.1.1. Water level management

To reduce GHG emissions from hydroelectric reservoirs, managing water levels is a crucial initial consideration. One management approach is to decrease the area of drawdown. Shi *et al* (2021) conducted in situ measurements in the water level fluctuation zone around the Three Gorges Reservoir in China to see if continuous flood (CF), periodic flood (PF) and no-flood (NF) scenarios would have different impacts on GHG emissions. Compared to the NF scenario, CH_4 emissions were 13.3 and 5.7 times higher for CF and PF, respectively. The lower CH_4 emissions in PF may be related to frequent exposure to oxygen, which converts CH_4 to CO_2, while continuous water inundation in CF inhibited CH_4 oxidation and the anaerobic environment stimulated CH_4 emissions. However, this study did not consider emissions from CH_4 ebullition and degassing, but it is possible that GHG emissions from inundated areas could be limited by controlling the drawdown area during water regulations (Grimardias *et al* 2017, Harrison *et al* 2017, Keller *et al* 2021).

Shorter operational cycles of water level management might also reduce CH_4 emissions. Encinas Fernández *et al* (2020) measured CH_4 ebullition from PSH using daily and seasonal operating modes in Autumn when water height and temperature were consistent and did not lead to large changes in CH_4 production. The daily operation mode resulted in lower CH_4 emissions than the seasonal operation mode. In the seasonal operating mode, PSH will experience long periods of stagnation and, in the absence of pumping and generation, CH_4 will accumulate in the sediment. This accumulation will increase the proportion of CH_4 in bubbles and lead to greater emissions when the hydrostatic pressure drops. For example, Harrison *et al* (2017) reported a positive relationship between ebullition flux and CH_4 concentration in bubbles. In contrast, shorter operating cycles allow for the periodic removal of CH_4 from the sediment, avoiding significant accumulation of CH_4 in pore water. In this case, shorter operating

Table 2. The main advantages, challenges and limitations of six solutions.

	Solutions	Advantages	Challenges and limitations	Citation
Physical mechanisms	Water level management	• CH_4 emissions could be reduced through shorter operational cycles. • Increasing water intake depth may achieve certain carbon reductions.	• There is a trade-off in water level management between carbon reduction objectives and energy generation, flood control, and downstream water usage objectives.	Encinas Fernández *et al* (2020), Wu *et al* (2022), Bambace *et al* (2007)
	Regular sediment flushing	• Sediment can be removed mechanically by regular hydraulic flushing.	• A drastic drop in water levels can lead to additional CH_4 emissions. • Potential impacts of sediment flushing approaches on downstream ecosystems should be considered.	McGinnis *et al* (2006), Deemer and Harrison (2019). Lessmann *et al* (2023)
	Improve water quality	• Can be implemented on a project-by-project basis. • Involve relatively simple strategies, such as installing fences around reservoirs or increasing O2 concentration in the water column. • Inhibit carbon emissions from the production stage.	Depends on cooperation with management bodies at the project level.	Li *et al* (2017b), Deemer and Harrison (2019), Malerba *et al* (2022)
Hydropower planning and design	Methane recovery system	• Captured CH_4 can then be utilized for further energy generation.	• Only economically feasible in reservoirs with CH_4 concentrations exceeded 6 g m^{-3}. • require significant capital investment.	Bambace *et al* (2007), Ramos *et al* (2009), McAnulty *et al* (2017), Wood *et al* (2023)
	New types of hydropower Reservoirs	Reducing environmental impact while meeting energy and water needs	Trade-offs for traditional reservoirs with multipurpose usage.	Kumar *et al* (2011), Hunt *et al* (2018), Hunt *et al* (2021)
	Basin strategy planning	Can optimize the carbon intensity of hydropower extensively.	Involving collaboration among various stakeholders.	Almeida *et al* (2019), Open Hydro (2022)

cycles could be a possible strategy to control GHG emissions from reservoirs (Encinas Fernández *et al* 2020).

Another way to reduce GHG emissions through water level management is to optimize the water intake depth to reduce CH_4 degassing. To avoid more CH_4 degassing, the intake depth should be higher than the thermocline depth, below which CH_4 can accumulate. Bambace *et al* (2007) proposed a sliding water extraction system to adjust the water intake depth to generate power. The system consists of a light metal structure as a barrier, and anchors and buoys as moderators to change the water level through the turbines and pipes. Real-time monitoring of CH_4 concentration and water level can inform the appropriate height at which water can be extracted to avoid CH_4 degassing and water shortages. Nevertheless, it is unlikely that every dam will be equipped with real-time CH_4 concentration monitoring and a sliding water intake system, but increasing the water intake depth may also alleviate GHG emissions. Wu *et al* (2022) examined the different water intake depths of the Wujiangdu Reservoir in China and found that when the intake depth increased by 30 m, downstream GHG emissions decreased by 1.9%. Therefore, optimization of the water depth at the dam intake may include certain carbon reduction objectives in addition to consideration of the minimum drawdown level to ensure downstream water usage and the full reservoir level for storage and flood control. Additionally, it needs to satisfy the water level necessary to meet potential energy demands for power generation.

5.1.2. Regular sediment flushing

Sedimentation is a key factor that can lead to higher CH_4 emissions as it provides the substrate necessary to produce and store CH_4. To reduce sedimentation, sediment can be removed mechanically or by hydraulic flushing. Hydraulic flushing utilizes the erosive force of water to carry sediment downstream through a dam outlet. The frequency of flushing depends on the sediment load of the reservoir and varies from twice a year to once every five years (Chang *et al* 2003, Grimardias *et al* 2017, Lessmann *et al* 2023). However, this sediment management strategy may be an alternative CH_4 emission pathway. As CH_4 stored in sediment pores can be degassed to the atmosphere, the additional likelihood of degassing due to disturbance could lead to additional CH_4 emission. For example, it is estimated that CH_4 emissions from a single flushing event can account for 7%–14% of the annual CH_4 emissions from the Schwarzenbach reservoir in Germany (Lessmann *et al* 2023).

Furthermore, flushing is often accompanied by a drastic drop in water levels due to the large amount of water being flushed downstream, which can lead to additional CH_4 emissions (McGinnis *et al* 2006, Deemer and Harrison 2019). However, regular flushing is expected to cause smaller increases in CH_4 emission than mechanical removal because the depth of sediment disturbed is typically greater when mechanically removed. For example, Lessmann *et al* (2023) indicate that the thicker the mobilized sediment layer, the greater the amount of CH_4 emissions that will be released per unit of sediment. Therefore, flushing should be carried out regularly and the amount of CH_4 emitted during flushing activities should also be considered when estimating the annual CH_4 emissions from the reservoir. The potential impacts of sediment flushing approaches on downstream ecosystems should, however, be carefully considered.

5.1.3. Improve the water quality

Deterioration of water quality is a controlling factor contributing to increased GHG emissions from hydropower reservoirs. Therefore, improving reservoir water quality and controlling eutrophication would reduce GHG emissions; however, achieving such improvements is challenging. One way to improve the water quality of reservoirs is to carry out pre-impoundment clearance, i.e. to remove all buildings, structures, solid wastewater and vegetation during the site preparation stage of reservoir construction (Li *et al* 2017b). For example, in China, national codes and regulations require stakeholders in hydropower to carry out pre-impoundment clearing before dam construction, which is usually done in the preparation phase (Li *et al* 2017b). This clearance will remove all vegetation and, if these areas involve resettlement, buildings, structures and solid waste are also removed. This significantly reduces the potential organic matter available for decomposition, in turn decreasing the production and release of GHGs. Li *et al* (2017b) estimated the carbon emission reductions from five large hydropower projects in China as a result of pre-impoundment clearance, also considering the carbon footprint from the clearance activities themselves. The results show that pre-impoundment clearance can reduce carbon emissions equivalent to 14.43%–246.80% of the carbon footprint of the clearance activities themselves, with hydropower projects involving higher population densities and lower energy densities having a larger carbon footprint from their clean-up activities. After a comprehensive assessment of the individual projects, pre-impoundment clearance can be an effective carbon reduction measure for reservoirs.

In addition to measures to control the eutrophication state of the reservoir before impoundment, measures can be taken to reduce eutrophication after reservoir creation. Small agricultural reservoirs are often exposed to high concentrations of nitrogen and phosphorus from fertilizers and livestock manure and, as such, are at high risk of methanogenesis and associated GHG emissions (Malerba *et al* 2022). For example, the installation of fences around small reservoirs can limit livestock disturbance of vegetation and soils, reducing direct OC inputs into the water and increasing vegetation cover that indirectly reduces OC by filtering dissolved nutrients in overland runoff (Westgate *et al* 2022). Malerba *et al* (2022) used controlled experiments to show that fenced reservoirs had 32% lower dissolved nitrogen and 39% lower phosphorus concentrations than unfenced reservoirs. Moreover, CH_4 diffusion was 56% lower in fenced reservoirs in comparison to unfenced ones (Malerba *et al* 2022). Therefore, fencing as a physical measure can reduce GHG emissions, which is a relatively cost-effective and simple strategy that can positively contribute to managing GHG emissions.

Increasing O_2 concentrations can also reduce GHG emissions. CH_4 production occurs primarily in the anaerobic zone, which is common in eutrophic waters. Therefore, to reduce CH_4 emissions, aeration of the water column and increased water mixing throughout the thermocline can increase O_2 concentration in the anaerobic zone, thereby inhibiting CH_4 production. In the epilimnion zone with aerobic environments, microbial decomposition tends to seek out O_2 to break down OC, but when O_2 is depleted, microbial decomposition tends to favor the presence of electron acceptors starting from NO_3^-, MnO_2, $Fe(OH)_3$, and CO_2 to oxidize the OC, which results in the accumulation of reduced Mn, Fe, and CH_4 (Hafeman *et al* 2007, Deemer and Harrison 2019). In addition, increasing the O_2 in the water column also increases the oxidation of CH_4, which will also reduce subsequent emissions (Deemer and Harrison 2019).

5.2. Solutions associated with hydropower planning and design

5.2.1. Methane recovery systems

CH_4 is not only a GHG but can also be a source of renewable energy. It can be converted into energy-dense liquid fuels or electricity with reduced CO_2 emissions per unit of energy (McAnulty *et al* 2017, Quaranta and Muntean 2023). Installing CH_4 collection systems in reservoirs where high concentrations of CH_4 accumulate can potentially reduce GHG emissions from reservoirs. The captured CH_4 can then be utilized for further energy generation (Bluemethane 2024). CH_4 capture systems work by transporting deep water containing high concentrations of CH_4 to the surface and then extracting the dissolved CH_4 into a sealed container by bubbling or spraying (Ramos *et al* 2009). The extraction system can be mobile so that when a site is depleted of CH_4 it can be moved to another area where the water is saturated with CH_4 (Kling *et al* 2005, Bambace *et al* 2007). Later, the CH_4 will be transported to a larger consumption center in which it can be safely stored and, when the electricity demand is high, it will be burned and its heat converted into electricity (Bambace *et al* 2007, Ramos *et al* 2009).

While the use of CH_4 capture systems holds promise for providing additional renewable energy from reservoirs, it is only economically feasible for large, CH_4-rich reservoirs. Bambace *et al* (2007) estimated the potential CH_4 equivalent electric energy of five reservoirs in the Amazon forest and evaluated the corresponding extraction costs to assess the economic impact of CH_4 capture systems. The efficiency of CH_4 extraction (i.e. extracted CH_4 minus consumed CH_4 during extraction) showed a positive correlation with CH_4 concentration (Bambace *et al* 2007, Ramos *et al* 2009). When the CH_4 concentration exceeded 6 g m^{-3}, the efficiency reached 40%; however, when the concentration fell below 3 g m^{-3}, the net energy output became negative, rendering the operation unfeasible (Ramos *et al* 2009). Additionally, CH_4 capture and conversion technology require large capital outlays, which are not practical for small-scale hydropower reservoirs (Wood *et al* 2023). In such cases, although small-scale hydropower reservoirs might have substantial CH_4 production, without sufficient financial support to develop such systems, the CH_4 recovery might not be an economically viable solution.

5.2.2. New types of hydropower reservoirs

Traditional hydropower storage systems can effectively provide energy and water storage capabilities. However, their structural design promotes the accumulation of sediment and nutrients which, as discussed above, can lead to significant GHG emissions. A potential solution is to consider alternative forms of hydropower reservoirs, such as PSH or run-of-river hydropower, which have a lower environmental impact (Hunt *et al* 2018, 2021, Silverthorn *et al* 2018, Blakers *et al* 2021). However, run-of-river and PSH do not provide a steady supply of energy compared to storage hydropower. Run-of-river relies on river discharge, while PSH depends on the availability of renewable energy being harnessed. Still, seeking alternatives from novel hydropower reservoirs is a promising approach to reducing GHG emissions from traditional hydropower reservoirs. For example, the seasonal Muquém PSH system in Brazil has been compared to conventional storage hydropower methods (Hunt *et al* 2018). The Muquém PSH is a hybrid system that combines run-of-river and PSH technologies. Its lower reservoir is a run-of-river hydropower that draws water directly from the São Francisco River into its upper reservoir, eliminating the need for a large lower reservoir, and minimizing impacts on the São Francisco River. Its upper reservoir is a seasonal PSH reservoir that can store water for extended periods, even months or years. The Muquém PSH system can release stored water during dry spells to meet both energy and water demands (Hunt *et al* 2018, 2021).

This hybrid system of run-of-river and PSH technologies is inherently designed to avoid extensive water retention for power generation, they typically do not trap large amounts of sediment behind the dam (Hunt *et al* 2018). When comparing the Muquém PSH to conventional storage hydropower, it is evident that, in terms of carbon reduction, the Muquém PSH presents itself as a promising alternative. Nevertheless, a more comprehensive assessment still should be undertaken to understand whether this hybrid run-of-river and PSH system significantly reduces carbon emissions compared to storage hydropower and which type of reservoir is more economical from an economic efficiency perspective (Hunt *et al* 2018).

This consideration is crucial because conventional hydropower reservoirs serve not only for power generation but also for various other purposes such as water supply, flood control, navigation, recreation, and irrigation (Kumar *et al* 2011). Regarding flood control and water supply, the upper reservoir of a hybrid run-of-river and PSH system might have the potential to replace conventional reservoirs if its volume is large enough to store sufficient water for downstream use. However, for purposes such as navigation, recreation and irrigation, it might not be able to provide these services in a convenient means. Consideration should be given to a holistic approach that goes further than carbon reduction targets, taking into account both the climate costs of emissions from reservoirs used for other purposes and the benefits derived from multi-purpose reservoirs (Open Hydro 2022). Therefore, the new hybrid run-of-river and PSH hydropower reservoir is placed in the lower-left matrix (figure 5), with a smaller scale of hydropower management that can be considered at the project level, but whose carbon-reduction effect is still questionable.

5.2.3. Basin-scale planning

Dams are typically planned on a project-by-project basis, without due consideration of their cumulative impacts on the basin (Schmitt *et al* 2018). In particular, different scales of hydropower generation can have different environmental impacts on a watershed, so dam planning should take a more holistic approach to basin-scale considerations, e.g. whether a series of small hydropower plants or a single large hydropower plant in a watershed will provide the greatest benefit to the watershed at the lowest cost (Maavara *et al* 2020).

A basin-scale planning approach was attempted by Almeida *et al* (2019), who conducted a study in the Amazon basin to optimize the selection of future dam locations to minimize the carbon intensity of proposed hydropower generation. Under the optimal scenario, electricity generation could reach 80% of the proposed target and keep the carbon intensity below that suggested for sustainable electricity generation by the International Energy Agency (IEA). If the dams were not selected optimally, the carbon intensity of the Amazon dam's portfolio could be 10% higher than the optimal scenario over a 100 year time horizon. However, it is important to note that this study primarily focused on reducing the carbon intensity of the Amazon basin and did not consider the other services that dams can provide. Each scheme should tailor its planning to meet the unique requirements of the basin within which it is situated.

Furthermore, basin-scale planning should not be limited solely to conventional infrastructure like dams; it should also encompass nature-based solutions (NBS) in managing GHG emissions from reservoirs (Open Hydro 2022). NBS can complement hydropower reservoirs in providing societal needs such as water, energy, and food by contributing to the sustainable management of runoff and sediment regimes in catchments (Stickler *et al* 2013, Moran *et al* 2018, Chung *et al* 2021). NBS refers to actions inspired by, supported by, or mimicking nature (European Commission 2015). Examples include protected wetlands and forests, and initiatives such as the Sponge City program in China (Chan *et al* 2018, 2022, Chung *et al* 2021). Emerging studies indicate that the incorporation of NBS in a basin can enhance the functioning of hydropower reservoirs by reducing sediment loads in catchments that can lead to sedimentation in reservoirs, the uptake of nutrients upstream in the catchment before they reach reservoirs and the regulation of surface runoff.

Stickler *et al* (2013) modeled hydropower generation in the Xingu basin, located in the eastern Amazon basin, under deforestation. The largest hydropower plant, the Belo Monte Dam, could have its maximum installed capacity reduced to a quarter due to deforestation. This is because half of the precipitation of the Amazon basin comes from its internal water cycle (Salati and Vose 1984) and, therefore, deforestation is estimated to significantly reduce regional precipitation and soil moisture levels (Stickler *et al* 2013). In addition, lower rainfall and stored water in watershed soils may lead to lower hydropower production (Stickler *et al* 2013, Moran *et al* 2018).

Given these considerations, basin-scale dam planning, customized to the unique requirements of each basin, emerges as imperative in mitigating environmental impacts, notably GHG emissions. Additionally, urgent attention must be directed towards advancing research on the optimal hydropower reservoir design strategies to enhance water, energy, and food provisioning in the basin, while minimizing GHG emissions from reservoirs.

6. Conclusion

The present paper provides an overview of the principal physical mechanisms modified by damming, which influence GHG emissions from hydropower reservoirs, encompassing water impoundment and water regulation. Across most climatic zones, CH_4 emissions per unit area are typically higher from small hydropower reservoirs with an average of 327.54 mg CH_4–C/m^2/d, compared to 12 mg C–CH_4/m^2/day for medium-sized reservoirs and 37.34 mg C–CH_4/m^2/day for large reservoirs. Small reservoirs are characterized by smaller storage compared to medium and large reservoirs. Nevertheless, the extensive coverage of larger reservoirs and the scarcity of data concerning the location and spatial extent of smaller schemes pose challenges in comparing total GHG emissions across hydropower installations of varying sizes. Run-of-river and closed-loop PSH systems generally exhibit superior water quality and reduced sedimentation rates compared to conventional reservoir hydropower, thereby being linked to lower GHG emissions. Nonetheless, further reservoir emission data is imperative to bolster these conclusions.

In order to enhance the sustainable management of hydropower GHG emissions, this study presents solutions from two key perspectives: (1) mitigating the physical mechanisms driving carbon emission through adjustments in hydropower operation to enhance water quality (e.g. pre-impoundment clearance, installing fences around reservoirs, increasing O_2 concentration), optimize water levels (e.g. increase water intake depth, shorter water operational cycle), and improve sedimentation management (e.g. regular sediment flushing); and (2) strategizing the design and planning of new hydropower schemes to mitigate carbon emission. Specifically, the focus lies on exploring innovative techniques (e.g. methane recovery system) and types of hydropower reservoirs, such as combined PSH and run-of-river schemes, to potentially replace conventional storage reservoir hydropower. Furthermore, this entails improved basin-scale hydropower planning, considering the cumulative impacts of hydropower plants and other stressors on watersheds, and integrating with NBS solutions to alleviate and mitigate certain pressures associated with hydropower.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5061/dryad.d2kv0.

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References

Almeida R M *et al* 2019 Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning *Nat. Commun.* **10** 4281

Anderson D H, Moggridge H L, Warren P H and Shucksmith J D 2015 The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers *Water Environ. J.* **29** 268–76

Bambace L A W, Ramos F M, Lima I B T and Rosa R R 2007 Mitigation and recovery of methane emissions from tropical hydroelectric dams *Energy* **32** 1038–46

Barros N, Cole J J, Tranvik L J, Prairie Y T, Bastviken D, Huszar V L M, Del Giorgio P and Roland F 2011 Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude *Nat. Geosci.* **4** 593–6

Bastviken D, Cole J J, Pace M L and Van de Bogert M C 2008 Fates of methane from different lake habitats: connecting whole-lake budgets and CH_4 emissions *J. Geophys. Res.: Biogeosci.* **113** G02024

Bastviken D, Cole J, Pace M and Tranvik L 2004a Methane emissions from lakes: dependence of lake characteristics, two regional assessments, and a global estimate *Glob. Biogeochem. Cycles* **18** GB4009

Bastviken D, Persson L, Odham G and Tranvik L 2004b Degradation of dissolved organic matter in oxic and anoxic lake water *Limnol. Oceanogr.* **49** 109–16

Beaulieu J J, Waldo S, Balz D A, Barnett W, Hall A, Platz M C and White K M 2020 Methane and carbon dioxide emissions from reservoirs: controls and upscaling *J. Geophys. Res.: Biogeosci.* **125** e2019JG005474

Blakers A, Stocks M, Lu B and Cheng C 2021 A review of pumped hydro energy storage *Prog. Energy* **3** 022003

Bluemethane 2024 *Bluemethane* (available at: www.bluemethane.com/) (Accessed 8 April 2024)

Chan F K S, Chen W Y, Gu X, Peng Y and Sang Y 2022 Transformation towards resilient sponge cities in China *Nat. Rev. Earth Environ.* **3** 99–101

Chan F K S, Griffiths J A, Higgitt D, Xu S, Zhu F, Tang Y-T, Xu Y and Thorne C R 2018 "Sponge City" in China—A breakthrough of planning and flood risk management in the urban context *Land Use Policy* **76** 772–8

Chang F-J, Lai J-S and Kao L-S 2003 Optimization of operation rule curves and flushing schedule in a reservoir *Hydrol. Process.* **17** 1623–40

Cheng Y, Voisin N, Yearsley J R and Nijssen B 2020 Reservoirs modify river thermal regime sensitivity to climate change: a

case study in the Southeastern United States *Water Resour. Res.* **56** e2019WR025784
Chung M G, Frank K A, Pokhrel Y, Dietz T and Liu J 2021 Natural infrastructure in sustaining global urban freshwater ecosystem services *Nat. Sustain.* **4** 1068–75
Cooley S W, Ryan J C and Smith L C 2021 Human alteration of global surface water storage variability *Nature* **591** 78–81
Deemer B R and Harrison J A 2019 Summer redox dynamics in a eutrophic reservoir and sensitivity to a summer's end drawdown event *Ecosystems* **22** 1618–32
Deemer B R, Harrison J A, Li S, Beaulieu J J, DelSontro T, Barros N, Bezerra-Neto J F, Powers S M, Dos Santos M A and Vonk J A 2016 Greenhouse gas emissions from reservoir water surfaces: a new global synthesis *Bioscience* **66** 949–64
Deemer B R, Harrison J A, Li S, Beaulieu J J, DelSontro T, Barros N, Bezerra-Neto J F, Powers S M, Dos Santos M A and Vonk J A 2020 Data from: greenhouse gas emissions from reservoir water surfaces: a new global synthesis
DelSontro T, Boutet L, St-Pierre A, Del Giorgio P A and Prairie Y T 2016 Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity *Limnol. Oceanogr.* **61** S62–S77
Delwiche K B, Harrison J A, Maasakkers J D, Sulprizio M P, Worden J, Jacob D J and Sunderland E M 2022 Estimating driver and pathways for hydroelectric reservoir methane emissions using a new mechanistic model *J. Geophys. Res.: Biogeosci.* **127** e2022JG006908
Denholm P and Kulcinski G L 2004 Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems *Energy Convers. Manage.* **45** 2153–72
Descloux S, Chanudet V, Serça D and Guérin F 2017 Methane and nitrous oxide annual emissions from an old eutrophic temperate reservoir *Sci. Total Environ.* **598** 959–72
Dones R, Bauer C, Bolliger R, Burger B, Heck T, Röder A, Emmenegger M F, Frischknecht R, Jungbluth N and Tuchschmid M 2007 Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE Countries
Downing J A *et al* 2006 The global abundance and size distribution of lakes, ponds, and impoundments *Limnol. Oceanogr.* **51** 2388–97
Duc N T, Crill P and Bastviken D 2010 Implications of temperature and sediment characteristics on methane formation and oxidation in lake sediments *Biogeochemistry* **100** 185–96
Elçi Ş 2008 Effects of thermal stratification and mixing on reservoir water quality *Limnology* **9** 135–42
Encinas Fernández J, Hofmann H and Peeters F 2020 Diurnal pumped-storage operation minimizes methane ebullition fluxes from hydropower reservoirs *Water Resour. Res.* **56** e2020WR027221
European Commission 2015 *Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities—Final report of the Horizon 2020 expert group on 'Nature-based solutions and re-naturing cities'—(full version)* (Publications Office)
Fearnside P M and Pueyo S 2012 Greenhouse-gas emissions from tropical dams *Nat. Clim. Change* **2** 382–4
Flury K and Frischknecht R 2012 Life cycle inventories of hydroelectric power generation (available at: www.esu-services.ch/fileadmin/download/publicLCI/flury-2012-hydroelectric-power-generation.pdf) (Accessed 14 May 2024)
Gemechu E and Kumar A 2022 A review of how life cycle assessment has been used to assess the environmental impacts of hydropower energy *Renew. Sustain. Energy Rev.* **167** 112684
Gibeau P, Connors B M and Palen W J 2016 Run-of-river hydropower and salmonids: potential effects and perspective on future research *Can. J. Fish. Aquat. Sci.* **74** 1135–49
Grimardias D, Guillard J and Cattanéo F 2017 Drawdown flushing of a hydroelectric reservoir on the Rhône River: impacts on the fish community and implications for the sediment management *J. Environ. Manage.* **197** 239–49
Grinham A, Albert S, Deering N, Dunbabin M, Bastviken D, Sherman B, Lovelock C E and Evans C D 2018 The importance of small artificial water bodies as sources of methane emissions in Queensland, Australia *Hydrol. Earth Syst. Sci.* **22** 5281–98
Hafeman D, Factor-Litvak P, Cheng Z, van Geen A and Ahsan H 2007 Association between manganese exposure through drinking water and infant mortality in Bangladesh *Environ. Health Perspect.* **115** 1107–12
Harrison J A, Deemer B R, Birchfield M K and O'Malley M T 2017 Reservoir water-level drawdowns accelerate and amplify methane emission *Environ. Sci. Technol.* **51** 1267–77
Heathcote A J and Downing J A 2012 Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape *Ecosystems* **15** 60–70
Holgerson M A and Raymond P A 2016 Large contribution to inland water CO_2 and CH_4 emissions from very small ponds *Nat. Geosci.* **9** 222–6
Huang J and Li Z 2023 Carbon emissions affected by real-time reservoir operation: a hydrodynamic modeling approach coupled with air-water mass transfer *Water Res.* **241** 120118
Hunt J D *et al* 2021 Hydropower and seasonal pumped hydropower storage in the Indus basin:pros and cons *J. Energy Storage* **41** 102916
Hunt J D, Byers E, Riahi K and Langan S 2018 Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective *Energy Convers. Manage.* **166** 385–401
IEA 2023 Tracking clean energy progress 2023 (available at: www.iea.org/reports/tracking-clean-energy-progress-2023)
IHA 2012 GHG measurement guidelines for freshwater reservoirs
IHA 2023 Facts about hydropower (available at: www.hydropower.org/iha/discover-facts-about-hydropower) (Accessed 1 October 2023)
IHA 2024 Pumped hydro (available at: www.hydropower.org/factsheets/pumped-storage) (Accessed 20 April 2024)
IPCC 2015 'Energy Systems', in intergovernmental panel on climate *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report* (Cambridge University Press) pp 511–98
IRENA 2020 *Global Renewables Outlook: Energy Transformation 2050* (International Renewable Energy Agency)
Jager H I, Griffiths N A, Hansen C H, King A W, Matson P G, Singh D and Pilla R M 2022 Getting lost tracking the carbon footprint of hydropower *Renew. Sustain. Energy Rev.* **162** 112408
Keller P S, Marcé R, Obrador B and Koschorreck M 2021 Global carbon budget of reservoirs is overturned by the quantification of drawdown areas *Nat. Geosci.* **14** 402–8
King G M 1992 Ecological aspects of methane oxidation, a key determinant of global methane dynamics *Advances in Microbial Ecology K C* Marshall ed (Springer) pp 431–68
Kling G W, Evans W C, Tanyileke G, Kusakabe M, Ohba T, Yoshida Y and Hell J V 2005 Degassing Lakes Nyos and Monoun: defusing certain disaster *Proc. Natl Acad. Sci.* **102** 14185–90
Kreiling R M, Thoms M C, Bartsch L A, Larson J H and Christensen V G 2020 Land use effects on sediment nutrient processes in a heavily modified watershed using structural equation models *Water Resour. Res.* **56** e2019WR026655
Kumar A, Schei T, Ahenkorah A, Caceres Rodriguez R, Devernay J-M, Freitas M, Hall D, Killingtveit Å and Liu Z 2011 Hydropower *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* eds O Edenhofer *et al* (Cambridge University Press)
Lehner B *et al* 2011 High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management *Front. Ecol. Environ.* **9** 494–502

Lessmann O, Encinas Fernández J, Martínez-Cruz K and Peeters F 2023 Methane emissions due to reservoir flushing: a significant emission pathway? *Biogeosciences* **20** 4057–68
Li M and He N 2022 Carbon intensity of global existing and future hydropower reservoirs *Renew. Sustain. Energy Rev.* **162** 112433
Li Z, Du H, Xiao Y and Guo J 2017a Carbon footprints of two large hydro-projects in China: life-cycle assessment according to ISO/TS 14067′ *Renew. Energy* **114** 534–46
Li Z, Lu L, Lv P, Du H, Guo J, He X and Ma J 2017b Carbon footprints of pre-impoundment clearance on reservoir flooded area in China's large hydro-projects: implications for GHG emissions reduction in the hydropower industry *J. Clean. Prod.* **168** 1413–24
Maavara T, Chen Q, Van Meter K, Brown L E, Zhang J, Ni J and Zarfl C 2020 River dam impacts on biogeochemical cycling *Nat. Rev. Earth Environ.* **1** 103–16
Maavara T, Lauerwald R, Regnier P and Van Cappellen P 2017 Global perturbation of organic carbon cycling by river damming *Nat. Commun.* **8** 15347
Maeck A, Hofmann H and Lorke A 2014 Pumping methane out of aquatic sediments—ebullition forcing mechanisms in an impounded river *Biogeosciences* **11** 2925–38
Malerba M E, Lindenmayer D B, Scheele B C, Waryszak P, Yilmaz I N, Schuster L and Macreadie P I 2022 Fencing farm dams to exclude livestock halves methane emissions and improves water quality *Glob. Change Biol.* **28** 4701–12
McAnulty M J, Poosarla G V, Kim K-Y, Jasso-Chávez R, Logan B E and Wood T K 2017 Electricity from methane by reversing methanogenesis *Nat. Commun.* **8** 15419
McGinnis D F, Greinert J, Artemov Y, Beaubien S E and Wüest A 2006 Fate of rising methane bubbles in stratified waters: how much methane reaches the atmosphere? *J. Geophys. Res. Oceans* **111** C09007
Mendonça R, Müller R A, Clow D, Verpoorter C, Raymond P, Tranvik L J and Sobek S 2017 Organic carbon burial in global lakes and reservoirs *Nat. Commun.* **8** 1694
Mollenhauer G and Eglinton T I 2007 Diagenetic and sedimentological controls on the composition of organic matter preserved in California Borderland Basin sediments *Limnol. Oceanogr.* **52** 558–76
Moran E F, Lopez M C, Moore N, Müller N and Hyndman D W 2018 Sustainable hydropower in the 21st century *Proc. Natl Acad. Sci.* **115** 11891–8
Mulholland P J *et al* 2008 Stream denitrification across biomes and its response to anthropogenic nitrate loading *Nature* **452** 202–5
Muller M 2019 Hydropower dams can help mitigate the global warming impact of wetlands *Nature* **566** 315–7
Ollivier Q R, Maher D T, Pitfield C and Macreadie P I 2019 Punching above their weight: large release of greenhouse gases from small agricultural dams *Glob. Change Biol.* **25** 721–32
Open Hydro 2022 Hydropower reporting guideline: climate-change mitigation (Open Hydro)
Paranaíba J R, Barros N, Mendonça R, Linkhorst A, Isidorova A, Roland F, Almeida R M and Sobek S 2018 Spatially resolved measurements of CO2 and CH4 concentration and gas-exchange velocity highly influence carbon-emission estimates of reservoirs *Environ. Sci. Technol.* **52** 607–15
Peacock M *et al* 2021 Small artificial waterbodies are widespread and persistent emitters of methane and carbon dioxide *Glob. Change Biol.* **27** 5109–23
Phyoe W W and Wang F 2019 A review of carbon sink or source effect on artificial reservoirs *Int. J. Environ. Sci. Technol.* **16** 2161–74
Prairie Y T *et al* 2018 Greenhouse gas emissions from freshwater reservoirs: what does the atmosphere see? *Ecosystems* **21** 1058–71
Prairie Y T, Alm J, Harby A, Mercier-Blais S and Nahas R 2017 The GHG reservoir tool (G-res) technical documentation *Updated Version 3.2 (2022–12-19). 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)
Prairie Y T, Mercier-Blais S, Harrison J A, Soued C, Giorgio P D, Harby A, Alm J, Chanudet V and Nahas R 2021 A new modelling framework to assess biogenic GHG emissions from reservoirs: the G-res tool *Environ. Modell. Software* **143** 105117
Quaranta E and Muntean S 2023 Wasted and excess energy in the hydropower sector: a European assessment of tailrace hydrokinetic potential, degassing-methane capture and waste-heat recovery *Appl. Energy* **329** 120213
Ramos F M, Bambace L A W, Lima I B T, Rosa R R, Mazzi E A and Fearnside P M 2009 Methane stocks in tropical hydropower reservoirs as a potential energy source *Clim. Change* **93** 1–13
Salati E and Vose P B 1984 Amazon Basin: a system in equilibrium *Science* **225** 129–38
Sawakuchi H O, Bastviken D, Enrich-Prast A, Ward N D, Camargo P B and Richey J E 2021 Low diffusive methane emissions from the main channel of a large amazonian run-of-the-river reservoir attributed to high methane oxidation *Front. Environ. Sci.* **9** 655455
SCDHEC 2023 Dams and reservoir definitiosn (available at: https://scdhec.gov/dams-reservoirs-definitions) (Accessed 29 September 2023)
Schmitt R J P, Bizzi S, Castelletti A and Kondolf G M 2018 Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong *Nat. Sustain.* **1** 96–104
Segers R 1998 Methane production and methane consumption: a review of processes underlying wetland methane fluxes *Biogeochemistry* **41** 23–51
Shi W, Du M, Ye C and Zhang Q 2021 Divergent effects of hydrological alteration and nutrient addition on greenhouse gas emissions in the water level fluctuation zone of the Three Gorges Reservoir, China *Water Res.* **201** 117308
Silverthorn V M, Bishop C A, Jardine T, Elliott J E and Morrissey C A 2018 Impact of flow diversion by run-of-river dams on American dipper diet and mercury exposure *Environ. Toxicol. Chem.* **37** 411–26
Sobek S, DelSontro T, Wongfun N and Wehrli B 2012 Extreme organic carbon burial fuels intense methane bubbling in a temperate reservoir *Geophys. Res. Lett.* **39** L01401
Sobek S, Durisch-Kaiser E, Zurbrügg R, Wongfun N, Wessels M, Pasche N and Wehrli B 2009 Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source *Limnol. Oceanogr.* **54** 2243–54
St. Louis V L, Kelly C A, Duchemin É, Rudd J W M and Rosenberg D M 2000 Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: a Global Estimate: Reservoirs are sources of greenhouse gases to the atmosphere, and their surface areas have increased to the point where they should be included in global inventories of anthropogenic emissions of greenhouse gases *BioScience* 50 766
Stickler C M, Coe M T, Costa M H, Nepstad D C, McGrath D G, Dias L C P, Rodrigues H O and Soares-Filho B S 2013 Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales *Proc. Natl Acad. Sci.* **110** 9601–6
Tranvik L J *et al* 2009 Lakes and reservoirs as regulators of carbon cycling and climate *Limnol. Oceanogr.* **54** 2298–314
Vachon D, Prairie Y T, Guillemette F and Del Giorgio P A 2017 Modeling allochthonous dissolved organic carbon mineralization under variable hydrologic regimes in boreal lakes *Ecosystems* **20** 781–95
Voeroesmarty C, Sharma K K, Fekete B M, Copeland A H, Holden J and Marble J C 1997 The storage and aging of continental runoff in large reservoir systems of the world
Wang X, He Y, Yuan X, Chen H, Peng C, Yue J, Zhang Q, Diao Y and Liu S 2017 Greenhouse gases concentrations and fluxes from subtropical small reservoirs in relation with watershed urbanization *Atmos. Environ.* **154** 225–35

Webb J R, Leavitt P R, Simpson G L, Baulch H M, Haig H A, Hodder K R and Finlay K 2019 Regulation of carbon dioxide and methane in small agricultural reservoirs: optimizing potential for greenhouse gas uptake *Biogeosciences* **16** 4211–27

West W E, Coloso J J and Jones S E 2012 Effects of algal and terrestrial carbon on methane production rates and methanogen community structure in a temperate lake sediment *Freshw. Biol.* **57** 949–55

West W E, Creamer K P and Jones S E 2016 Productivity and depth regulate lake contributions to atmospheric methane *Limnol. Oceanogr.* **61** S51–S61

Westgate M J *et al* 2022 Improved management of farm dams increases vegetation cover, water quality, and macroinvertebrate biodiversity *Ecol. Evol.* **12** e8636

Wik M, Crill P M, Varner R K and Bastviken D 2013 Multiyear measurements of ebullitive methane flux from three subarctic lakes *J. Geophys. Res.: Biogeosci.* **118** 1307–21

Wik M, Thornton B F, Bastviken D, Uhlbäck J and Crill P M 2016 Biased sampling of methane release from northern lakes: a problem for extrapolation *Geophys. Res. Lett.* **43** 1256–62

Winton R S, Calamita E and Wehrli B 2019 Reviews and syntheses: dams, water quality and tropical reservoir stratification *Biogeosciences* **16** 1657–71

Wood T K, Gurgan I, Howley E T and Riedel-Kruse I H 2023 Converting methane into electricity and higher-value chemicals at scale via anaerobic microbial fuel cells *Renew. Sustain. Energy Rev.* **188** 113749

Wu S, Li S, Zou Z, Hu T, Hu Z, Liu S and Zou J 2019 High methane emissions largely attributed to ebullitive fluxes from a subtropical river draining a rice paddy watershed in China *Environ. Sci. Technol.* **53** 3499–507

Wu X, Wang Z, Xiang X, Yang H, Li C, Li S and Wu L 2022 Dynamic simulation of CO_2 flux in a hydropower reservoir in Southwest China *J. Hydrol.* **613** 128354

Yang C-J and Jackson R B 2011 Opportunities and barriers to pumped-hydro energy storage in the United States *Renew. Sustain. Energy Rev.* **15** 839–44

Yang L 2019 Contrasting methane emissions from upstream and downstream rivers and their associated subtropical reservoir in eastern China *Sci. Rep.* **9** 8072

Yang M, Geng X, Grace J, Lu C, Zhu Y, Zhou Y and Lei G 2014 Spatial and seasonal CH_4 flux in the littoral zone of Miyun Reservoir near Beijing: the effects of water level and its fluctuation *PLoS One* **9** e94275

Yang M, Li H-L, Lei T, Zhou Y, Lu C, Li L, Lei G, Wang J S and Lu X G 2011 Spatial-temporal characteristics of methane emission flux and its influence factors at miyun reservoir in Beijing *Wetland Sci.* **9** 191–7

Zarfl C, Lumsdon A E, Berlekamp J, Tydecks L and Tockner K 2014 A global boom in hydropower dam construction *Aquat. Sci.* **77** 161–70

Zhou Y, Davidson T A, Yao X, Zhang Y, Jeppesen E, de Souza J G, Wu H, Shi K and Qin B 2018 How autochthonous dissolved organic matter responds to eutrophication and climate warming: evidence from a cross-continental data analysis and experiments *Earth Sci. Rev.* **185** 928–37