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Greenhouse gas emissions from an arid-zone reservoir and their environmental policy significance: Results from existing global models and an exploratory dataset

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ABSTRACT

Reservoirs in arid regions often provide critical water storage but little is known about their greenhouse gas (GHG) footprint. While there is growing appreciation of the role reservoirs play as GHG sources, there is a lack of understanding of GHG emission dynamics from reservoirs in arid regions and implications for environmental policy. Here we present initial GHG emission measurements from Lake Powell, a large water storage reservoir in the desert southwest United States. We report CO_2-eq emissions from the shallow (< 15 m) littoral regions of the reservoir that are higher than the global average areal emissions from reservoirs (9.4 vs. 5.8 g CO_2-eq m^{-2} d^{-1}) whereas fluxes from the main reservoir were two orders of magnitude lower (0.09 g CO_2-eq m^{-2} d^{-1}). We then compared our measurements to modeled $CO_2 + CH_4$ emissions from the reservoir using four global scale models. Factoring these emissions into hydropower production at Lake Powell yielded low GHG emissions per MWh^{-1} as compared to fossil-fuel based energy sources. With the exception of one model, the estimated hydropower emissions for Lake Powell ranged from 10–32 kg CO_2-eq MWh^{-1}, compared to ~400–1000 kg CO_2-eq MWh^{-1} for natural gas, oil, and coal. We also estimate that reduced littoral habitat under low water levels leads to ~50% reduction in the CO_2 equivalent emissions per MWh. The sensitivity of GHG emissions to reservoir water levels suggests that the interaction will be an important policy consideration in the design and operation of arid region systems.

1. Introduction

Water storage is critical in many arid regions of the world for social, economic, and environmental functions. As reservoirs are increasingly recognized as significant contributors to global greenhouse gas (GHG) budgets (Deemer et al., 2016; Rudd et al., 1993), their GHG emissions are factored into environmental policy. For example, GHG emissions are now a component of national GHG inventories for the Intergovernmental Panel on Climate Change (Lovelock et al., 2019). Other proposed decision frameworks consider GHG budgets alongside other factors including economic costs and life cycle analyses of water and land use impacts in arid regions (Mahlooji et al., 2020). Despite critical water storage questions in arid regions, these systems are relatively under-studied with respect to GHG dynamics (Lovelock et al., 2019). This remains true in the U.S. even though arid region reservoirs, such as in the Colorado and Rio Grande basins, generally store high proportions of the regional mean annual streamflow (Graf, 1999) suggesting their importance in regional watershed carbon (C) budgets.

Estimates of emission are particularly important for larger reservoirs where total emissions potentially contribute significantly to regional or national GHG inventories. Here we discuss GHG dynamics in the two largest reservoirs in the United States, both located in the desert southwest. The Colorado River system provides drinking water to 40 million people and irrigates 4.5 million acres of cropland (U.S. Bureau of Reclamation, 2017). Water levels of the two largest reservoirs in the Colorado River Basin, Lake Powell and Lake Mead, have been in decline since the early 2000s due to over-appropriation, drought, and increasing temperatures, and are projected to decline to historic lows under

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business-as-usual scenarios (Udall and Overpeck, 2017; Xiao et al., 2018). Guidelines and policies that determine how water from the Colorado River is allocated are part of the Law of the River, an informal accumulation of treaties, laws, Supreme Court decisions, interstate compacts, and administrative agreements. The scope of these guidelines and policies include varying consideration of social, economic, and environmental impacts and priorities. To our knowledge, GHG emissions from Lake Powell and Lake Mead have not been factored into Colorado River basin water management guidelines and policies despite an increasing recognition that some reservoirs can be large GHG sources (Deemer et al., 2016; Scherer and Pfister, 2016).

Methane (CH_4) emissions tend to constitute the majority of reservoir GHG emissions on a carbon dioxide (CO_2) equivalent basis (Deemer et al., 2016), but are also often highly variable in space and time (Wik et al., 2016). Generally speaking, autochthonous production has been positively related to methane emissions in lakes and reservoirs at a variety of scales (Deemer et al., 2016; DelSontro et al., 2018; West et al., 2015). Depth may also be an important regulator of total methane emission, with less capacity for oxidation/dissolution of methane bubbles at shallower sites (McGinnis et al., 2006) and thus higher emissions (West et al., 2015). Reservoir inlets, which often support shallow deltaic habitats, elevated primary production, and elevated organic matter deposition, are also often methane emission hot spots (Beaulieu et al., 2016; Berberich et al., 2019; DelSontro et al., 2011). CO_2 generally constitutes a small fraction of the GHG emissions from reservoirs on a global warming potential-basis, with many systems close to net zero CO_2 emissions and about 15% of the systems studied globally exhibiting net uptake (Deemer et al., 2016).

Here we present an exploratory dataset containing the first-ever measurements of CH_4 emission and some of the first CO_2 emissions (but see Therrien et al., 2005) from Lake Powell collected in July of 2017. We use this dataset together with ancillary measurements to identify the best predictors of emission. We then estimate Lake Powell's surface water GHG emissions (with uncertainty ranges) and compare this range to estimates for both Lake Mead and Lake Powell that we calculated using several models (DelSontro et al., 2018; Hertwich, 2013; Prairie et al., 2018; Scherer and Pfister, 2016). Finally, we explore the role that reservoir water levels may play in total and per MWh GHG emissions. The aim of this study is to describe the magnitude and uncertainty surrounding the GHG emissions of Lake Powell and Lake Mead as well as to explore the role of water storage decisions (e.g. reservoir water level) on these dynamics. The climate impact of these reservoirs is but one of many factors that could be accounted for in decision-making processes, along with priorities such as water supply, energy production, ecosystem function and services, and cultural and social considerations. However, reducing uncertainty associated with emissions and management of arid region reservoirs is needed to improve environmental policy.

2. Methods

2.1. Study area

Lake Powell and Lake Mead are a coordinated, cascading water storage system on the Colorado River. Lake Powell is the second largest reservoir in the United States by capacity (30 km^3) with a surface area of 653 km^2, maximum depth of 178 m at full pool, and a mean residence time of about 2 years. The reservoir began to form in 1963 with the completion of Glen Canyon Dam, initially filled in 1980, and has undergone fluctuations in water level upwards of 30 m during its 55-year lifetime. Water is generally withdrawn from a fixed elevation, which has corresponded to a water depth ranging from about 24−70 m depending on reservoir water levels (out of a total depth of 110−156 m). Lake Powell floods a particularly canyon-bound landscape resulting in a highly dendritic shoreline that is longer than the west coast of the continental U.S. This morphology also means that there is more littoral habitat at full pool, with over 50% of the storage capacity in the highest 30 m of elevation. In 2005 Lake Powell reached its lowest elevation since filling, resulting in a surface area of only 55% of full pool (362 km^2). During the field sampling campaign in July 2017, the reservoir surface area was 467 km^2, 71% of full pool. The level of the reservoir also has an important effect on hydraulic head and thus energy production. Glen Canyon Dam has a nameplate capacity of 1320 MW, with the average energy production during a relatively low water year (2004: 3,320,196 MW h yr^{-1}) only ~60% of the energy production during higher water years (1978−1999: 5,196,113 MW h yr^{-1}; Harpman and Douglas, 2005; U.S. Department of Interior, 2016).

Lake Mead is the largest reservoir in the United States by capacity (34.9 km^3), with a surface area, maximum depth, and mean residence time that are similar to Lake Powell's (640 km^2, 162 m, and 2–4 years, respectively). The reservoir is located ~410 km downstream from Lake Powell and ~40 km southeast of Las Vegas. Lake Mead has also been affected by persistent drought conditions: it has not reached full capacity since 1983 and has had a smaller surface area to Lake Powell since 2013. Key differences between the two reservoirs are age, watershed characteristics, and morphology. Lake Mead is ~28 years older than Lake Powell, formed with the completion of the Hoover Dam in 1935. Its productivity and nutrient budget is more impacted by urban runoff in its watershed, as the reservoir receives effluent from the City of Las Vegas, City of Henderson, and Clark County municipal wastewater treatment plants (Ding et al., 2014). Lake Mead is located in the Southern Basin and Range and is less canyon-bound and less dendritic than Lake Powell, with a shoreline ~40% as long. The average energy production at Hoover Dam is 4,500,000 MW h yr^{-1}.

2.2. Limnological and GHG emission measurements

GHG sampling in Lake Powell was supplemented by general limnological measurements of temperature, conductivity, dissolved oxygen, turbidity, and pH, taken as part of a long-term monitoring program. At a subset of sites (Figure S1) water samples were collected from 1 m below the surface and 1 m off the bottom with a niskin-type sampler for chlorophyll *a* (surface only) total N, total P, SO_4^{2-}, Ca^{2+}, and HCO_3-analysis. Details of these measurements are described in Vernieu (2015) and in the supplemental materials.

Emission rates of CO_2 and CH_4 (diffusive and ebullitive, see SI) were measured at 28 sites across Lake Powell using 10-minute floating chamber deployments from 17 to 22 July 2017 (Zhao et al., 2015). We also estimated rates of ebullition using funnel traps at a subset of sites (Figure S1), although these measurements were not included in upscaling efforts. Chamber-based diffusion and ebullition emission rate calculation methods as well as more information about funnel trap deployments can be found in the supplemental materials.

2.3. Controls on reservoir emissions & upscaling

Relationships between floating chamber-based CH_4 and CO_2 emissions and potential predictor variables were examined using generalized linear models in the R package glmm. Potential predictor variables were identified from the suite of physical, chemical, and biological measurements made during the survey (see supplemental materials for more information). We modeled all combinations of predictor variables, based on a literature review, and the best models were selected based on Akaike information criteria (AIC) values.

Reservoir-wide CO_2 emissions (g CO_2-eq m^{-2} y^{-1}) from Lake Powell were estimated by multiplying the arithmetic mean of the measurement sites' ($n = 28$) CO_2 emission estimates by the total surface area of the reservoir. To upscale CH_4 emissions, we treated shallow littoral regions (<15 m) and open-water regions separately. The relative surface areas of these regions were estimated using a combination of topographic and depth information in ArcGIS (see supplemental material; Deemer et al., 2021). Emission factors were defined as the arithmetic mean of floating

Table 1

Mean (range, number of observation) values of key measured water quality parameters during the July 2017 Lake Powell survey. *Funnel ebullition measurements were not included in upscaling exercises given their limited coverage, but chamber ebullition was included. ˆDissolved organic carbon concentrations were only measured at Wahweap (main reservoir, n = 1) and at the inflow sites (shallow tributary, n = 3).

Region	Shallow Tributary (n = 8 sites)	Main Reservoir (n = 20 sites)
Depth (m)	5.7 (0.5–9, n = 6)	87.2 (34–132.5, n = 17)
Surface Water Temperature (°C)	27.4 (25.4–28.6, n = 6)	27.9 (26.9–28.7, n = 17)
Bottom Water Temperature (°C)	26.5 (25.2–27.4, n = 6)	8.4 (7.4–13.3, n = 17)
Surface pH	8.36 (8.19–8.53, n = 6)	8.44 (8.27–8.58, n = 17)
Surface Bicarbonate (mg L^{-1})	160 (116–192, n = 3)	126 (95–148, n = 9)
Surface Calcium (mg L^{-1})	58.2 (51.4–67.2, n = 3)	47.7 (38.9–61.2, n = 9)
Surface Chlorophyll *a* (μg L^{-1})	2.8 (1.6–3.8, n = 6)	1.5 (0.6–2.9, n = 17)
Bottom Dissolved Oxygen (mg L^{-1})	5.4 (0.1–7.1, n = 6)	4.9 (0.3–6.3, n = 17)
Bottom Conductivity (μS cm^{-1})	539 (332–696, n = 6)	848 (451–941, n = 17)
Bottom Turbidity (NTU)	16.5 (3.4–24.4, n = 6)	2.6 (0.7–14, n = 17)
Total Phosphorus (mg L^{-1})	0.53 (0.31–0.96, n = 3)	0.08 (0.01–0.29, n = 9)
Total Nitrogen (mg L^{-1})	1.45 (0.7–2.1, n = 3)	0.52 (0.3–0.7, n = 9)
Sulfate (mg L^{-1})	96.3 (77–117, n = 3)	108 (66–164, n = 9)
Surface Dissolved Organic Carbon (mg L^{-1})ˆ	0.43 (0–0.8, n = 3)	3.9 (n = 1)
Total CH_4 Flux mg CH_4 m^{-2} d^{-1}	255.2 (sd = 12.4, n = 8)	2.1 (sd = 0.1, n = 20)
Chamber Diffusion mg CH_4 m^{-2} d^{-1}	66.4 (sd = 3.2, n = 8)	2.0 (sd = 0.1, n = 20)
Chamber Ebullition mg CH_4 m^{-2} d^{-1}	188.8 (sd = 10.6, n = 8)	0.07 (sd = 0.01, n = 20)
*Funnel Ebullition mg CH_4 m^{-2} d^{-1}	0 (n = 1)	46.2 (sd = 4.1, n = 5)
Total mg CO_2 m^{-2} d^{-1}	757.4 (sd = 42.0, n = 8)	24.8 (sd = 18.5, n = 20)
Total mg CO_2-eq m^{-2} d^{-1}	9434.2	96.2

chamber emission estimates for each of the two regions sampled. We characterized uncertainty using the propagated 95% confidence intervals (see supplemental material).

2.4. *Emission rate estimates from existing models*

We calculated annual reservoir-scale areal CO_2 equivalent (CO_2-eq) emissions (g CO_2-eq m^{-2} yr^{-1}) and total emissions relative to energy production (kg CO_2-eq MWh^{-1}) for Lake Powell and Lake Mead using an online tool and three published models for comparison with the upscaled July 2017 Lake Powell emission measurements. The CO_2 equivalent emissions were calculated by multiplying the mass-based flux (in units of mg or kg CH_4 and CO_2) by the 100-year global warming potential of each gas (1 for CO_2 and 34 for CH_4, Myhre et al., 2013). The existing sources we use are the GHG Reservoir Tool (G-res, www.hydropower.org/gres-tool; Prairie et al., 2017), and the following published models: the size-productivity model (SPM, DelSontro et al., 2018), generalized linear modeling (GLM, Scherer and Pfister, 2016), and multiple linear regressions (MLR, Hertwich, 2013). We used July 2017 conditions as inputs to the models where applicable. More details on the background and use of these existing sources can be found in the supplemental materials.

2.5. *Per MWh emissions at different reservoir water levels*

Reservoir water levels can affect per MWh GHG emissions via changes in energy production, changes in reservoir surface area, and changes in the proportion of the waterbody that is shallow tributary vs. main reservoir. To look at the relationship between Lake Powell's water surface elevation and the GHG emissions per MWh, we first estimated the degree to which energy production changes at different reservoir elevations using the relationship:

$$P_{af} = 3.0033e^{-3}E - 2.86$$

where P_{af} is the energy production in units of MWh per acre-foot[2] of water released through the dam and E is the elevation of Lake Powell in meters. This equation was developed using Harpman (1999), assuming a constant release of water, and changes in powerplant efficiency were updated using observed historical data (Jerry Wilhite pers comm.). We estimated P_{af} at 5-meter increments for reservoir elevations ranging from 1065 to 1125 m. The minimum surface elevation examined is just above the elevation of Lake Powell's penstocks (1058 m). The maximum surface area elevation examined is about 3 m below full pool.

To estimate total waterbody emissions at different water levels, the surface area of Lake Powell at each elevation increment was estimated based on an elevation/area curve (Ferrari, 1988). Total surface area was used together with mean areal fluxes to estimate CO_2 flux, whereas regional surface areas and regional mean total (ebullitive + diffusive) areal fluxes (e.g. shallow tributary vs. main reservoir) were needed for CH_4 flux estimates. Shallow tributary littoral surface area at each elevation band was estimated using the methods described above (section 2.5) with more detailed methods available in the supplemental materials. Main reservoir surface area was calculated as the difference between total surface area and littoral surface area for each elevation increment. Once total annual CO_2 and CH_4 emissions were calculated and converted into CO_2-eq units, the CO_2-eq MWh^{-1} was calculated assuming the powerplant is generating energy at maximum capacity for a given reservoir elevation (P_{af} calculated above) and releasing 8.23 million acre-feet yr^{-1} of water. All surface area data as well as measured emissions and model inputs are available in an associated data release (Deemer et al., 2021).

3. Results

3.1. *July 2017 survey emission results*

Lake Powell was thermally stratified for the duration of the measurement survey, with at least a 10 °C difference between surface and bottom waters in the main body of the reservoir. Inflow and littoral sites were weakly stratified or isothermic, ranging from 0 to 3.4 °C differences between surface and bottom water and were generally fresher (lower conductivity) than the main reservoir. Consistent with previous work (Gloss et al., 1980), nutrient concentrations were approximately triple (TN) and an order of magnitude (TP) greater in the inflow and littoral sites than in the main body of the reservoir, and chlorophyll *a* concentrations in these shallow regions were nearly double their concentration in the main body of the reservoir and about five times more turbid (Table 1).

Methane emissions ranged from 0.64 to 1095 mg CH_4 m^{-2} d^{-1} with

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[2] We chose to specify the volume of water in non-SI units (acre-feet) given the longstanding policy relevance in the Colorado River Basin of characterizing the management and allocation of water resources in acre-feet.

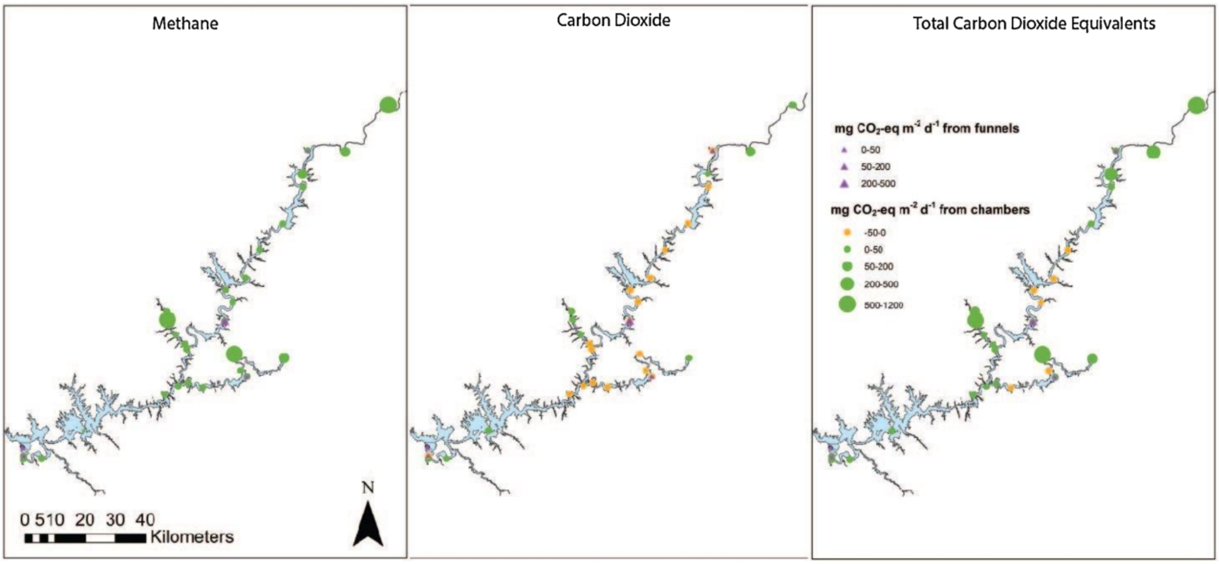

Fig. 1. CH_4, CO_2 and total CO_2-equivalent emissions from the July 2017 Lake Powell survey. Funnel-based ebullition estimates are denoted as purple triangles whereas floating chamber-based total emissions are circles (orange for sink, green for source). All emission values are scaled based on CO_2-equivalent emissions over a 100-year timeline. with green indicating a source of GHGs from the water surface and orange indicating a sink for GHGs in the reservoir.

ebullition contributing anywhere between 0 and 99% of the total flux. CO_2 fluxes ranged from uptake of 3280 mg CO_2 m^{-2} d^{-1} to emission of 10,310 mg CO_2-C m^{-2} d^{-1} (Fig. 1, Table S3). Both CH_4 and CO_2 fluxes displayed spatial patterns: CH_4 emissions tended to be higher in the tributary arm littoral regions of Lake Powell, and lower in the pelagic regions (Fig. 1, Table 1). Ebullition was also only observed in the further upstream, littoral sites (Table S2), with the exception of one shallow site in the downstream portion of the reservoir. Emission of CO_2 from the water to the atmosphere was observed in the edges of the reservoir, both in the upstream littoral areas and at the mouth of the reservoir near the dam, while uptake from the atmosphere to the water was observed in the middle reaches of the reservoir (Fig. 1). Transitional zones where a CO_2 diffusive flux could not be discerned were observed between the emission and uptake regions.

3.2. Controls on emissions and upscaling

Water measurements indicated key differences between shallow tributary areas of the reservoir and deeper, open water areas (Table 1, supplemental material). General linear modeling identified total phosphorus and depth as the best predictors of CH_4 emission, with higher fluxes coming from higher P, shallower depth sites (Table 2). This formed the basis of our CH_4 upscaling method, wherein the shallow tributary regions were treated separately from the main reservoir. CO_2 emissions were best predicted by surface pH and bicarbonate concentrations, with higher fluxes coming from sites where surface pH was lower and bicarbonate concentrations were higher (Table 2). In the absence of a model for the lake that is able to predict pH or bicarbonate, we upscaled CO_2 emissions based on average fluxes.

Table 2
The top five models for floating chamber-based total CH_4 and CO_2 emissions from the July 2017 Lake Powell survey. The increase in the Akaike Information Criteria (AIC) score from the top model is also shown.

Gas	Model	Delta AIC
CH_4	Total P + Depth	0
	Bottom Temp + Bottom Conductivity	2
	Total P * Bottom Temperature	5
	Bottom Conductivity	10
	Total P	12
CO_2	Surface pH + Surface HCO_3^-	0
	Surface pH + Surface Ca^{2+}	3
	Surface pH + Surface Temperature	5
	Surface HCO_3^-	11
	Total N	13

3.3. Reservoir-scale GHG emissions from measurements and literature estimates

Our upscaled emission measurements (mean and 95% CI range) yield 331 [153–854] g CO_2.eq m^{-2} yr^{-1} from Lake Powell, almost three quarters of which is attributable to CH_4 emissions: 245 [92–745] g CO_2.eq m^{-2} yr^{-1}, the remainder as CO_2: 85.5 [-8.3–179] g CO_2.eq m^{-2} yr^{-1} (Table 3). The modeled emissions from the SPM (DelSontro et al., 2018) were most similar to the upscaled emission estimate based on our measurements, with a percent bias of −17%, followed by the G-res, MLR, and GLM at −57% and −107%, and 136%, respectively. Additionally, the SPM model predicted that 70% of the total GHG footprint would be due to CH_4 (vs. CO_2) emissions, very similar to that estimated by upscaling the July 2017 survey. While no measurements of Lake Mead GHG emissions were made for this study, model-based estimates indicate slightly larger emissions with uncertainty ranges that overlap those of Lake Powell (Table 3).

3.4. Per MWh emissions at different reservoir water levels

Estimated annual-scale per MWh emissions from Lake Powell declined by over 50% (from 45.5–20.8 kg CO_2.eq MWh^{-1}) from pool elevations of 1125 to 1065 m (Fig. 2). Energy production across this same range of elevations declined by about 36% from 0.52 to 0.34 MW h per acre-foot released. This implies that the steep drop in per MWh GHG emission we report with declining water levels is largely driven by the higher emissions in the littoral tributary regions. Littoral surface area (< 15 m) declined from 39.6 km^2 at 1125 m to 11.2 km^2 at 1065 m and generally constituted a declining fraction of overall surface area with declining water level (6.4% at 1125 m vs. 5.5 at 1065 m; Fig. 2C).

Lake Powell per MWh emissions during our July 2017 sampling campaign were estimated at 33.0 kg CO_2.eq MWh^{-1}, which is lower than the estimated annual-scale per MWh emissions (Fig. 2). The discrepancy between July 2017 and annual-scale emission is due to higher monthly water releases in July relative to average annual-scale release, and thus a higher than average energy production (5.2 million MWh yr^{-1} versus an assumed 3.9 million MWh yr^{-1} in model). We expect the relationship

Table 3

Characterizations of greenhouse gas footprints of Lake Powell and Lake Mead based on published models and measurements from this study. Numbers in brackets indicate the 95% confidence interval (CI). Estimates for 95% CI are not included for GLM and MLR. GLM does not estimate an uncertainty range for individual reservoirs. The log transformations in the MLR yield very large uncertainty ranges: from a factor of 10 to 10^5.

		Annual Areal Emission Rate			Energy Production Emission Factor[a]		
		CH_4	CO_2	Σ (CO_2, CH_4)	CH_4	CO_2	Σ (CO_2, CH_4)
		(g CO_2eq m^{-2} yr^{-1})			(kg CO_2eq MWh^{-1})		
Lake Powell	G-res[b]	86 [41–156]	99 [47–179]	185 [116–291]	8.5 [4.1–16]	9.8 [4.7–18]	18.4 [8.8–33.3]
	SPM[c]	197 [46–348]	81.8 [74.4–89.2]	279 [128–430]	19.6 [4.6–34.6]	8.1 [7.4–8.9]	27.7 [12.7–42.7]
	GLM[d]	1380	371	1751	137	594	662
	MLR[e]	5.0	95.5	100	0.50	9.5	10
	This Study	245 [92–745]	85.5 [-8.3–179]	331 [153–854]	24.4 [9.1–74.1]	8.5 [-0.83 – 17.8]	33.0 [15.2–84.9]
Lake Mead	G-res	384 [212–648]	236 [130–398]	620 [418–930]	32.3 [17.8–54.4]	19.8 [10.9–33.4]	52.1 [35.1–78.1]
	SPM	338 [206–470]	87.5 [83.5–91.5]	425 [293–557]	28.4 [17.3–39.5]	7.4 [7.0–7.7]	35.7 [24.6–46.8]
	GLM	905	221	1130	63.0	551	614
	MLR	1.7	56	58	0.17	5.5	5.7

[a] Based on reservoir and power production conditions for July 2017 Prairie et al., 2018.

[b] Size Productivity Model, DelSontro et al., 2018.

[c] Generalized Linear Modeling, Scherer and Pfister, 2016.

[d] Multiple Linear Regression, Hertwich, 2013.

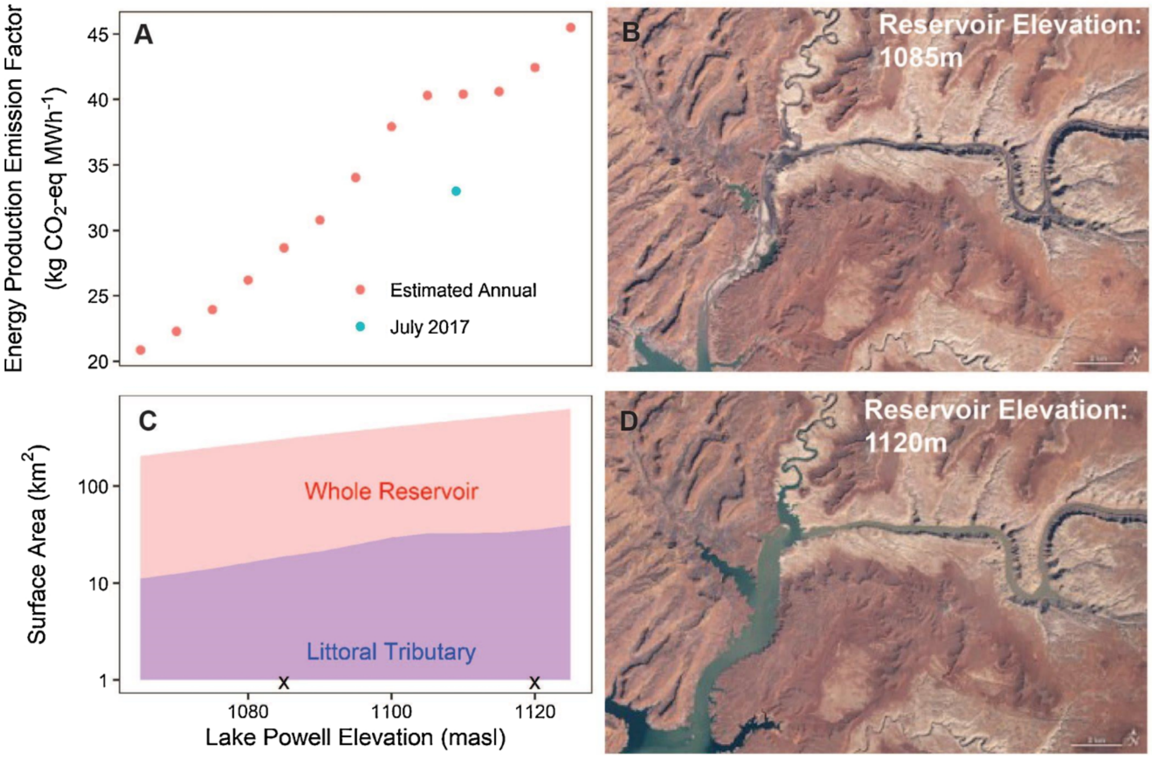

Fig. 2. A) Estimated annual scale CO_2-eq emission from the Lake Powell water surface per MWh of power production at various pool elevations (A), inundated reservoir surface areas at different water elevations (C), and images of the Colorado River where it flows into Lake Powell at low (B) and high (D) water levels. Images in panels B and D match those in the graphical abstract. In panel A, pink dots depict emissions per MWh assuming the dam is generating energy at capacity for a given reservoir elevation at a constant release totaling 8.23 million acre-feet yr^{-1}. The blue dot shows the estimated emissions per MWh for the July 2017 survey conducted as part of this study. Lower CO_2-eq emissions in July of 2017 relative to annual-scale estimates are due to higher monthly water releases in July relative to average annual-scale release. In panel C, the littoral tributary surface area represents tributary regions <15 m deep as was used for methane emission upscaling, note the log scale on the y axis, x marks the elevations at which aerial photos were taken in panels B and D.

between energy production emission factor (at a given annual release volume) and Lake Powell elevation to be constant, and not to affect the overarching relationship between reservoir elevation and emissions.

4. Discussion

4.1. *Magnitude and controls on CO_2 and CH_4 emissions*

Here we report a range of GHG emission estimates from a large arid zone reservoir from field measurements and global models. Given very few GHG measurements from arid-zone reservoirs (Lovelock et al., 2019), the field survey results reported here help fill a key knowledge gap. We report littoral CH_4 emissions that are higher than the mean areal emission from global reservoirs (255 mg CH_4 m^{-2} d^{-1} here vs. 160 mg CH_4 m^{-2} d^{-1} globally; Table 1 and Deemer et al., 2016) and two orders of magnitude higher than open water portions of the reservoir (2.1 mg CH_4 m^{-2} d^{-1}). Higher emissions in shallow, phosphorus rich and productive littoral areas associated with tributaries have been previously reported for numerous reservoirs (Beaulieu et al., 2016; DelSontro et al., 2011; Grinham et al., 2011) and are likely a result of higher temperatures at the sediment-water interface, high sediment deposition rates, and nutrient inputs that support phytoplankton biomass, a labile carbon source for methanogens. CO_2 emission rates were negatively related to pH, suggesting that carbonate buffering exerts an important influence on CO_2 concentration in Lake Powell surface waters (as has been observed in other alkaline reservoirs, Saidi and Koschorreck, 2017). Previous work has documented high rates of reservoir calcite precipitation as well as significant spatial variation in the importance/prevalence of this process (Deemer et al., 2020; Reynolds, 1978). Similarly, we observed spatial variation in Lake Powell wherein certain zones were CO_2 sinks and others were CO_2 sources (Fig. 1). Previous measurements of CO_2 emission from Lake Powell reported only positive emission values (575–824 mg CO_2 m^{-2} d^{-1}; Therrien et al., 2005). While these emissions fall in between the average emissions reported for the two reservoir zones we used for upscaling (Table 1), they do not highlight the zones of negative flux that we captured in our survey.

4.2. *Upscaling, uncertainty, and model comparisons*

Given limited field-based measurements of GHG emission, we also generated multiple model-based estimates of reservoir emission in order to reduce uncertainty (e.g. via different data parameterizations and uncertainty sources between the measurements and the models; Uusitalo et al., 2015). The models we used were based on large datasets from diverse ecoregions, reservoir sizes, and productivity statuses, and to a lesser extent, time of year. The model estimates provide context in terms of the range of uncertainty within and among models, and show what the best available estimate of Lake Powell's carbon footprint would be absent direct measurements. The models implemented here were designed to answer a different set of questions over generally large-scale, aggregated spatial and temporal frameworks (see supplemental materials). In addition, the models were trained with data sets that had relatively few CH_4 emission estimates as well as relatively few estimates from large reservoirs (>200 km^2) and reservoirs in arid zones (see supplemental materials).

Overall, the upscaled measurements and several of the models converged on similar values for annual areal emission rates from Lake Powell and Lake Mead. The SPM and G-res results were most similar to our Lake Powell survey results, and these models also had the smallest uncertainty ranges (Table 3, Fig. 3b). SPM and G-res rely on different inputs and have different parameterizations, so their similarity with the survey results gives some confidence in this characterization of Lake Powell's GHG emissions.

4.3. *Effect of reservoir water levels on per MWh emission*

As reservoir water levels decline, the capacity for energy production declines (due to lower hydraulic head) as does the surface area of shallow tributaries where the highest methane emission rates are located. The degree to which declining water levels reduce or increase per MWh GHG emissions depends on how powerplant capacity declines relative to total waterbody emissions. Due to the canyon bound geomorphology of Lake Powell, the spatial extent of shallow tributary areas declines rapidly with falling water levels (Fig. 2B and D), areas which have GHG emission rates two orders of magnitude greater than open-water portions of the reservoir (Table 1). This results in a large decline in total reservoir emissions and a relatively strong reduction in per MWh GHG emission as water levels drop (Fig. 2A)

The coincidence of shallow water and high nutrient/sediment inputs in tributary areas likely drives the high GHG emission rates observed in our survey. As water levels decline and shallow tributary areas become less extensive, sediment and nutrients will be delivered directly to deeper portions of the reservoir. Given the much colder bottom water temperatures in deeper portions of Lake Powell (Table 1), these materials are unlikely to fuel the same level of GHG production as in shallow tributaries. Furthermore, CH_4- and CO_2-rich bubbles released from deep sediments are more likely to dissolve while rising through the water column than when released from shallow sediments, further limiting GHG emissions (McGinnis et al., 2006). While this hypothesis is consistent with our survey data and mechanistic understanding of aquatic GHG biogeochemistry, it should be tested empirically before being incorporated into policy. In reservoirs with more gradual

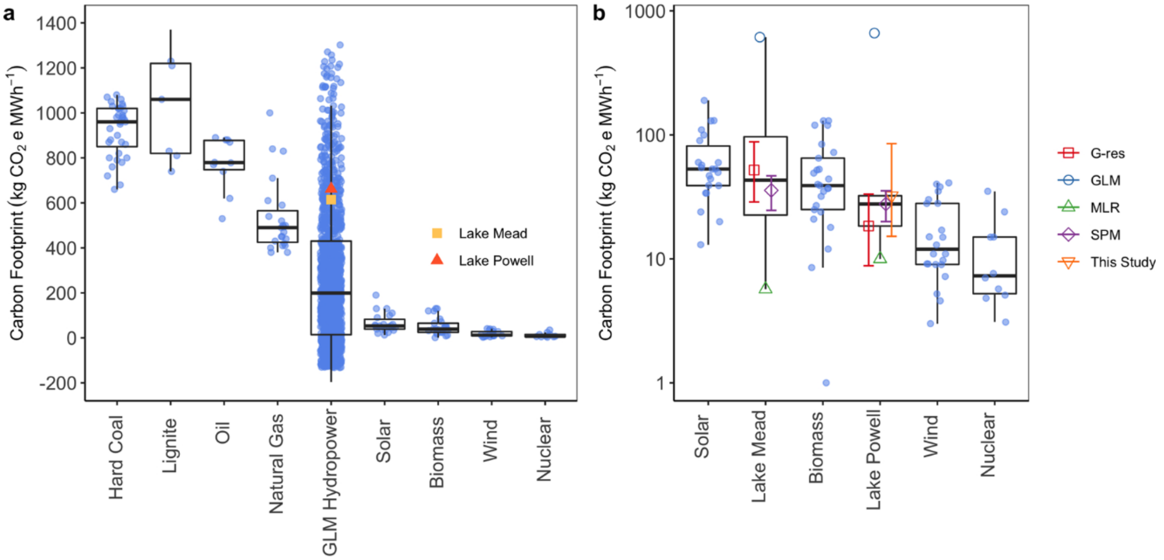

Fig. 3. Panel a: Adaptation from Fig. 2 of Scherer and Pfister (2016): Carbon footprints of various energy sources. The dots show all values included for each source (although only the 10th and 90th percentile of systems are shown for GLM hydropower to improve visualization). The boxes show upper and lower quartiles (25% and 75%), and the horizontal line indicates the median. The whiskers extend to the largest values no more than 1.5 * the IQR. Panel b: the renewable energy subset of panel a, plotted on a log scale and including the multiple carbon footprint estimates for Lake Powell and Lake Mead discussed in this study. Color and shape of the marker indicates the source of the carbon footprint estimate for Lake Powell and Lake Mead. Whiskers indicate model or measurement uncertainty; measurement 95% CI range ("This Study") is on the same order as upper and lower emission estimates in high and low reservoir water level scenarios pictured in Fig. 2.

(non-canyon bound) morphology, we do not expect that water level will cause the same steep decline in kg CO_2.eq MWh^{-1}. Instead, the zone of shallow productive tributary inlet water is expected to shift further downstream. The effect of water level on per MWh emissions from Lake Mead is not quantified here, but the strong reductions in per MWh emissions observed under declining water levels that we quantify here for Lake Powell are unlikely to be observed in Lake Mead due to such differences in reservoir morphology.

4.4. *Sources of uncertainty*

While falling water levels will decrease GHG emissions from shallow littoral regions in Lake Powell, declining water levels could increase emissions from other pathways. For example, punctuated drops in water level can cause upwards of 90% of annual emission (e.g. bubble release due to hydrostatic pressure drop as in Harrison et al., 2017) and several studies have measured relatively high fluxes from recently exposed sediment along reservoir margins ("drawdown regions"; Deemer et al., 2016). Time series studies show that these drawdown emissions are generally concentrated over short time periods (on the order of 1 month) immediately after the reservoir water levels decline and again immediately after reflooding (Kosten et al., 2018; Paranaíba et al., 2020). Still, per area emissions can be high, with CO_2 emissions from drying inland waters elevated by an order of magnitude over surface water fluxes (Almeida et al., 2019; Keller et al., 2020; Kosten et al., 2018). Observations of CH_4 bubbling from mud volcanoes on the exposed inlet sediment deltas of Lake Powell (Malenda et al., 2020) contrast with other work reporting that dried reservoir sediments may sometimes function as CH_4 sinks (Yang et al., 2012), suggesting the importance of constraining this emission pathway. Here we evaluated the potential sensitivity of our findings to greenhouse gas emissions from drying sediments by assuming that CO_2 emissions increase by an order of magnitude for a 31-day period in the drawdown region of the reservoir (see supplemental materials for more detail). Water level declines in Lake Powell occur over time scales of years to decades, so the drawdown area exhibiting elevated CO_2 emission rates is a small fraction of the total drawdown area (average annual 8.75 m water level fluctuation). We estimate that additional CO_2 production from these drying sediments could elevate the per MWh emissions we report here by an average of 5%, but does not affect the overall pattern of declining per MWh emission with declining water level (Figure S2). Overall, the strong effect of water levels on per MWh emissions that we estimate here suggests that these effects could be important in other reservoirs, especially in reservoirs with similar canyon bound geomorphology. This finding could inform environmental policy in systems where GHG emissions are a policy consideration.

Additional sources of uncertainty in the survey measurements include: a.) limited temporal scope (1 survey in the month of July, <30 min per site), b.) a lack of longer term (>24 h) measurements to estimate diel emission patterns, and c.) limited spatial scope (sampling density of 0.06 sites per km^2 and no measurements from dried sediments on the margins of the reservoir). The first source of uncertainty may bias our measurements high, since we are scaling up using warm-season measurements, but it may also bias emissions low if hot moments (or times of disproportionately high flux) associated with reservoir mixing and/or changes in hydrostatic pressure are missed (Harrison et al., 2017; Linkhorst et al., 2020). It is unknown if our estimates are biased by a lack of diel measurements. The literature on this topic is mixed, with some investigators reporting persistent diel patterns in CH_4 emission rates and others reporting no diel patterns (Erkkilä et al., 2018; Podgrajsek et al., 2015, 2014; Sieczko et al., 2020). In general, undersampling tends to bias methane emissions low (Wik et al., 2016) because hot-spots (i.e., small areas with high emission rates) are likely to be missed.

Given considerable variability in sedimentation rates across 27 selected tributary canyons to Lake Powell (ranging from undetectable to 0.76 m yr^{-1}; Kasprak and Schmidt, 2019), it is likely that productivity and associated CH_4 emissions from these regions are also quite variable. The survey conducted here only represents 4 of the 95+ tributary arms, suggesting the importance of more resolved sampling for better constraining whole system emissions. Our results also highlight the sensitivity of our estimate to the way in which shallow tributary areas are identified. Overall CO_2-eq emissions are two orders of magnitude higher in shallow tributary and inlet regions than they are in the main body of the reservoir due to lower emissions of both methane and carbon dioxide in the main body of the reservoir (Table 1). If the shallow tributary and inlet regions were double their currently estimated surface area (at the July 2017 pool elevation and power production), then our overall emission estimates for this time frame would increase by ~ 50% to 49.3 kg CO_2-eq MWh^{-1}.

4.5. *Contribution to policy context*

Recent controversy over water storage allocation in the desert southwest reservoirs Lake Mead and Lake Powell has considered how alternative water management strategies would influence water losses (via changes in evaporation and groundwater storage) and critical aspects of Colorado River ecology (i.e. stream flow, water temperature, sediment supply, and the distribution of native and non-native fish populations; Dibble et al., 2020; Schmidt et al., 2016). Together, these desert southwest reservoirs represent approximately 70% of the total water storage for the Colorado River Basin (Miller, 2012), but ongoing drought (Udall and Overpeck, 2017) and the high human demand for water relative to supply (Sabo et al., 2010) have led to a situation where neither reservoir has reached full capacity since 2000. This study provides context regarding the environmental tradeoffs between energy generation and GHG production in these systems as well as demonstrating relationships between water storage, energy production, and per MWh GHG emissions that may be important to consider in both the planning and management of other systems.

By comparing different modeled estimates of GHG emissions from the two reservoirs with measurements, we aim to both communicate current uncertainty and inform discussion as to the utility of better narrowing this uncertainty. Previous work has implied that Lake Mead's Hoover Dam and Lake Powell's Glen Canyon Dam have a larger carbon intensity than natural gas, and even some oil and coal power plants (Table 3, Fig. 3a, Scherer and Pfister, 2016). The authors compared their GLM modeling results for 1473 hydropower reservoirs to carbon intensity (termed "carbon footprint") values published in a life cycle assessment of other energy sources (Turconi et al., 2013). The results suggested that the emissions from hydropower were far higher than previously assumed and called into question the sustainability of hydropower, though the GLM was intended to be used at an aggregate scale and not for specific reservoirs (see Section 4.2 and supplemental materials). The results we present here (e.g. from the G-res tool, the SPM, and the July 2017 Lake Powell survey measurements) indicate that the carbon intensity of these systems is likely much lower than was suggested by Scherer and Pfister (2016), more similar to that of energy from solar or biomass (Table 3, Fig. 3b). More recent studies have estimated the regional greenhouse gas footprint of hydropower reservoirs in the Mekong River Basin (Räsänen et al., 2018) and in Québec, Canada (Levasseur et al., 2021) and have found that the majority of systems have emissions comparable to other renewable energy sources. Our results also suggest that Lake Mead and Lake Powell are similar in the magnitude of their per MWh GHG emissions, with modeled emissions from Lake Mead ranging from 0.57 to 2.8 times that of Lake Powell based on the G-res, SPM, and MLR models respectively (Table 3, Fig. 3), but this is without field-based measurements from the Lake Mead system.

Here we have presented the best available estimates of gross surface GHG emissions from Lake Powell and Lake Mead, but many frameworks stress the importance of reporting net reservoir GHG emissions, or the difference between emissions from the reservoir and the previous landscape. Parsing pre-existing ecosystem GHG emissions from those due specifically to reservoir formation is unfortunately not a straightforward task. While CH_4 emissions are generally thought to originate from reservoir waterbody formation, some fraction of a reservoir's CO_2 balance would exist in the absence of a reservoir, making the net effect of the reservoir on the CO_2 balance difficult to quantify (Prairie et al., 2018). In addition, we do not take into account factors such as potential dam decommissioning effects (e.g. fate of C stored in sediments, Pacca, 2007), nor do we consider the magnitude of C burial occurring in the reservoir.

Future water storage decisions may not only affect the water levels and associated per MWh emissions from the reservoirs (as in Fig. 2) but may also affect limnological conditions within the two reservoirs that ultimately determine total emission. For example, the warm water releases expected from Lake Powell under lower water levels (Dibble et al., 2020) may reduce cold underflow mixing in Lake Mead leading to lower oxygen conditions and more CH_4 production. Nevertheless, our results demonstrate a substantial difference in per MWh GHG emissions contingent on water level. This finding has implications for managing arid region reservoir levels in conjunction with replacement energy production and the planning and design of future hydropower facilities. For example, the impact of declining water levels on overall per MWh GHG emissions should include GHG emissions from energy production to replace the lost powerplant capacity. These considerations could play an important role in the operation of arid region reservoirs, as integration of renewables into the electricity sector continue, and the seasonal drawdown of reservoirs influence the total change in GHG emissions. Our results demonstrate that changes in reservoir design and operation could have a significant impact on aggregate per MWh GHG emissions.

5. Conclusions

Some of the first measurements of GHG emission from Lake Powell indicate a capacity for high emissions from littoral tributary regions, with average areal fluxes from this zone that are approximately 1.6 times the global average for reservoir systems. Still, when upscaled, Lake Powell's CO_2-eq per MWh emissions are on the low end of those estimated for other reservoir systems (as are the majority of the estimates produced by global scale models; Fig. 3). The large disparities in emission between different reservoir zones that we report here call for additional sampling to further constrain system-wide emissions. In addition, a number of phenomena (including drops in hydrostatic pressure and thermal mixing) could significantly affect annual emission estimates but were beyond the scope of this study. While global models suggest that per MWh emissions are likely similar between Lake Powell and Lake Mead, important differences between the systems may result in differential responses to environmental policy decisions. Overall, the work presented here highlights reservoir water level as an important determinant of per MWh GHG emissions – a finding with potentially important implications for environmental policy in arid zone reservoirs.

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CRediT authorship contribution statement

Sarah Waldo: Investigation, Data curation, Formal analysis, Writing - original draft, Visualization. **Bridget R. Deemer:** Conceptualization, Investigation, Formal analysis, Writing - original draft, Visualization. **Lucas S. Bair:** Writing - review & editing. **Jake J. Beaulieu:** Methodology, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.02.006.

References

Almeida, R.M., Paranaíba, J.R., Barbosa, Í., Sobek, S., Kosten, S., Linkhorst, A., Mendonça, R., Quadra, G., Roland, F., Barros, N., 2019. Carbon dioxide emission from drawdown areas of a Brazilian reservoir is linked to surrounding land cover. Aquat. Sci. 81, 68. https://doi.org/10.1007/s00027-019-0665-9.

Beaulieu, J.J., McManus, M.G., 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.

Berberich, M.E., Beaulieu, J.J., Hamilton, T.L., Waldo, S., Buffam, I., 2019. Spatial variability of sediment methane production and methanogen communities within a eutrophic reservoir: importance of organic matter source and quantity. Limnol Oceanogr lno. 11392. https://doi.org/10.1002/lno.11392.

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., Vonk, J.A., 2016. Greenhouse gas emissions from reservoir water surfaces: a new global synthesis. BioScience 66, 949–964.

Deemer, B.R., Stets, E.G., Yackulic, C.B., 2020. Calcite precipitation in Lake Powell reduces alkalinity and total salt loading to the Lower Colorado River Basin. Limnol Oceanogr lno 11399. https://doi.org/10.1002/lno.11399.

Deemer, B.R., Waldo, S., Gushue, T., 2021. Modeled and Measured Greenhouse Gas Emissions From Lake Powell and Bathymetric Analysis of Tributary Littoral Habitat at Different Water Levels. U.S. Geological Survey data release. https://doi.org/10.5066/P9PRW8JX.

DelSontro, T., Kunz, M.J., Kempter, T., Wüest, A., Wehrli, B., Senn, D.B., 2011. Spatial heterogeneity of methane ebullition in a large tropical reservoir. Environ. Sci. Technol. 45, 9866–9873. https://doi.org/10.1021/es2005545.

DelSontro, T., Beaulieu, J.J., Downing, J.A., 2018. Greenhouse gas emissions from lakes and impoundments: upscaling in the face of global change. Limnol. Oceanogr. Lett. 3, 64–75. https://doi.org/10.1002/lol2.10073.

Dibble, K.L., Yackulic, C.B., Kennedy, T.A., Bestgen, K.R., Schmidt, J.C., 2020. Water storage decisions will determine the distribution and persistence of imperiled river fishes. Ecol. Appl. https://doi.org/10.1002/eap.2279.

Ding, L., Hannoun, I.A., List, E.J., Tietjen, T., 2014. Development of a phosphorus budget for Lake Mead. Lake Reserv. Manag. 30, 143–156. https://doi.org/10.1080/10402381.2014.899656.

Erkkilä, K.-M., Ojala, A., Bastviken, D., Biermann, T., Heiskanen, J.J., Lindroth, A., Peltola, O., Rantakari, M., Vesala, T., Mammarella, I., 2018. Methane and carbon dioxide fluxes over a lake: comparison between eddy covariance, floating chambers and boundary layer method. Biogeosciences 15, 429–445. https://doi.org/10.5194/bg-15-429-2018.

Ferrari, R.L., 1988. 1986 Lake Powell Survey (Technical Report No. REC-ERC-88-6). Bureau of Reclamation, Denver, Colorado.

Gloss, S.P., Mayer, L.M., Kidd, D.E., 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnol. Oceanogr. 25, 219–228.

Grinham, A., Dunbabin, M., Gale, D., Udy, J., 2011. Quantification of ebullitive and diffusive methane release to atmosphere from a water storage. Atmos. Environ. 45, 7166–7173. https://doi.org/10.1016/j.atmosenv.2011.09.011.

Harpman, D.A., 1999. Assessing the short-run economic cost of environmental constraints on hydropower operations at Glen Canyon Dam. Land Econ. 75, 390. https://doi.org/10.2307/3147185.

Harpman, D.A., Douglas, A.J., 2005. Status and Trends of Hydropower Production at Glen Canyon Dam, Chapter 10 in The State of the Colorado River Ecosystem in Grand Canyon: A Report of the Grand Canyon Monitoring and Research Center 1991-2004 (U.S. Geological Survey Circular No. 1282). U.S. Geological Survey, Reston, Virginia.

Harrison, J.A., Deemer, B.R., Birchfield, M.K., O'Malley, M.T., 2017. Reservoir water-level drawdowns accelerate and amplify methane emission. Environ. Sci. Technol. 51, 1267–1277. https://doi.org/10.1021/acs.est.6b03185.

Hertwich, E.G., 2013. Addressing biogenic greenhouse gas emissions from hydropower in LCA. Environ. Sci. Technol. 47, 9604–9611. https://doi.org/10.1021/es401820p.

Kasprak, A., Schmidt, J.C., 2019. Sedimentation of Lake Powell Tributary Canyons, 1959-2017 (Research Briefing). Center for Colorado River Studies.

Keller, P.S., Catalán, N., von Schiller, D., Grossart, H.-P., Koschorreck, M., Obrador, B., Frassl, M.A., Karakaya, N., Barros, N., Howitt, J.A., Mendoza-Lera, C., Pastor, A., Flaim, G., Aben, R., Riis, T., Arce, M.I., Onandia, G., Paranaíba, J.R., Linkhorst, A., del Campo, R., Amado, A.M., Cauvy-Fraunié, S., Brothers, S., Condon, J., Mendonça, R.F., Reverey, F., Rõõm, E.-I., Datry, T., Roland, F., Laas, A., Obertegger, U., Park, J.-H., Wang, H., Kosten, S., Gómez, R., Feijoó, C., Elosegi, A., Sánchez-Montoya, M.M., Finlayson, C.M., Melita, M., Oliveira Junior, E.S., Muniz, C. C., Gómez-Gener, L., Leigh, C., Zhang, Q., Marcé, R., 2020. Global CO_2 emissions from dry inland waters share common drivers across ecosystems. Nat. Commun. 11, 2126. https://doi.org/10.1038/s41467-020-15929-y.

Kosten, S., van den Berg, S., Mendonça, R., Paranaíba, J.R., Roland, F., Sobek, S., Van Den Hoek, J., Barros, N., 2018. Extreme drought boosts CO_2 and CH_4 emissions from reservoir drawdown areas. Inland Waters 8, 329–340. https://doi.org/10.1080/20442041.2018.1483126.

Levasseur, A., Mercier-Blais, S., Prairie, Y.T., Tremblay, A., Turpin, C., 2021. Improving the accuracy of electricity carbon footprint: estimation of hydroelectric reservoir greenhouse gas emissions. Renewable Sustainable Energy Rev. 136, 110433 https://doi.org/10.1016/j.rser.2020.110433.

Linkhorst, A., Hiller, C., DelSontro, T.M., Azevedo, G., Barros, N., Mendonça, R., Sobek, S., 2020. Comparing methane ebullition variability across space and time in a Brazilian reservoir. Limnol. Oceanogr. 65, 1623–1634. https://doi.org/10.1002/lno.11410.

Lovelock, C.E., Evans, C., Barros, N., Prairie, Y.T., Alm, J., Bastviken, D., Beaulieu, J.J., Garneau, M., Harby, A., Harrison, J.A., Pare, D., Raadal, H.L., Sherman, B., Zhang, C., Ogle, S.M., Grinham, A., Deemer, B.R., dos Santos, M.A., Kosten, S., Peacock, M., Zhe Li, Z., Stepanenko, V., 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC chap. 7, v. 4, p. 7.1-7.54.

Mahlooji, M., Gaudard, L., Ristic, B., Madani, K., 2020. The importance of considering resource availability restrictions in energy planning: what is the footprint of electricity generation in the Middle East and North Africa (MENA)? Sci. Total Environ. 717, 135035 https://doi.org/10.1016/j.scitotenv.2019.135035.

Malenda, M., Betts, T., Simpson, W., Wizevich, M., Simpson, E., Sherrod, L., 2020. Methane emissions from muds during low water-level stages of Lake Powell, southern Utah, USA. GIW 7, 121–136. https://doi.org/10.31711/giw.v7.pp121-136.

McGinnis, D.F., Greinert, J., Artemov, Y., Beaubien, S.E., Wüest, A., 2006. Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? J. Geophys. Res. 111, 1–15. https://doi.org/10.1029/2005JC003183.

Miller, M.P., 2012. The influence of reservoirs, climate, land use and hydrologic conditions on loads and chemical quality of dissolved organic carbon in the Colorado River. Water Resour. Res. 48 https://doi.org/10.1029/2012WR012312.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pacca, S., 2007. Impacts from decommissioning of hydroelectric dams: a life cycle perspective. Clim. Change 84, 281–294. https://doi.org/10.1007/s10584-007-9261-4.

Paranaíba, J.R., Quadra, G., Josué, I.I.P., Almeida, R.M., Mendonça, R., Cardoso, S.J., Silva, J., Kosten, S., Campos, J.M., Almeida, J., Araújo, R.L., Roland, F., Barros, N., 2020. Sediment drying-rewetting cycles enhance greenhouse gas emissions, nutrient and trace element release, and promote water cytogenotoxicity. PLoS One 15, e0231082. https://doi.org/10.1371/journal.pone.0231082.

Podgrajsek, E., Sahlée, E., Rutgersson, A., 2014. Diurnal cycle of lake methane flux: diurnal cycle of lake methane flux. J. Geophys. Res. Biogeosci. 119, 236–248. https://doi.org/10.1002/2013JG002327.

Podgrajsek, E., Sahlée, E., Rutgersson, A., 2015. Diel cycle of lake-air CO_2 flux from a shallow lake and the impact of waterside convection on the transfer velocity. J. Geophys. Res. Biogeosci. 120, 29–38. https://doi.org/10.1002/2014JG002781.

Prairie, Y.T., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., del Giorgio, P., DelSontro, T., Guérin, F., Harby, A., Harrison, J., Mercier-Blais, S., Serça, D., Sobek, S., Vachon, D., 2018. Greenhouse gas emissions from freshwater reservoirs: What does the atmosphere see? Ecosystems 21, 1058–1071. https://doi.org/10.1007/s10021-017-0198-9.

Räsänen, T.A., Varis, O., Scherer, L., Kummu, M., 2018. Greenhouse gas emissions of hydropower in the Mekong River Basin. Environ. Res. Lett. 13, 034030 https://doi.org/10.1088/1748-9326/aaa817.

Reynolds, R.C., 1978. Polyphenol inhibition of calcite precipitation in Lake Powell. Limnol. Oceanogr. 23, 585–597. https://doi.org/10.4319/lo.1978.23.4.0585.

Rudd, J.W.M., Hecky, R.E., Harris, R., Kelly, C.A., 1993. Are hydroelectric reservoirs significant sources of greenhouse gases. Ambio 22, 246–248.

Sabo, J.L., Sinha, T., Bowling, L.C., Schoups, G.H.W., Wallender, W.W., Campana, M.E., Cherkauer, K.A., Fuller, P.L., Graf, W.L., Hopmans, J.W., Kominoski, J.S., Taylor, C., Trimble, S.W., Webb, R.H., Wohl, E.E., 2010. Reclaiming freshwater sustainability in the Cadillac Desert. Proc. Natl. Acad. Sci. 107, 21263–21269. https://doi.org/10.1073/pnas.1009734108.

Saidi, H., Koschorreck, M., 2017. CO_2 emissions from German drinking water reservoirs. Sci. Total Environ. 581–582, 10–18. https://doi.org/10.1016/j.scitotenv.2017.01.004.

Scherer, L., Pfister, S., 2016. Hydropower's biogenic carbon footprint. PLoS One 11, e0161947. https://doi.org/10.1371/journal.pone.0161947.

Schmidt, J.C., Kraft, M., Tuzlak, D., Walker, A., 2016. Fill Mead First: a Technical Assessment (No. 1). Center for Colorado River Studies, Quinney College of Natural Resources, Utah State University.

Sieczko, A.K., Duc, N.T., Schenk, J., Pajala, G., Rudberg, D., Sawakuchi, H.O., Bastviken, D., 2020. Diel variability of methane emissions from lakes. Proc. Natl. Acad. Sci. U.S.A. 117, 21488–21494. https://doi.org/10.1073/pnas.2006024117.

Therrien, J., Tremblay, A., Jacques, R.B., 2005. CO_2 emissions from semi-arid reservoirs and natural aquatic ecosystems. In: Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M. (Eds.), Greenhouse Gas Emissions- Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments. Springer, New York, pp. 233–250.

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renewable Sustainable Energy Rev. 28, 555–565. https://doi.org/10.1016/j.rser.2013.08.013.

U.S. Bureau of Reclamation, 2017. Quality of water, Colorado River Basin, Progress Report No. 25. U.S. Department of the Interior.

U.S. Department of Interior, 2016. Glen Canyon Dam Long-term Experimental and Management Plan Final Environmental Impact Statement (LTEMP FEIS). U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, National Park Service, Intermountain Region.

Udall, B., Overpeck, J., 2017. The twenty-first century Colorado River hot drought and implications for the future. Water Resour. Res. 53, 2404–2418. https://doi.org/10.1002/2016WR019638.

Uusitalo, L., Lehikoinen, A., Helle, I., Myrberg, K., 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ. Model. Softw. 63, 24–31. https://doi.org/10.1016/j.envsoft.2014.09.017.

West, W.E., Creamer, K.P., Jones, S.E., 2015. Productivity and depth regulate lake contributions to atmospheric methane. Limnol. Oceanogr. 61, S51–S61. https://doi.org/10.1002/lno.10247.

Wik, M., Thornton, B.F., Bastviken, D., Uhlbäck, J., Crill, P.M., 2016. Biased sampling of methane release from northern lakes: a problem for extrapolation. Geophys. Res. Lett. 43, 1256–1262. https://doi.org/10.1002/2015GL066501.

Xiao, M., Udall, B., Lettenmaier, D.P., 2018. On the causes of declining Colorado River streamflows. Water Resour. Res. 54, 6739–6756. https://doi.org/10.1029/2018WR023153.

Yang, L., Lu, F., Wang, X., Duan, X., Song, W., Sun, B., Chen, S., Zhang, Q., Hou, P., Zheng, F., Zhang, Y., Zhou, X., Zhou, Y., Ouyang, Z., 2012. Surface methane emissions from different land use types during various water levels in three major drawdown areas of the Three Gorges Reservoir. J. Geophys. Res. 117, 1–11. https://doi.org/10.1029/2011JD017362.

Zhao, Y., Sherman, B., Ford, P., Demarty, M., DelSontro, T., Harby, A., Tremblay, A., Øverjordet, I.B., Zhao, X., Hansen, B.H., Wu, B., 2015. A comparison of methods for the measurement of CO_2 and CH_4 emissions from surface water reservoirs: results from an international workshop held at Three Gorges Dam, June 2012. Limnol. Oceanogr. Methods 13, 15–29. https://doi.org/10.1002/lom3.10003.

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