Greenhouse Gas Emissions from Lakes & Reservoirs: The Likely Contribution of Hydroelectric Project Reservoirs on the Mid-Columbia River

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Introduction

A Pre-Publication draft of Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis by Deemer et al. was released by Bioscience in late 2016. Premises stated in the report are that reservoirs created by dams, including reservoirs created by hydroelectric dams, are thought to be an important source of greenhouse gas emissions to the atmosphere, and, "while reservoirs are often thought of as "green" or carbon neutral sources of energy, a growing body of work has documented their role as greenhouse gas sources." Based on this report, a headline in the September 28, 2016 edition of the Seattle Times read: "Hydropower isn't carbon neutral after all, WSU researchers say." This headline invoked serious attention within the hydroelectric industry, resulting in the production of this whitepaper. The purpose of this paper is to:

1. Review recent research and conclusions of the recent Bioscience paper (Deemer et al. 2016) on the subject of greenhouse gas (GHG) (CH_4, CO_2, and N_2O) production in, and emissions from, freshwater bodies, particularly reservoirs behind hydroelectric dams;
2. To summarize principle controllers of GHG production and release from reservoirs in general;
3. To review the worldwide database of GHG-producing water bodies to relate GHG emissions release rates to controlling aspects of watershed and water body;
4. To review environmental factors controlling GHG production and release particularly in Northwest U.S. and mid-Columbia R. reservoirs; and
5. To estimate likely ranges of GHG production and release processes specifically in the mid-Columbia reservoirs Rock Island, Rocky Reach, and Lake Chelan.

Findings of Deemer et al. 2016, Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis.

The Deemer et al. report is a multinational synthesis (of the worldwide database and their own work, essentially all published in the last 20 years) of reservoir GHG emissions. Their synthesis incorporates CH_4 ebullition measurements, updates global estimates of the magnitude of GHG emissions from reservoirs, discusses environmental controllers of CH_4, CO_2, and N_2O emissions, discusses policy implications of their conclusions, and recommends foci of future research.

The artificial lakes created by hydroelectric dams can, in some cases, be significant producers of GHG gases to the atmosphere because:

1. Hydroelectric reservoirs can flood large quantities of terrestrial organic matter stored in above- and below- ground biomass, fueling microbial decomposition, converting stored organic matter (OM) to CO_2, CH_4, and N_2O;
2. Water level drawdowns alter hydrostatic pressure on littoral sediments thereby enhancing CH_4 ebullition (bubbling rates) to the water column. Normal oxidation processes converting CH_4 to CO_2 (a less potent GHG) in surface sediments and water column are thus bypassed as less soluble CH_4 bubbles rise to the air/water interface; and
3. Hydroelectric reservoirs tend to have large catchment area-to-reservoir surface area ratios and are located on larger streams, thereby receiving higher water, nutrient, sediment, and OM loading than natural lakes.

The review by the Deemer et al. points out that CH_4 and N_2O are 34 and 298 times, respectively, more potent as climate forcing agents than CO_2, a fact somewhat ameliorated by the shorter residence times of CH_4 and N_2O in the atmosphere. For that former reason, most recent studies have concluded that worldwide CH_4 emissions are responsible for 80% of the radiative forcing from reservoir surfaces over a 100-year span and 90% over a 20-year span. This paper therefore, will focus primarily on CH_4 emissions.

Even though CH_4 releases are most important to consideration of climate impacts, relatively few limnological studies have considered CH_4 aspects of carbon cycling. Measurement of CH_4 in waters is relatively new (compared to the research base for inorganic and other organic forms of carbon) so that until very recently, inter-study and inter-lake comparison of CH_4 cycles has been difficult. Earlier studies have often relied on measured CH_4 concentration in sediments and water to calculate CH_4 releases from the air/water interface as a function of calculated gas exchange. These approaches greatly overestimated CH_4 oxidation in the water column and have underestimated (or ignored entirely) ebullition short-circuiting CH_4 delivery to the atmosphere.

The Deemer et al. (2016) analysis evaluated CH_4, CO_2, and N_2O flux estimates from 161, 229, and 58 worldwide reservoir systems, respectively; 75 of those reservoirs met their established methodological criteria for inclusion in their analyses. Primary criteria for inclusion were whether the studies calculated *both* diffusive and ebullitive CH_4 release and rigor of study design (i.e., sampling intensity, placement, and representativeness of sampling to the studied water body. Only 52% of the studies in their evaluation measured CH_4 ebullition. They found that mean ebullition + diffusion fluxes in their worldwide database averaged 103 mg CH_4 –C m-^{2} day-^{1}, compared to 43 mg CH_4 –C m-^{2} day-^{1} diffusion-only fluxes; CH_4 emission rates varied significantly between reservoirs on the basis of ebullition measures inclusion. In reservoir studies they assessed, ebullition averaged 65% of total CH_4 flux compared to 40 – 60% of the total flux in natural lakes.

From the large global database they established that ebullitive emissions from lakes of all latitudes are likely the dominant form of CH_4 emissions to the atmosphere and that studies focusing on diffusive emissions may underestimate the total by many fold. Their revised diffusion + ebullition global reservoir CH_4 fluxes (120.4 mg CH_4 –C m-^{2} day-^{1}) averaged 25% greater than previous global estimates. These higher mean estimates of CH_4 flux were attributed to their exclusion of “diffusion-only” studies from the database analysis. This analysis also found higher average CH_4 flux rates from temperate reservoirs compared to earlier studies which had believed that reservoir GHG emissions were largely a low latitude phenomena. The commonly held view that low latitude reservoirs had higher emission rates than higher latitude pools was simply attributed to the predominance of early GHG research *focusing* on low latitude reservoirs. More research on temperate and subtropical research published since 2000, has shown that CH_4 flux rates from temperate reservoirs were statistically indistinguishable from tropical Amazonian pools.

CO_2 fluxes (329.7 mg CH_4 –C m-^{2} day-^{1}) averaged 30% smaller than previous global estimates. The first ever global mean estimate of N_2O they developed was 0.30 mg N_2O-N m-^{2} day-^{1}. The mean N_2O was an order of magnitude less than the estimated mean for U.S. reservoirs but in line with values of Yang et al

(2014). All of the reservoirs assessed by Deemer et al. 2016 were either CH_4 – neutral or sources while 16% were net N_2O sinks and 15% were net CO_2 sinks, which means that those reservoirs reduced atmospheric levels of N_2O and CO_2.

The Deemer et al. review is the most comprehensive synthesis to date of the global database on reservoir GHG emissions. Their analysis distilled a number of data-supported generalizations from the global database on GHG gas production, especially CH_4:

1. Mid-latitude reservoirs CH_4 emissions were statistically indistinguishable from tropical reservoirs;
2. CH_4 emissions from hydroelectric reservoirs were not different from non-hydro reservoirs or from natural lakes;
3. CH_4 emissions varied inversely with reservoir age, a covariation with the decline in decomposable OM in the early years after reservoir formation;
4. Reservoir productivity predicted the radiative forcing capacity of reservoir GHG emissions, i.e. CH_4 emissions, were best predicted by pelagic chlorophyll *a* when evaluated by multiple-reservoir least squared regression analyses. Other less comprehensive analyses agree with this relationship, going further in linking CH_4 emissions with within-site availability of all forms of OM, from all sources;
5. Trophic status was also positively correlated with CH_4 emissions. Eutrophic systems emitted approximately 10 times more CH_4 than oligotrophic systems;
6. The particulate organic material (POM) and dissolved organic material (DOM) produced by eutrophic reservoirs was also found to feed higher rates of CH_4 production than comparable amounts of terrestrial organic matter;[1]
7. In boreal reservoirs (e.g. eastern Canada and Scandinavia) CH_4 ebullition appears to be a lower percent of total CH_4 emissions. Most of these well-studied reservoirs are fairly new, with CH_4 emissions primarily driven by decomposition of drowned terrestrial OM; and
8. Faster moving, more oxygenated 'lotic' waters, i.e., reservoirs with low HRT typically support more CO2 production with less CH_4 production.

Methanogenesis, the formation of methane in aquatic environments, requires POM and/or DOM reduced under anaerobic conditions. A common thread in the global GHG research reviewed for this present review is the association of CH_4 production with shallow depth systems, shallow (littoral) areas of reservoir systems, marshlands, embayments, stream deltas, etc., all concentration points for OM and the conditions required for methanogenesis. These habitats account for much of the system variability in reservoirs and thus of the extreme variability CH_4 measurement studies have shown between and even within reservoirs. In run-of-river reservoirs, as on the mid-Columbia River, a littoral AM (aquatic macrophyte) bed may have CH_4 production rates per unit area 3 or 4 orders of magnitude greater than in the pelagic habitat only meters away. This is particularly relevant for the Rock Island and Rocky Reach reservoirs explaining the need for quantification (size, characteristics, and CH_4 emissions of these littoral areas. The following table gives principal controllers of CH_4 emissions for reservoirs in general (Table 1).

[1] Author's Note: Eutrophic lakes are more common in mid-latitudes because watershed soils are rich in divalent cation-associated nutrients and are more basic, compared to the very low nutrient levels in tropics where waters are derived from nutrient-depleted, acidic soils of lateritic origin. This partially explains the paradox of low pelagic production in tropic reservoirs. The extremely high rates of CH_4 production in new tropical reservoirs are explained by the drowning of extremely high terrestrial biomass densities.

Table 1. Controllers of CH_4 Emissions to Atmosphere – Reservoirs in General

Controllers of CH4 Production & Release (Bold = major forcing factor)	Relationship to CH4 Production & Release - Reservoirs in General
Reservoir age	CH_4 production sharply drops after 3 years; Release of soluble OM & nutrients from drowned terrestrial vegetation tails out to near zero after 30-50 years.
Reservoir surface area (size)	CH_4 production higher in small lakes/reservoirs; Dramatically increased in water bodies less than 1 – 2 km^2.
Lake length	Greater length provides greater shoreline length and potential for littoral development.
Shoreline development (S_{DL}): compares shoreline length to a same area circle	Higher S_{DL} related to potentially higher littoral thus potential sites of CH_4 production & release
Lake orientation	Wind fetch strongly correlated to mixing, thus sediment entrainment and gas diffusion at S/W & A/W interfaces
Hydraulic Retention Time (HRT)	CH_4 production directly correlated w/ HRT; Low HRT water bodies have very low CH_4 emission rates in pelagic waters.
Lake level fluctuation – Load following	CH_4 release from shallow sediments positively correlated with fluctuation frequency magnitude, & rapidity of water surface change.
Year-round top-to-bottom water circulation	Precludes development of anoxia, hence CH_4 production in water column and surficial sediments year-round; Anaerobic conditions with accompanying methanogenesis may occur in deeper sediments. Thicker sediment deposits may store more CH_4, subject to release @ S/W interface with sufficient currents.
Winter ice cover	Winter ice cover in a water body can provide a months-long seal of the A/W interface leading to lower under-ice oxygen levels & CH_4 accumulation both in the water column and sediments. Large volumes of CH_4 releases can then occur at Spring overturn.
Vertical water stratification	Stratification permits vertical layering & isolation from atmosphere of deeper areas of water column and sediments. Anoxia is enhanced with subsequent CH_4 production.
Near-bottom velocity	CH_4 production in, and release from sediments @ S/W interface negatively correlated w/ near-bottom velocity.
Fine sediment accumulation	CH_4 production is inversely correlated with sediment particle size, i.e. Finer sediments can have higher rates of methanogenesis.
Littoral fine, organic-rich sediment	Strongly correlated with near-shore band of OM accumulation, potential CH_4 production, and AM, then release via either: 1) direct diffusion to water [least important], ebullition; or 2) the AM pathway to water. Relative areal coverage determines total CH_4 release of the total reservoir.
Organic content of watershed soils	Aquatic CH_4 production is positively correlated with allochthonous (loading from terrestrial sources) OM inputs to reservoir.
Organic content and nutrients of lake sediments	High CH_4 production is correlated with organic matter & nutrients of sediments. Drowned timber & terrestrial vegetation extremely important drivers of methanogenesis in early life of reservoir.
Littoral sediment development	Littoral fine sediments tend to be rich in OM and nutrients, correlating with methanogenesis and CH_4 release to water via diffusion, ebullition, or AM piping….per unit area, the highest rates of CH_4 production in a reservoir.
Nutrient loading from watershed to reservoirs	CH_4 production increases with non-point watershed nutrient supply (irrigated agriculture, orchards, forest practices, and roads).
Nutrient loading to reservoirs	Higher nutrient loading usually leads to higher lake productivity, organic sediments, & CH_4 production.

In-Reservoir (autochthonous) production	Higher autotrophic production provides more OM to sediments for anaerobic decomposition in sediment, thus higher CH_4 production. Autotrophic OM production from within the water body is more efficient at CH_4 production.
Water temperature	Higher water temperatures correlate very strongly with higher CH_4 production
Water transparency	More clear waters indicate lower plankton but higher potential littoral AM production; Balance of resulting OM accrual dependent on physical characteristics, e.g., steep shorelines limit littoral area greatly reducing CH_4 production rates.
Rooted aquatic macrophyte (AM) development	Shore bands of AM reduce water velocity; form, trap, and build OM- and nutrient-rich bottom sediments. By reducing velocity in thick beds, deeper anoxic sediments conducive to methanogenesis develop.
CH_4 Ebullition to surface	Generally a large factor in CH_4 release to atmosphere in littoral waters < 3 m for several reasons: 1) drawdown-enhanced release of CH_4 from sediments occurs mostly in the drawdown band; 2) OM deposits form there from settling in quiescent water along with high OM production from ABA and AM; 3) AM release bubbles in the shallow littoral ensuring that more CH_4 reaches the surface; and 4) AM piping of gaseous CH_4 to the A/W. In deeper water columns, most of CH_4 bubbles are absorbed and/or oxidized to CO_2 before reaching the A/W interface.
ABA = attached benthic algae	AM = aquatic macrophytes WS = Watershed of reservoir
S/W = sediment/water interface	A/W = air/water interface CH_4 = CH_4 or methane gas
OM = organic matter	O2 = O_2 or dissolved oxygen CO2 = CO_2 or carbon dioxide

Likely ranges of GHG production and release processes in the mid-Columbia reservoirs, specifically Rocky Reach, Rock Island, and Lake Chelan

Most northwest rivers generally have high water quality, with modest levels of nutrient inflow impacts compared to other US regions. Streams are colder, swifter, and well oxygenated. Nonetheless, the mid-Columbia watershed, given its very large drainage area, does have significant nutrient loading from irrigated agricultural lands orchards, urban/suburban runoff, and treated wastewater, boosting productivity of Rock Island and Rocky Reach Reservoirs to lower mesotrophic levels. Lake Chelan retains its historic ultra-oligotrophic condition of its pelagic and littoral areas.

Table 2 below considers the same controllers of Table 1 but with their likely effects on/in the Rock Island and Rocky Reach Reservoirs. There are no CH_4 data for these 2 reservoirs, so it is only possible now to assess general effects of CH_4 controllers on reservoir production and emission tendencies.

Table 2. Controllers of CH_4 Emissions to Atmosphere – Rock Island & Rocky Reach Reservoirs

Controllers of CH_4 Production & Release	Effect on Rock Island & Rocky Reach Reservoirs' CH_4 Production & Release
(Bold = major forcing factor)	
Reservoir age	At 83 & 49 years, tendency is towards very low CH_4 production; Both reservoir basins were cleared of vegetation before flooding; Initially-flooded small vegetation OM is long decomposed.
Reservoir surface area (size)	Towards low CH_4 production given large size and less littoral area.
Lake length	Long relative to width; CH_4 production (and ebullition) favored by relatively more littoral AM communities on longer shoreline. Small % of reservoirs are littoral though. Increased wave action in these N/S trending pools, however, is a strong limitation on AM development.
Shoreline development: S_{DL} compares shoreline length to a circle w/ same area	Very High S_{DL} (9.3) creates a situation of potentially more CH_4 production & release in the littoral.
Lake orientation	General SE-NW & S-N alignment favors strong top to bottom wind-driven mixing; Aerated sediments inhibit methanogenesis at A/W interface.
Hydraulic Retention Time (HRT)	Towards low CH_4 production; Run-of-River; very low HRT (~1 day @ high flow; ~2.3 days @ typical July flow). Provides for oxygenated water column and surficial sediments.
Lake level fluctuation – Load following	Slight tendency to increase CH_4 release from littoral; Most of the drawdown zone, however, is in the swash or wave zone where OM & the fine sediments required for a CH_4 –forming environment will be low.
Year-round top-to-bottom water circulation	A polymictic lake continuously circulation top-to-bottom with deep layers only slightly below O2 saturation, resulting in very low CH_4 potential production in pelagic zones & surficial sediments. Circulation slightly inhibiting to littoral AM communities.
Winter ice cover	The absence of winter ice cover stratification limits CH_4 production in the pelagic zone and sediments over the year by pushing the oxidation/reduction boundary deep into the sediments. The potential for CH_4 production and accumulation is greatly reduced. Attached algae production at some sites is in the meso-eutrophic range indicating high enough rates of OM production for methanogenesis in shallow waters (shown by high winter Autotrophic Indices in the ABA) but oxygenated water in constant contact with the A/W interface keeps those ABA-rich rocky sediments aerobic.
Vertical water stratification	Potential CH_4 production in pelagic zones very low. Some microhabitats of stratification may develop in narrow bays and delta areas. Those as well as littoral AM bands are likely hot spots for significant CH_4 production rates per unit area.
Near-bottom velocity	Towards low CH_4; High near-bottom velocities (1-3 fps) aerate surface sediments very well beneath most of the open waters, precluding methanogenesis.
Fine sediment accumulation	Towards low CH_4; Cobbles predominate beyond 6 m depth
Littoral fine, organic-rich sediment	Enhanced tendency for CH_4 release, but partially ameliorated by lake level fluctuation continually reducing fines in 0 – 2 m depth zone and reducing AM zone to ~2 – 6 m depth
Organic content of watershed soils	Sandy, low OM supply to reservoirs contributing little OM towards CH_4 production.
Organic content and nutrients of lake sediments	Towards low CH_4; low OM inundated; low OM & sediment nutrients now predominate in the rocky, sand-embedded cobble bottoms beyond 6 m depth.
Littoral sediment development	In Rock Island, littoral development is greatly reduced by naturally steep, rocky shorelines and by the prevalence of rip-rap boulders banks built on the reservoir. Slightly higher propensity for more littoral AM bands in Rocky Reach.

Nutrient loading from watershed to reservoirs	Towards moderate CH_4 levels; WS soils moderately nutrient-rich but prone to water & wind erosion exacerbating potential agricultural loading.
Nutrient loading to reservoirs	High upstream irrigated agriculture & orchard activity, leading to mesotrophic nutrient levels and new sediment, thus more CH_4 formation; On the other hand, turbidity reduces photic zone to ~6-10 m or 40-60% of water column coupled with deep circulation carrying algae < photic zone, thus held to mesotrophy with reduced CH_4 potential.
In-Reservoir (autochthonous) production	Modest CH_4 production because of above physical constraints
Water temperature	Summer temperatures peak ~18 C, helping to hold plankton and AM production to moderate levels, hence modest CH_4 production.
Water transparency	Modest CH_4 production expected because of above physical constraints resulting in only mid-level plankton and AM production
Rooted aquatic macrophyte (AM) development	Methanogenesis has not been measured in these reservoirs. Because of low allochthonous and autochthonous OM in them, present CH_4 production and release is thought to be low, in lower ranges for large oligo-mesotrophic reservoirs. Littoral areas of potential CH_4 production, but low surface area of the AM beds would keep overall total reservoir CH_4 production low.
CH_4 ebullition to surface	Expected to be the principle mechanism of CH_4 production in Rock Island and Rocky Reach, on areal as well as per-total-reservoir basis. CH_4 production should be low since CH_4 ebullition year-round controlled primarily by:1) extremely low HRT; 2) high O2 throughout water column and into sediments; 3) strong horizontal water velocities throughout the reservoirs, important in scouring sediments from beneath pelagic zones, and shoreline scour reducing, but not eliminating, near-shore sediment deposits; 4) modest water temperatures throughout the growing season; 5) mesotrophic level of production through the reservoirs with production attenuated by inorganic turbidity to less than the production expected from present nutrient loading; 6) prevalence of steep, rocky shorelines not conducive to development of fine sediments; and 7) very limited embayments or shallow marshy areas along the shorelines which can be focal points of fine, rich sediments beneath AM beds which could facilitate CH_4 formation & release at the A/W via piping and short distances.
ABA = attached benthic algae	AM = aquatic macrophytes WS = Watershed of reservoir
S/W = sediment/water interface	A/W = air/water interface CH_4 = CH_4 or methane gas
OM = organic matter	O_2 = O_2 or dissolved oxygen CO_2 = CO_2 or carbon dioxide

Deemer et al. (2016) calculated a range of CH_4 emissions hydroelectric reservoirs worldwide (reservoir means) of 24-112 mg CH_4-C m -2 day -1 and a mean 120 mg CH_4-C m -2 day -1 over all reservoirs worldwide.

Priest Rapids Reservoir is the only mid-Columbia reservoir with similar morphology and limnological features which has published CH_4 data on it. These data are shown in Table 3; surface diffusion estimates of open water (very low mean of 0.004 mg CH_4 –C $m^{-2}day^{-1}$) and littoral mean of 362 mg CH_4 –C m^{-2} day^{-1}. The extremely large difference between the two lake zones reflected: 1) the underestimation of CH_4 flux by gas diffusion methodology, and 2) the high potential CH_4 production in littoral waters of even a moderately productive water body. Lower Monumental Reservoir on the Snake River was also assessed with comparable mean flux rates. Both reservoirs were net sinks for CO_2. Both reservoirs were also sinks for CH_4 and CO_2 at the outflows (i.e. negative degassing at outflows).

That available data from Priest Rapids (very comparable limnology to Rock Island and Rocky Reach) supports the probable GHG situation in Rock Island and Rocky Reach Reservoirs, namely very low CH_4 emissions from pelagic waters and sporadic distribution of moderately high CH_4 emission pockets of littoral sediment accumulation and AM beds. The high ratios of pelagic:littoral area is expected to keep overall reservoir-wide mean emissions low on a regional or national scale.

Application of the above CH_4 emission controllers along with those summarized by Deemer et al. (2016) permits estimated CH_4 emissions from Rock Island and Rocky Reach Reservoirs. Pelagic methanogenesis is undoubtedly very low in Rock Island and Rocky Reach Reservoirs and exceptionally low in Lake Chelan. There are, however, probable ‘hot spots’ of sediment deposition (stream deltas, backwater embayment areas, some nearshore deposition areas of organic sediment deposition) areas conducive to AM beds and ABA high production. We can expect these ‘hot spots’ to have locally high rates of methanogenesis and release to water and the atmosphere. Reservoir’s morphometry and hydrology indicates that these relatively high CH_4 emission rates presently expected to occur in littoral bands are a small portion of the reservoir area. Review of the environmental controllers of CH_4 production in Rock Island and Rocky Reach Reservoirs suggests that present CH_4 emissions per reservoir are likely at low levels and extremely low on the national and worldwide ranges of hydro project CH_4 emissions.

Table 3. CH_4 and CO_2 release from freshwater bodies (various sources).

Water Body	Lat.	Type of Water Body	Res. Surface Area	HRT	Nature of Water Body	Reservoir Age When Studied	CH_4 Efflux from Surface: Summer	CH_4 Efflux from Surface: Year-round	CH_4 Ebullition from Littoral	CH_4 Degassing from Outflow	CO_2 Flux from Surface: Summer	CO_2 Degassing from Outflow	Source	MW Capacity
			km^2	Days		Years	mg CH_4-C $m^{-2}day^{-1}$		mg CH_4-C $m^{-2}day^{-1}$	t CH_4-C $dam^{-1}day^{-1}$	mg CO_2-C $m^{-2}day^{-1}$	t CO_2-Cdam^{-1} day^{-1}		MW
Hanford Reach, Columbia R., WA, U.S.	47 ° N	Free-flowing river	-	< 1	Littoral embayments; coowater; settling enviroment; high OM seds	-	~ 0	-	-	-	2.9	-	Arntzen, et al. 2013	-
Lower Monumental Res., WA, U.S.	46 ° N	Run-of-River Res.	26.7	6	Res.-wide; warmwater; Eutro; deep silt/OM-rich seds throughout; mod-low transp.	35	~ 0	-0.4 g CH_4 -C yr^{-1}	-	-4.2 x 10-4 (PRR & LMR mean)	-71	-32 (PRR & LMR mean)	Arntzen, et al. 2013	810
Priest Rapids Res., WA, U.S.	47 ° N	Run-of-River Res.	31.3	0.8	Res.-wide; coolwater; Mesotr; current-swept cobble; mod-high transp; flocculent OM-rich littoral seds	51	0.004	263 g CH_4 -C yr^{-1}	-	-4.2 x 10-4 (PRR & LMR Mean)	-13.1	-32 (PRR & LMR mean)	Arntzen, et al. 2013	956
Hanford Reach, Columbia R., WA, U.S.	47 ° N	Free-flowing river	-	< 1	Riverwide; coolwater; O - M; current-swept cobble; high velocity; littoral flocculent OM over cobbles	-	0.006	-	-	-	5.9	-	Arntzen, et al. 2013	-
200 Lakes of Finland	Boreal	Lakes	variable	-	Coldwater; boreal lakes; Meso-Eutro; mean depth generally <6 m; peat-rich WS;	-	1.7	-	-	-	-	-	Juutinen, et al. 2009 Huutinen, et al. 2003	-
Grand Coulee Res., WA, U.S.	48 ° N	Storage Res.	306	45	Res.-wide; coolwater but surf > 20 C; Oligo-Meso; oxic water column; very high upstream storage	61	2.4	268 g x 106 yr^{-1}	-	0.14	-125	88	Soumis, et al. 2004	6,809
Dworshak Res., Idaho, U.S.	47 ° N	Storage Res.	37	307	Res.-wide; coolwater but surf > 20 C; Oligo-Meso; oxic water column; nutrient-limited	30	3.3	-	-	0.008	-323	4	Soumis, et al. 2004	400
Three Gorges Reservoir, China	31 ° N	Storage Res.	1,084		Warmwater; storage reservoir; high silt input but relatively low DOM	5	4.7	-	-	-	-	-	Chen, et al. 2011	22,500
Wallulla Res., Washington, U.S.	46 ° N	Run-of-River Res.	157	1.2	Coolwater but surf > 20 C; Meso; oxic water column; high up-stream storage; moderately high WS nutrient input with productive soils along res.; large shallow areas.	49	7.0	-	-	0.6	-94	60	Soumis, et al. 2004	1,120
Shasta Res., California, U.S.	41 ° N	Storage Res.	77	372	Coolwater but surf > 20 C; Oligo-Meso; oxic water column	59	8.3	-	-	0.05	369	35	Soumis, et al. 2004	629
Harsha Res., Ohio, U.S.	39 ° N	Flood control Res.	9	~700	Warmwater; relatively shallow; storage reservoir; high inputs of silt, nutrients, and OM; deep high OM seds	35	85	177 (mg CH_4 -C m^{-2} day^{-1})	17	-	-	-	Beaulieu, et al. 2014	-
Aare Res., Switzerland	47 ° N	Run-of-River Res.	2.5	~1.5	Res.-wide; coolwater; Meso-Eutro; oxic water column; seds heavily metal contaminated; AM absent; very high OM	89	117	107 g x 10^6 yr^{-1}	431	-	-	-	Delsontro, et al 2010	-
Tucuri Res.	4 ° S	Storage Res.	2,850		Tropical storage reservoir; very high mass submerge OM; deepwater oxygen depletion	32	53	-	21				Deemer, et al. 2016	8,370
Priest Rapids Res., WA, U.S.	47 ° N	Run-of-River Res.	-	0.8	**Littoral embayments;** Mesotr; coolwater; settling enviroment; high OM seds	51	362	-	8 - 400	-	~ 5	-	Arntzen, et al. 2013	-
Lower Monumental Res., WA, U.S.	46 ° N	Run-of-River Res.	-	6	**Littoral embayments**; M-E; warmwater; settling enviroment; high silt sediments	35	24	-	8 - 400	-	92	-	Arntzen, et al. 2013	-
Petit Saut, French Guyana	5 ° N	Storage Res.	365		Tropical storage reservoir; very high mass submerge OM; deepwater oxygen depletion	3	426	-	-	-	-	-	Galy Lacaux, et al. 1997 Abril, et al. 2005 Gue'rin et	116

Summary

This whitepaper indentifies numerous controllers of reservoir GHG emissions and highlights those that are the most significant contributors to reservoir GHG emissions. The primary contributing controllers of reservoir GHG emissions are associated with organic content and amount of reservoir sediments, reservoir trophic status (reservoir/watershed nutrient loading; primary productivity; water temperature), rooted aquatic macrophyte development, and CH_4 ebullition to the reservoir surface. Strong correlations to reservoir GHG emissions were identified in the Deemer et al. report to organic matter and nutrient accumulation in nearshore sediments, nutrient loading in reservoirs (eutrophic conditions), higher water temperatures, and presence of aquatic macrophytes. Analysis of controllers and existing for Mid-Columbia River reservoirs, specifically Rocky Reach and Rock Island reservoirs and Lake Chelan were conducted and compared to reservoir conditions described in Deemer et al. The available data and comparisons presented in this whitepaper support the probable GHG emissions situation in Rock Island and Rocky Reach Reservoirs and Lake Chelan, namely very low CH_4 emissions from pelagic waters and sporadic distribution of moderately high CH_4 emission pockets of littoral sediment accumulation and AM beds. The high ratios of pelagic:littoral area are expected to keep overall reservoir-wide mean GHG emissions low in comparison to reservoirs on a regional or national scale.

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