Greenhouse Gas Emissions from a Hydroelectric Reservoir and a Natural Lake in the Squamish Area

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Emma Linde
Advised by: Dr. Rich Wildman

Abstract

Hydroelectricity is commonly viewed as a method of energy production free of greenhouse gas (GHG) emissions. Recent research, however, has documented GHG emissions from tropical and temperate hydroelectric reservoirs. Evidence is lacking for reservoirs in the Squamish area. In this study, methane emissions from two lakes were measured. The average methane emission flux from Alice Lake, a natural lake, was 2.46 mg m⁻² day⁻¹ and from Daisy Lake, a hydroelectric reservoir, was 11.44 mg m⁻² day⁻¹. Implications of these findings include a broader base of information to inform trade-offs between methods of energy production, and proof that other methane-emitting temperate reservoirs are not isolated cases, suggesting the existence of many other methane-emitting reservoirs.
### Acronyms:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>CH$_4$</td>
<td>methane</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>nitrous oxide</td>
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<tr>
<td>Ar</td>
<td>argon</td>
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<td>GHG</td>
<td>greenhouse gas</td>
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<tr>
<td>BLE</td>
<td>boundary layer equation</td>
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<tr>
<td>IPCC</td>
<td>International panel on climate change</td>
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<tr>
<td>µECD</td>
<td>micro electron capture detector</td>
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<tr>
<td>OM</td>
<td>organic matter</td>
</tr>
<tr>
<td>UBC</td>
<td>University of British Columbia</td>
</tr>
<tr>
<td>GC</td>
<td>gas chromatograph</td>
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<tr>
<td>DO</td>
<td>dissolved oxygen</td>
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<tr>
<td>FID</td>
<td>flame ionization detector</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<td>VOC</td>
<td>volatile organic compound</td>
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1. Introduction

The existence of climate change is unequivocal, as evidenced by documented warming of the atmosphere, ocean, and rising sea levels. Climate change is largely due to increased levels of greenhouse gases in the atmosphere, most notably carbon dioxide (CO$_2$) methane (CH$_4$), and nitrous oxide (N$_2$O) (IPCC, 2007). Hydropower is a method of energy production that is commonly viewed as being free of greenhouse gas (GHG) emissions because it does not involve the combustion of fossil fuels. However, recent research documents the GHG emissions from hydroelectric reservoirs (Guérin et al., 2008; Guérin et al., 2006; del Sontro et al., 2010) to be equivalent to an estimated 7% of the global warming potential of current documented anthropogenic carbon emissions (St. Louis et al., 2000). The experimental conversion of a natural lake into a reservoir by Kelly et al. (1997) increased CH$_4$ emissions by a factor of 6 and CO$_2$ emissions increased by a factor of 3. The area turned from a small net carbon sink to a large net source. These results indicate increased GHG emissions due to the creation of northern reservoirs (Kelly et al., 1997). Converting a natural lake into a reservoir is likely to reduce the oxygen content of the water and thus increase the likelihood that carbon is converted into CH$_4$ rather than CO$_2$ (Friedl & Wuest, 2002). As CH$_4$ has 21 times the global warming potential as CO$_2$, this increases anthropogenic contributions to climate change (IPCC, 1996). BC Hydro, British Columbia’s largest electric distributor, refers to hydropower as a clean source of energy (BC Hydro, 2013b). Finding GHG emissions from hydroelectric dams in the Squamish, British Columbia area has the potential to impact the technology’s emissions-free reputation.

Several studies have documented GHG emissions from hydroelectric reservoirs in other areas of the world. Although there have been studies on reservoirs in tropical regions (Guérin et al., 2008, Guérin et al., 2006) and in temperate regions (del Sontro et al., 2010; Matthews et al., 2011), research is lacking for reservoirs in North America and in regions similar to Squamish. It is necessary to investigate the phenomena of GHG emissions from hydroelectric reservoirs in specific areas because each reservoir has unique characteristics that influence emissions. Therefore, generalizations based on research from specific areas cannot be assumed valid for all areas.

The production of GHGs in reservoirs is due to the decay of organic matter (OM) under water. Upon construction of a dam, land area, including its vascular plants and other OM, is flooded. Lacustrine phytoplankton production and material from upstream rivers also add to the amount of OM in the reservoir (Rosa et al., 2004). OM is decomposed by bacteria that convert organic carbon previously stored in the plants into mainly CO$_2$ and, under anoxic conditions, CH$_4$. CH$_4$ is produced most often in reservoir sediments where it faces various fates. It may be mixed into the water column, oxidized or released into the atmosphere. CH$_4$ is released into the atmosphere through diffusive exchange across the air-water interface or, more commonly, ebullition. To be emitted via diffusive exchange, it must escape oxidation at the oxic-anoxic interface within the water column. CH$_4$ release via ebullition is a factor of bubble size, temperature, and gaseous concentration in ambient water (Del Sontro et al., 2011). Reservoir CH$_4$ emissions peak when CH$_4$ concentration in sediment porewaters allow for bubbles to form and, if they
exceed the hydrostatic pressure of overlying waters, ascend the water column (Schlesinger, 1991).

Some determining factors in CH$_4$ emissions are the presence of OM (De Junet et al., 2009; Schlesinger, 1991), the oxygen content of water (Schmid et al., 2007; Schubert et al., n.d.), and lake depth (Ostrovsky et al., 2008). The presence of OM is important because it determines how much carbon is available to be converted into CH$_4$ or CO$_2$. The oxygen content of water is important in determining CH$_4$ emissions via surface diffusion. (Schmid et al., 2007; Schubert et al., n.d.). It is unlikely that surface diffusion from oxic lakes account for a significant source of atmospheric CH$_4$ because the CH$_4$ is likely to be oxidized as it ascends the water column. This is the case, for example, for Lake Baikal in Russia, the most voluminous freshwater lake in the world, which is highlyoxic due to turbulent mixing. Although CH$_4$ production in the sediment and in CH$_4$ hydrates is high, the average CH$_4$ flux is low at $10^{-5}$ μmol/m/s. The sediment is a net sink for CH$_4$ because oxidation rates surpassed production rates (Schmid et al., 2007). A study of Lake Rotsee, a small lake in Switzerland, showed that CH$_4$ was produced in anoxic water but was oxygenated as it ascended the water column into oxic waters (Schubert et al., n.d.). The CH$_4$ concentration was 400-900 μM in anoxic waters and 5-30 μM in oxic waters. Although the sediment released a large amount of CH$_4$, emissions from the reservoir were very small at less than 1 mM. Without oxidation, the CH$_4$ produced in the sediment, which is 500,000 times oversaturation with respect to the atmosphere, would be released from the surface at a rate of 1700 t/year. However, due to oxidation from aerobic and anaerobic microorganisms, the lake as a whole released only 2.3 t/year (Schubert et al., n.d.). These examples demonstrate that the oxygen level in greatly affects their CH$_4$ emissions.

Lake depth is also a determining factor in CH$_4$ emissions via ebullition (Ostrovsky et al., 2008). As CH$_4$ bubbles ascend the water column, CH$_4$ gas dissolves into the water column and dissolved gases in the ambient water enter the bubble. Therefore, shallower lakes emit more CH$_4$ because bubbles spend less time ascending the water column and therefore lose less CH$_4$ to mixing and oxidation. Both Zheng et al. (2010) and Del Sontro et al. (2011) found the depth of the water column to be important in determining emissions. Regions that were near the shore had significantly lower fluxes of CH$_4$. In Lake Baikal, emissions via ebullition were significant only in shallow regions (Schmid et al., 2007).

The primary purpose of this study is to serve as an initial survey to assess the presence of GHG emissions from a hydroelectric reservoir as compared to a natural lake, and to lay the groundwork for further research in this area. The secondary purpose is to expand the analytical capacity of Quest University. A substantial percentage of this project consisted of developing protocol and collecting information outside of fieldwork. For instance, a Quest-specific standard operating procedure document for University of British Columbia’s (UBC) gas chromatograph (GC) was co-authored along with the lab technician. Techniques developed to collect and analyze samples, along with three gas-collecting chambers built, can be used for future research in the area. In addition, an
understanding of the testing locations was developed. This is especially valuable for Daisy Lake, which is difficult to access.

2 Methodology

2.1 Background

2.1.1 Purging exetainers
In traditional studies, exetainers are vacuum-purged prior to sample collection. To limit costs and shipping time, previously used and thus contaminated exetainers were used. Exetainers were purged with Argon (Ar) gas in the Quest lab prior to sample collection. One end of plastic tubing was affixed to the Ar gas tank regulator and the other end to a hypodermic needle. The line was flushed at a high flow for 10 seconds. The attached needle was inserted deep into the exetainer with an outgoing needle inserted shallowly. The placement of the needles was to avoid evacuating Ar before it was flushed through the exetainer (fig. 1). The gas was run at a medium-high flow, flushing Ar through the exetainer for a minimum of 2 minutes. The gas was turned to the lowest possible flow and the outgoing then ingoing needles were removed in quick succession.

![Diagram of the set up used to purge exetainers with argon gas.](image)

*Figure 1: Diagram of the set up used to purge exetainers with argon gas.*

2.1.2 Microcosms
Two rounds of microcosms were conducted in the Quest lab prior to field-testing. The primary purpose was to develop and practice testing methods to make more complicated field sampling streamlined and efficient. The secondary purpose was to more thoroughly understand CH$_4$ production in inundated lake sediments.

Both rounds consisted of buckets roughly 22 L in size containing 2 to 5 inches of sediment from littoral zones of Alice Lake and 3 to 7 inches of water from Alice Lake.
An aquarium oxygenator bubbled air through the water in one control microcosm to prevent CH\textsubscript{4} production by encouraging the oxidation of carbon released from decaying OM in the sediment. Ar was bubbled through the waters of remaining microcosms to turn the water anoxic and encourage CH\textsubscript{4} production by inducing methanogenesis. Dissolved gas samples were taken according the method used in field-testing. Emissions samples were taken using a scaled-down prototype of the gas chambers. They were constructed from the top portion of 2 L soda bottles. Segments of swimming pool “noodles” were taped to the lower edges to allow it to float partially submerged on the surface of the water. A 3-way stopcock was fitted through a hole in the lid (fig. 2). They were stabilized within the microcosms with tape and cardboard transects across buckets.

![Diagram](image)

Figure 2: Diagram of scaled-down emissions collection chamber used in microcosms.

Testing rounds 1 and 2 consisted of 5 microcosms. The control microcosm contained sand and debris-rich sediment from a North Western edge of the lake. The remaining microcosms contained sandy sediment- the second and fifth from the North Western edge of the lake and the third and forth from the lake’s northern beach (table 3). Dissolved gas samples were collected from each microcosm. Chamber samples were collected after floating chambers for 20 minutes for round 1 and after 4 hours for round 3.

Testing rounds 3 and 4 consisted of 4 microcosms. All sediment was from the North Western edge of Alice Lake. The first and second microcosms contained debris-rich sediment and the third and forth microcosms contained sediment rich in sand, rocks, and soil (table 1). Chamber samples were collected after floating chambers for 12 hours for round 3 and after 2 weeks for round 4.
Table 1. Characteristics of microcosms.

2.1.3 Alice Lake Observations
Prior to official testing, initial observations of GHGs in Alice Lake were made to confirm that gases could be effectively collected from the field, stored, and detected. Chamber samples were taken using the method described in section 2.3. Two were taken in the standard way and two were floated on the surface of the water while sediment under the chamber was stirred, thus ensuring the release of CH$_4$ into the chamber. Chamber samples above stirred sediments were taken in the outgoing river and on the Northeastern side of the lake (fig. 3).

![Figure 3](image)

*Figure 3.* Locations of chamber testing on Alice Lake during initial observation. Red dots denote locations where standard floating chamber samples were taken. The red line denoted the approximate path of the chamber not tethered to a buoy line. Yellow dots denote locations where sediment was stirred under chambers.

2.2 Site descriptions
Daisy and Alice Lakes are located between Squamish and Whistler in British Columbia, Canada (fig. 4).
Daisy Lake is a hydroelectric reservoir with a surface area of 5.2 km² and a mean depth of 10m (fig. 5). A 1981 survey found the average water residence time to be 6 days. Water temperature during the summer ranged from 12° C to 10° C. The lake is oligotrophic. The shorelines are generally steep, rocky, and forested. The immediate surrounding area is heavily forested, with mountains and glaciers in the wider surrounding area. There is a considerable amount of organic debris surrounding the reservoir and some floating logs and other debris in the water. The water colour is turquoise-blue. Whistler’s wastewater treatment plant is located upstream of the lake’s main tributary, the upper Cheakamus River (Hirst, 1991).
Alice Lake is a natural lake with a mean depth of 9.3 m and a maximum depth of 18.0 m (fig. 6). The surrounding area is heavily forested. The shorelines are rich in debris and muddy sediment. The water is brown in colour with some floating debris.
Options for study sites were fairly limited because only sites within a reasonable radius of Quest that were accessible to the public were considered. Within these constraints, Daisy and Alice Lakes have similar geographical surroundings and mean depth, thus controlling for those two factors. Alice Lake was chosen out of other natural lakes due to the ease at which it is studied due to its size and accessibility. Daisy Lake was chosen over other reservoirs despite its limited accessibility due to its interesting characteristics such as large size and fetch, variation in water level, and carbon loading from Whistler's wastewater treatment plant. A hydroelectric reservoir and a natural lake were chosen to contrast those two factors though other factors were not controlled for.

2.3 Sampling methods

Testing for both sites was conducted between July 22 and August 8, 2013.

Surface emissions
Total emissions (both diffusive and ebullitive) were sampled using floating chambers. Three 22-liter buckets were outfitted with wooden frames and pool “noodles” to allow them to float upside down, partially submerged. A 3-way stopcock attached to plastic tubing was affixed through a hole in the top of the bucket (fig. 7). Potential areas of gas escape from the chamber were sealed with silicone caulk with low volatile organic compounds (VOC). Buckets were allowed to de-gas for three days to avoid the
contamination of samples from the caulk. Chambers were covered with aluminum foil to reduce the effect of solar heating on the temperature and pressure of the contained gas.

![Diagram of a floating chamber used to collect gas emissions.](image)

*Figure 7:* Diagram of a floating chamber used to collect gas emissions.

For testing, chambers were anchored using a rope secured to a brick. The chamber was then allowed to drift slightly so as not to sample emissions directly above sediment that had been recently disturbed by the brick. Chambers floated for 45 minutes to 1 hour, after which a gas sample was extracted via the stopcock with a 60 mL syringe. A hypodermic needle was affixed to the syringe that was then purged to 30 mL. The sample was injected into a 12 mL exetainer that had been pre-purged with argon while an outgoing hypodermic needle dispelled displaced gas.

12 chamber measurements were taken in Alice Lake and 25 in Daisy Lake (fig. 8).
Figure 8. The left map is of Daisy Lake and the right map is of Alice Lake. Yellow dots denote chamber sampling locations and red dots denote both chamber and dissolved gas sampling locations.

Surface gas exchange was calculated using the following equation,

\[
\text{Flux} = \frac{\{(V \cdot C_{t1}) - (V \cdot C_{t0})\} \cdot 24 \cdot \pi r^2}{t}
\]

where \( V \) is the volume of air in the chamber, \( C_{t1} \) is the concentration of gas in the chamber at time=1 in mg, \( C_{t0} \) is the concentration of gas in the chamber at time=0 in mg, \( r \) is the radius of the water surface within the chamber in meters and \( t \) is the amount of time the chamber was floated for in hours. Multiplying \( V \) by a concentration of gas gives an amount of gas in the chamber at a given time. Multiplying the difference between the concentration at time=0 and at time=1 by 24 gives the rate of gas emission in one day. Dividing by \( \pi r^2 \) gives the cross-sectional area of the water surface within the chamber to restrict the rate of emissions found in the numerator to the area that was sampled. Dividing by \( t \) corrects for the length of time for which a chamber was floated. The quotient is the emissions flux in mg m\(^{-2}\) d\(^{-1}\).
Emission fluxes were evaluated using the static chamber method rather than the boundary layer equation (BLE). The BLE calculates emissions flux based on diffusion at the air-water interface as a factor of temperature, partial pressure of gas in the surface water, and the concentration of gas that the water would have if it were at equilibrium with the atmosphere. The inexpensive method was originally developed for marine environment applications (Broecker & Peng, 1997) and is now rarely used by limnologists (Kelly et al., 1997). The BLE method was found to underestimate fluxes of CO$_2$ and CH$_4$ in large water bodies (Duchemin et al., 1999; Schiller & Hastie, 1994). It was inappropriate for the present study because the effect of wind speed on fluxes of CO$_2$ and CH$_4$ should vary considerably between the two study sites given differences in lake depth, surrounding terrain, and fetch. The BLE does not sufficiently account for these differences.

The inexpensive chamber method is favourable because it is better suited to measuring special variability within the a site within a short time period while allowing for considerable coverage due to the ease at which the apparatus can be moved. The chamber method has been used in a large number of studying to determine CO$_2$ and CH$_4$ emission fluxes from “peat bogs, forest soils, salt marshes, lakes, rice field, and estuaries” (Duchemin et al., 1999).

Fluxes may vary over different sections of each lake due to factors including surroundings, depth, and sediment characteristics. To account for this, fluxes were calculated for subsections of lakes that were likely to be fairly homogenous based on factors such as depth and location. Multiple samples were collected within each subsection to determine an average flux for the area. The lake’s total flux was calculated using a weighted average of subsections. Alice Lake was divided into subsections based on depth using a bathymetric map that was created using the program Tecplot 360. The subsections were “shallow” (1m – 6m), “medium depth” (7m – 12m), and “deep” (13m – 18m). Daisy Lake was divided into eight subsections: “Northern drawdown zone”, “sediment delta”, “Northern middle”, “Eastern middle”, “Western middle”, “Eastern side arm”, “near dam”, and “Southern drawdown zone” (fig. 9).
Dissolved gas samples
Water samples were collected from various depths within the water column using a Niskin sampling bottle. Water was poured from the bottle into a 12mL exetainer. The traditional headspace analysis method was used. A 6mL headspace of Ar gas was added to the exetainer via hypodermic needle while a second hypodermic needle expelled displaced water. Samples were then shaken vigorously for 2 minutes to equilibrate the gases between the water and the headspace. A 3mL headspace sample was extracted and injected into a separate exetainer.

Manta profiles
Two profiles were taken in Daisy Lake using a Manta water quality sonde (Eureka Environmental, Austin, TX) (fig. 10). The manta was lowered at a rate of 1 m/minute, measuring depth in meters, temperature in degrees Celsius, specific conductance in microsiemens/cm, dissolved oxygen (DO) in milligrams per liter, and pH. pH and DO measurements were not calibrated due to instrument error.
Sample analysis
Samples were stored upside down in water between collection and analysis and were analyzed within 8 days of collection. Samples were analyzed on a gas chromatograph (GC) with a flame ionization detector (FID). The instrument was in the UBC Integrated Watershed Analysis Laboratory. See appendix B for instrument details.

3. Results

3.1 Background

Microcosms
All microcosms, including controls, produced CH$_4$. Chamber emission fluxes and dissolved CH$_4$ and CO$_2$ concentrations varied widely (See table A1 in the appendix). Two of the dissolved gas samples yielded a result of 0 ppm but chamber test results above 0.

Alice Lake Observations
Preliminary chamber sampling was successful in collecting measurable samples. The concentration of CH$_4$ in gas sampled from chambers under which sediment was stirred was 1290.97 ppm and 461.53 ppm. Samples from chambers that were floated had CH$_4$ concentrations of 3.00 ppm and 8.37 ppm (table 2).

Figure 10. Manta sampling locations in Daisy Lake.
Table 2. Results of preliminary chamber samples from Alice Lake during initial observations.

3.2 Alice Lake
Atmospheric temperatures during testing ranged from 19° C to 20° C. Mean daily wind speed at the Squamish airport, 2.7 km from Alice Lake, was 4 and 5 km/hour during testing days. The CH$_4$ emission flux from Alice Lake is 2.46 mg m$^{-2}$ day$^{-1}$ (Fig. 11). This number is relevant to summer months of similar temperature and wind speed. Highest and lowest emissions from Alice Lake occurred in shallow regions. Emissions in deep and medium regions are similar with overall slightly lower emissions from deep regions, though one data point in the medium region showed lower emissions than data points in the deep region (fig. 12, 13). See table A3 in the appendix for results of all chamber and dissolved gas samples.

Figure 11. Results from chamber samples at Alice Lake. Numbers represent CH$_4$
emission fluxes in mg m$^{-2}$ day$^{-1}$. Yellow dots represent locations that dissolved gas samples were taken in addition to chamber samples.

*Figure 12. CH$_4$ emissions and lake depth in Alice Lake.*
Figure 13. Spatial variability of CH$_4$ emission fluxes within Alice Lake.

Dissolved gas samples were used to create vertical profiles of dissolved gas concentrations. Different coloured lines denote different sampling locations. Solid lines denote dissolved CH$_4$ concentrations and dashed lines denote dissolved CO$_2$ concentrations (fig. 14).
3.3 Daisy Lake
Atmospheric temperature during testing was 20 °C. Mean daily wind speed during testing at the Squamish airport, 21.5 km from Daisy Lake, was 4.5 km/hour. The CH\(_4\) emission flux for Daisy Lake is 11.44 mg m\(^{-2}\) day\(^{-1}\) (fig. 15). This number is relevant to summer months of similar temperature and wind speed. See table A3 in the appendix for results off all chamber samples.

*Figure 14.* Vertical profiles of dissolved CH\(_4\) and CO\(_2\) in three locations in Alice Lake. Solid lines denote CH\(_4\) profiles and dashed lines denote CO\(_2\) profiles. Different colors represent different locations.
The highest emissions by a considerable margin, 3.9 and 2.9 mg m\(^{-2}\) day\(^{-1}\), occurred in the deep Northern middle zone. The lowest recorded emission, 1.3 mg m\(^{-2}\) day\(^{-1}\), occurred in the sediment delta followed closely by 1.4 mg m\(^{-2}\) day\(^{-1}\) in the Northern drawdown zone. The rest of the emissions are relatively uniform, ranging from 2.3 to 1.6 mg m\(^{-2}\) day\(^{-1}\). CH\(_4\) emissions increase with depth, probably due to the depth differences in those zones rather than CH\(_4\) emission-determine characteristics of those areas (fig. 16, 17).

Figure 15. Results of chamber sampling on Daisy Lake. Numbers represent CH\(_4\) emission fluxes in mg m\(^{-2}\) day\(^{-1}\).
Figure 16. CH$_4$ emissions per lake depth in Alice Lake.

Figure 17. Spatial variability of CH$_4$ emission fluxes within Daisy Lake. Each “x” represents one data testing point.
Manta profiles
Vertical profiles of Daisy Lake’s DO content, temperature, and specific conductance were created for each of the two manta testing locations. Due to improper DO calibration, only relationships and patterns between data points should be observed and not numerical value. Temperature and DO first decline between 3 and 4 meters. At location B, they do not decline significantly until approximately 16 m depth. Overall patterns of DO patterns and temperature patterns mirror each other. Specific conductivity is relatively low (fig. 18).
Figure 18. Vertical profiles of two locations in Daisy Lake created by Manta readings of dissolved oxygen (DO), temperature (Temp), and specific conductance (SC).
3.4 Factors determining methane emissions

Multiple factors were compared to CH$_4$ emissions flux for several reservoirs for which previous studies have been conducted. The studies and their sources are listed in table A2 in the appendix.

There is a generally increasing trend between surface area and CH$_4$ emissions. Daisy Lake is the smallest reservoir in the data set and has a mid-range emissions flux (fig. 19).

![Reservoir Surface Area & Methane Emissions](image)

*Figure 19. Reservoir surface area and CH$_4$ emissions. The red marker is Daisy Lake.*

Average water residence time is the amount of time, on average, water spends inside the reservoir. There is not a clear relationship between water residence time and CH$_4$ emissions within this data set. Daisy Lake has a comparatively short water residence time and a small emissions flux (fig. 20). Older reservoirs have consistently lower emissions than reservoirs that are <30 years old (fig. 21). Reservoirs at higher latitudes emit less CH$_4$. Daisy Lake follows in the trend (fig. 22).
Figure 20. Reservoir average water residence time and CH$_4$ emissions. The red marker is Daisy Lake.

Figure 21. Reservoir age and CH$_4$ emissions. The red marker is Daisy Lake.
4. Discussion

A basic yet important conclusion from this research is that GHG emissions from a reservoir in this area exist, are measurable, and exceed the emission flux from a natural lake. The calculated CH$_4$ emission fluxes for Daisy and Alice Lakes are valid only for times of similar temperature, wind speed, and water level. They must be extrapolated with caution, as factors that influence emissions have not been fully identified. Although more research is needed to evaluate the importance of certain factors on emissions, some observations and speculations can be made.

4.1 Background

Microcosms and Alice Lake observations confirmed some previous assumptions. The presence of CH$_4$ in most microcosms confirmed that CH$_4$ production occurs when lake sediment is inundated for at least 20 minutes and exceeds oxidization rates. Alice Lake observations confirmed that CH$_4$ in sediment is released when sediment is stirred, most likely due to the release of bubbles trapped under the hydrostatic pressure of overlying waters. The primary goal of microcosms and observations, to design and practice testing methods, was realized.

Figure 22. Reservoir latitude and CH$_4$ emissions. The red marker is Daisy Lake.
4.2 Alice and Daisy Lake

Manta profiles
As manta profiles were collected in only two locations, they can be used to make only speculations about Daisy Lake. It is unclear if a thermocline exists. It is present at location A where the thermocline extends from 3m to 11.5 m depth, but no thermocline exists in location B. That DO and temperature mirror each other is expected. Deeper waters are colder due to less solar heating and are less oxygen-rich due to less contact with the atmosphere. Data points that do not follow trends are most likely a testing error due to movement of the manta due to underwater currents (fig. 18).

Effect of depth on emissions
In both lakes, shallow areas demonstrated a wide range of CH$_4$ emissions (fig. 12, 16). Perhaps there are two competing forces at play: CH$_4$ production due to an oxic water column, and the trapping CH$_4$ in sediment due to the hydrostatic pressure of overlying waters. Shallow waters produced high emissions when production outweighed trapping and low emissions when water was deeper or less oxic and CH$_4$ trapping exceeded production.

In vertical profiles of Alice Lake, CH$_4$ and CO$_2$ concentrations mirror each other, suggesting the same rate, but not amount of, production. Alice Lake’s vertical profiles of dissolved CH$_4$ and CO$_2$, however, are abnormal in appearance, suggesting a possible error in testing or analysis. This may be due to consumption of CH$_4$ by microbes between water sample collection and headspace analysis (fig. 14).

The effect of location within Daisy Lake on emissions
It is surprising that the highest CH$_4$ fluxes in Daisy Lake occur in deep middle zones. It was originally hypothesized that deep zones will emit less CH$_4$ due to the hydrostatic pressure of the water above deep sediments, reducing ebullitive releases. This is especially surprising if the manta profile of location B is considered, which shows a well-oxygenated water column in which DO and temperature do not decline steeply until 16 m deep, because a warm and oxygenated water column is less conducive to CH$_4$ production.

It is also surprising that the sediment delta does not emit more CH$_4$. A sediment delta is the area in which sediment from the inflowing river is deposited. It is important to consider when investigating CH$_4$ emissions because sediment accumulation correlates with CH$_4$ production and ebullitive release rates (del Sontro, 2013). Sedimentation is more important for CH$_4$ emissions in smaller reservoirs where deposition zones of allochthonous carbon constitute a larger percentage of reservoir surface area. Intense sedimentation in a small reservoir has the potential to turn sediment anoxic due rapid deposition of carbon-rich sediment loads, turning the reservoir into a significant source of CH$_4$ (Maeck et al., 2013).

The drawdown zones of Daisy Lake are of particular interest because they likely vary most significantly upon fluctuations in water level, although this is speculation and has not been confirmed by testing. As water levels fall, shoreline in the drawdown zone is exposed and OM grows and accumulates. When water levels rise, the new OM is
inundated and begins the process of decomposing and produces CH$_4$ and CO$_2$. In this case, CH$_4$ and CO$_2$ is produced not only from the decomposition of OM that was inundated upon the flooding of the reservoir, but also from decomposing OM that is re-inundated every time water levels rise. In Daisy Lake, water levels peak 2 to 3 times a year. Testing on Daisy Lake was conducted during medium and falling water levels. It can be speculated that CH$_4$ production will drop as the water level does and will rise again along with water level as drawdown zones are inundated. Emissions may also rise as water levels drop and the hydrostatic pressure above drawdown zones drops. Highest emissions likely occur when water levels rise after being low for a long time period. Historically this occurs in early April and mid May which is also when spurts of plant growth occur in the Squamish area. See figure A1 in the appendix for Daisy Lake water level history.

4.3 Determining factors of methane emissions

Results from this data set indicate that reservoir surface area, latitude, OM supply, and sedimentation are determining factors in CH$_4$ emissions. Average water residence time did not appear to be a determining factor. Due to the small sample size investigated, more research is required to affirm conclusions suggested here.

Reservoir surface area seems to be a determining factor in CH$_4$ emissions. Perhaps larger surface areas correspond with deeper, more anoxic waters that experience more CH$_4$ production. Daisy Lake in an outlier among this data set. This is perhaps due to the recorded emissions flux being higher than the year’s average, as sampling was conducted in the summer when the decomposition of OM and therefore potential for CH$_4$ production peaks due to increased temperatures.

Latitude seems to be a determining factor in CH$_4$ emissions. This is not surprising because vegetation experiences more decomposition in lower latitudes due to the warmer climates.

Residence time does not appear to be a determining factor in CH$_4$ emissions. This is surprising because it was initially suspected that as water spends more time in a lake CH$_4$ has more time to be emitted via diffusion. However, since ebullition is commonly the principal pathway by which CH$_4$ is released, water residence time may have less of an effect on emissions.

For a new reservoir, the amount of freshly inundated OM is the major source of CH$_4$ creation while as a reservoir ages, sedimentation, which deposits carbon into the reservoir, becomes more important (Maeck et al., 2013). For this data set, reservoirs that are < 30 years old emitted less CH$_4$, indicating a threshold effect in which the amount of inundated OM is more important for CH$_4$ emission than sedimentation. This is not surprising for this data set, as the sediment deltas likely constitute a small percentage of these large reservoirs.
4.4 Implications
The existing body of research on GHG emissions from reservoirs makes clear that tropical reservoirs emit GHGs, but it lacks substantive evidence that temperate reservoirs do. The presence of CH$_4$ and CO$_2$ emissions from Daisy Lake show that temperate reservoirs that emit GHGs (del Sontro et al., 2012) are not isolated cases. This suggests that thousands of other non-tropical reservoirs are doing the same, strongly indicating that GHG emissions from reservoirs must be considered in GHG emissions accounting. This is especially important for British Columbia, which generates over 90% of its electricity from hydropower (BC hydro, 2013a).

Other BC reservoirs may emit CH$_4$ at similar rates as Daisy Lake due to similar geographic location and climate. At the measured emissions flux, Daisy Lake emits 4,163.9 kg CH$_4$/km$^2$ in one year. Although this number is poorly constrained at present because my sampling did not evaluate a range of water levels and river inflow conditions, this number provides a starting point for discussion of the methane emissions of B.C. reservoirs. A total of 3680.5 km$^2$ of B.C. is occupied by reservoirs that are large enough to exhibit lacustrine zones. Although the surface area of strictly riverine reservoirs is not insignificant, they were excluded in this calculation because it is difficult to determine surface areas due to ambiguity between which the reservoir and the river. If these B.C. reservoirs emit CH$_4$ at the same rate per km$^2$ as Daisy Lake, then 15.32 metric tonnes of CH$_4$ is emitted from large B.C. reservoirs in 1 year. The correlations between emission and both surface area and latitude lend some credence to this extrapolation.

The yearly global warming potential of 15.32 metric tonnes of CH$_4$ in one year is equivalent to the annual GHG emissions from 67 passenger vehicles. A passenger vehicle is defined as a “2-axle 4-tire vehicles, including passenger cars, vans, pickup trucks, and sport/utility vehicles” (EPA, 2013a). It is also equivalent to the electricity use of 48.2 homes for one year and 0.0001 coal-fired power plants. It is also important to know what would sequester this amount of CH$_4$. The global warming potential of 15.32 metric tonnes of CH$_4$ is equivalent to the greenhouse gas emissions avoided by recycling 636,390 tons of waste instead of sending it to the landfill as well as the carbon sequestered annually by 1,392,756 acres of U.S. forests. See appendix C for extended calculations.

These results have implications for hydroelectricity. Benefits and drawbacks of methods of energy production must be weighed when determining which is best suited for our warming world. Though emissions reported here seem insignificant, they must be recorded in order to make informed decisions when considering trade-offs of hydroelectricity.

Although this study can be used as a very basic preliminary survey of CH$_4$ emissions from reservoirs in the area, further research is required to draw more substantive conclusions. Future studies should have tighter, more accurate sampling methods. Many caveats exist in the sampling methods the present research. Some that may cause the reported rate of emissions to be too low includes using exetainers with previously pierced septa that may have leaked gasses between collection and analysis and the possibility that
silicon seals on chambers are not airtight and may have leaked gas from chambers during collection. Some caveats may have caused reported emissions to be too high, such as the possibility that brick anchors disturbed the sediment under chambers and caused CH$_4$ to be released at a higher-than-natural rate. Further research should also include a larger sample size of lakes and reservoirs as well as a longitudinal study to relate temporal variability through years and days as well as changing water levels and of day to CH$_4$ emissions.

A more in-depth investigation of CH$_4$ emissions is necessary to tie CH$_4$ production to determining factors. Factors can be “controlled for” by testing reservoirs that hold everything but one factor in common. Trends in the influence of factors will likely become clearer if emissions fluxes were known for more reservoirs globally. However, at the current stage of this body of research, most reservoirs are studied because they are intriguing to someone who is interested in CH$_4$ emissions. Therefore reservoirs that have abnormal fluxes are more likely to be studied. A more accurate picture of determining factors can be established if more standard reservoirs are tested. Once determining factors are identified, methods of limiting GHG emissions can be more thoroughly explored.

Future research on reservoirs should test rivers downstream of dams. Rivers downstream of reservoirs are important to consider when quantifying greenhouse gas emissions. When water exits a reservoir through turbines, the sudden decrease in hydrostatic pressure causes the sudden release of CH$_4$ with little time for bacteria to oxidize it (Kemenes et al., 2007). Zheng et al. found higher CH$_4$ fluxes closer to the dam (Zheng et al., 2010). The significance of CH$_4$ and CO$_2$ emissions from rivers downstream of tropical reservoirs was examined in a study by Guérin et al. who surveyed three tropical reservoirs with different characteristics including age, water residence time, water surface area, and depth (Guérin et al., 2006). They found that emissions occurring in rivers account for 9-33 percent of a reservoir’s total CH$_4$ emissions and 7-25 percent of total CO$_2$ emissions (Guérin et al., 2006). A more in-depth study of one of these reservoirs found that 55% of the reservoir’s CH$_4$ emissions occurred downstream of the dam (Kemenes et al., 2007). Concentrations of CH$_4$ downstream from dams were 100 times higher than those downstream from natural lakes. The impact of damming was less pronounced for concentrations of CO$_2$ (Guérin et al., 2006). However, both of these studies caution against extrapolating single estimates from a small number of reservoirs to all reservoirs, as gas concentrations change with time and other factors (Kemenes et al., 2007; Guérin et al., 2006).

These findings call for the consideration of emissions from reservoirs in GHG accounting. More research on CH$_4$ emissions from diverse hydroelectric reservoirs and their rivers will give a more comprehensive picture of CH$_4$ emissions and will point to determining factors. This will allow better information-based decisions to be made when considering the trade-offs of different methods of energy production.
Acknowledgments

I would like to extend my gratitude to everyone who helped make this project possible through continuous assistance, support, and generosity. Especially sincere thanks go to Dr. Rich Wildman and to Quest University to making this fellowship possible. This study also would not be possible without Iain Hawthorn and the analytical facilities of the UBC Watershed Analysis Laboratory. I am grateful to those who assisted with field-testing including Kyle Kirkegaard and Caleb Raible-Clark, to those who supplied the necessary gear including Neal Melvin, Colin Bates and the Quest University Laboratory, to those who assisted with access to Daisy Lake including Alexis Hall of BC Hydro and the Sea to Sky Retreat Centre and to proof-readers of this report.
Table A1. Complete results from chamber samples and dissolved gas samples of microcosms. CO₂ results are corrected for contamination from Ar gas.

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<td>1 (control) 2 3 4</td>
</tr>
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<td>debris debris sand/rock/soil sand/rock/soil</td>
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<td>Northwestern edge of Alice Lake Northwestern edge of Alice Lake Northern beach of Alice Lake Northern beach of Alice Lake Northwestern edge of Alice Lake</td>
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<tr>
<td><strong>Origin of sediment</strong></td>
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<td>2 weeks 24230.03 - 40.89 50.84</td>
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<tr>
<td></td>
<td>20 minutes 1.1 120.1 0.5 0.2 0.4</td>
<td>12 hours 32.6 81.1 5.1 2.4</td>
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<tr>
<td>Chamber sample</td>
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* (Mauser et al., 1989)
*Figure A1.* Daisy Lake water levels at 14:00 between January 12, 2012 and August 13, 2013. Testing days of the present study are marked in red.
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<th>Longitude</th>
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<th>CO concentration (ppm)</th>
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Table A3. Results of sampling in Daisy and Alice Lake. AL = Alice Lake, DL = Daisy Lake, C = chamber sample, DG = dissolved gas sample.
Appendix B
Gas chromatograph instrument details

This section co-authored with Iain Hawthorne of UBC’s Watershed Analysis Laboratory

Headspace greenhouse gas analysis is performed using an Agilent 7890A gas chromatogram system (GC) with Combi Pal autosampler (CTC). The CTC can be loaded with two trays holding up to 50 samples each. The CTC is programmed to draw samples from 12 ml or 6 ml exetainers (a glass vial with a rubber septum) using a 2.5 ml N₂ purged glass with silicone plunger and a 23 gauge needle. It then injects the sample into the purged packed inlet on the GC. The analysis method is designed to carry the injected gas mixture, using N₂ gas, through two 1/8” stainless steel packed columns (6 ft then 12 ft HaySep Q 80/100) heated to 250 °C, separating water vapor, heavy compounds and air, preventing contamination and their inclusion in the chromatogram.

Using three pneumatic valves, the GC system directs the gas-flow through a methanizer, packed with nickel catalyst heated to 375 °C, converting CO to CH₄. The gas then enters the flame ionization detector (FID) calibrated to detect a first round of CH₄ (0-5 ppm) and lower concentrations (0-600 ppm) of a second round of CH₄, which represents the CO concentration of the sample. Finally, the gas is directed down a fused silica line and through a micro-electron capture detector (µECD) used to measure ppb values (0-1 ppm) of N₂O. In this way the GC system evaluates the three gases (CO, CH₄, and N₂O) from each sample vial using a single injection that is split along parallel flow-paths to FID and the ECD detectors. A control PC operates the instrument measurement parameters and chromatogram integration through ChemStation software. Corrections to the data are applied based on standard injections taken in the field e.g., using Calibration Standards of 1 ppm N₂O, 5 ppm CH₄, 600 ppm CO, and, in the laboratory additional Praxair calibration quality standards of 0, 1.11, 2 and 4 ppm CH₄ and 0 ppm of CO and N₂O are tested. See below for elaboration on calibration standards.

![Figure B1. Pathways of gas through the GC.](image-url)
Appendix C
BC extrapolation equivalents calculations

Conversion of emissions flux, mg m$^{-2}$ day$^{-1}$, into kg/km$^2$/year:

$$(11.4 \text{ mg}) \cdot (365.24 \text{ days}) = 4,163.9 \text{ kg/km}^2/\text{year}$$

because the conversion of mg to kg and m$^2$ to km$^2$ cancel each other out. Conversion without the cancelation:

$$\left\{ \frac{(11.4 \text{ mg} \cdot (1.0 \cdot 10^{-6} \text{ kg}))}{(1.0 \cdot 10^{-6} \text{ km}^2)} \right\} \cdot 365.24 \text{ days}$$

Performing the calculations given here may not return the exact results reported due to rounding. For calculations, CH$_4$ was converted into CO$_2$ global warming potential equivalent due to lack of information on CH$_4$ emission.

All calculations are from EPA, 2013a.
<table>
<thead>
<tr>
<th>Equivalent</th>
<th>Calculation</th>
<th>Sources</th>
</tr>
</thead>
</table>
| 353,992 Passenger vehicles for one year | Calculation: \(8.92 \times 10^{-3}\) metric tons CO\(_2\)/gallon gasoline \(\times\) 11,493 vehicle miles traveled \(\text{car/truck average} \times 1/21.5\) miles per gallon \(\text{car/truck average} \times 1\) CO\(_2\), CH\(_4\), and N\(_2\)O/0.985 \(\text{CO}_2 = 4.8\) metric tons CO\(_2\)/E/vehicle/year | • U.S. department of transportation, 2012  
• EPA, 2012a |
| Electricity use of 254,366 homes for one year: | 11,319 kWh per home \(\times\) 1,301.31 lbs CO\(_2\) per megawatt-hour delivered \(\times\) 1 mWh/1,000 kWh \(\times\) 1 metric ton/2,204.6 lb = 6.68 metric tons CO\(_2\)/home. | • U.S. energy information administration. 2009  
• EPA, 2013a |
| Annual CO\(_2\) emissions of 0.481 coal fired power plants | 1.614,625,638.1 metric tons of CO\(_2\) \(\times\) 1/457 power plants = 3,533,098 metric tons CO\(_2\)/power plant | EPA, 2013b |
| Greenhouse gas emissions avoided by recycling 636,390 tons of waste instead of sending it to the landfill | 0.73 metric tons of carbon equivalent/ton \(\times\) 44 g CO\(_2\)/12 C = 2.67 metric tons CO\(_2\) equivalent /ton of waste recycled instead of landfilled | EPA 2012b |
| Carbon sequestered annually by 1,392,756 acres of U.S. forests | -0.33 metric ton C/acre/year (44 units CO\(_2\) / 12 units C) = -1.22 metric tons CO\(_2\) sequestered annually by one acre of average U.S. forest. | • EPA, 2012a  
• IPCC, 2006 |
Works Cited


