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## ***Interactive comment on “Greenhouse gas emissions (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) from perialpine and alpine hydropower reservoirs” by T. Diem et al.***

**T. Diem et al.**

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We thank Ivan Bergier and four anonymous reviewers for providing detailed comments on our manuscript, mentioning several ambiguous and unclear points. We agree with the reviewer, that changes are needed in the paper, to clarify the intentions and limitations of our study and to prevent the possibilities of misunderstandings.

In the following we will focus on the mutual remarks made by all or most reviewers and later focus on detailed remarks and suggestions. But first we would like to mention the intentions we had with this paper and highlight some of the specific features of Swiss reservoirs compared to other reservoirs, as these were insufficiently described in the manuscript.

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The idea of this paper was first to get an overview of the greenhouse gas emissions from Swiss reservoirs, as there was previously no data for reservoirs in similar settings. Secondly, we wanted to look for possible differences in diffusive flux caused by altitude and thirdly to estimate the importance of methane inflow into the reservoir compared to interior methane production. The third point gives us a way to estimate one aspect of the distinction between 'anthropogenic' emission due to reservoir production and methane from sources not belonging to the reservoir. Originally this third point should have included CO<sub>2</sub> as well, but insufficient CO<sub>2</sub> inflow data did not allow this. Thus we restricted our discussion about CO<sub>2</sub> to a comparison between our reservoirs and other previously measured reservoirs. The main focus was put on methane and the fact that methane inputs from inflows are the main source of methane for high alpine reservoirs, with an increasing importance of interior methane production at lower elevations.

Swiss reservoirs have several peculiarities worth mentioning: - Most of the water in winter is stored as snow in winter and reservoirs drain during this time, with losses in water volume of up to 90 %. This is accompanied with a large drop in water level and exposes a large part of the sediment to the atmosphere. Reservoirs will refill during snow-melt in spring/early summer. - As many reservoirs are situated in alpine valleys, the resulting lakes have very steep flanks. Water depth decreases quickly and littoral areas are small. - Reservoirs higher than 1900m very often are fed mostly by glacial water with a very high particle content resulting in low light transmission (< 10%) in the lake. Here conditions for photosynthetic activity in the water are not favorable due to very limited light availability. - Water inflow of the reservoirs is very often not restricted to the watershed of the valley the dam was built in, but water is transported via tunnels and pipes from neighboring valley or from reservoirs at lower elevation (some of them only built to store water). - Electricity production for alpine reservoirs takes place several hundred meters below the reservoir to utilize potential energy. Water is transported through tunnels and pipelines to the turbine and then returned to the river, often several kilometers downstream of the reservoir. Reservoir owners are forced by law to discharge some amount of water from the reservoir into

the river right below the dam to prevent drying-out. This water is called spill-water (or residual water) in the manuscript.

**Water loss at the turbine** The calculation of methane lost during passage of the turbine was not adequately described. We will try to improve that in a revised version of the manuscript. Briefly, loss was calculated from the difference of the methane concentration (in the dam basin) closest to the water outlet and the methane concentration from the water after passage of the turbine but before it re-entered the river. Both times water samples were taken with Niskin bottles. In case of Lake Wohlen and Lake Sihl, two reservoirs, which return the turbined water immediately to the river below the dam, water was sampled just below the dam.

**Sediments** Our assumption that methane input from sediments in alpine reservoirs of high elevations is less important than methane input from inflows has drawn massive criticism. Part of it is surely due to insufficient explanations on our part and due to the limited available data. However, as we tried to state in Section 5.3 methane concentrations in Lake Oberaar and in the inflow from the glacier are nearly equal during the filling stage at a time, when the reservoir is filling with water. This would suggest that a major part of methane in the reservoir contributed from the inflow. Definitely we did not have the purpose to state there is no methane produced in sediments. We merely wanted to suggest the high importance of methane inflows for methane content in alpine reservoirs, which are completely oxic throughout the year and low productivity environments. As suggested we will try to illustrate the importance of the inflow with a table.

**Ebullition** We only measured ebullition in one reservoir (and there only because of very high rates) and assumed ebullition to be irrelevant in alpine reservoirs at high elevations. This assumption is based on the methane concentration necessary in the sediment of a nearly 100m deep reservoir to form bubbles, which would be in the mM range (depending on N<sub>2</sub> and other gases in the bubble) and the oxygen gradient towards the sediment this would generate and on the steep slopes, which are not suited to accumulate organic carbon. As no oxygen gradient is visible in high alpine

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reservoirs and even the sediment methane concentrations in Lake Lungern, which is nearly anoxic close to the sediment surface are below 1 mM we think this argument is probably valid. However, we can not exclude the presence of bubbles, especially during times of large water level changes and thus we will no longer discuss ebullition in the revised manuscript.

Figures will be condensed and hydrographic data will be added to better support our mixing and inflow arguments.

Additional information Several reviewers suggested the necessity of additional information, for example water chemistry, trophic state, catchment area characteristics, flooded ecosystems and others. We will try to add what is possible and available.

Now, for the specific comments of each reviewer:

Ivan Bergier

We think there are several misunderstandings concerning the scope of the paper. We did not intend to speculate on the origins of CO<sub>2</sub> and the distinction between 'naturally' produced and 'anthropogenic' carbon dioxide in hydroelectric reservoirs. As important as this topic is for the net greenhouse gas emissions, we feel there are still several uncertainties, which are not yet completely solved. We would need to include not only just the reservoir and its previous land-use, but namely the whole river-reservoir-system from the source to the ocean. For example, carbon sequestration in the reservoir is not necessarily a new sink when downstream lakes would have sequestered similar amounts of carbon that are now stored in the newly build reservoir and no longer in the downstream lake. Thus the whole net sequestration would be close to zero and the attribution of the reservoir as a sink for carbon happens at the cost of another reservoir/lake. But this is more than we can do with the limited dataset we have (and the lack of data from the pre-dam conditions).

1 - CO<sub>2</sub> was not measured by headspace technique for several reasons. At first the

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use of NaOH to preserve samples did not allow headspace measurements of CO<sub>2</sub>, as the high pH of the samples shifts the leads to precipitation of carbonates. Later, when Cu(I)Cl was used for preservation we detected changes in pH during sample storage. Changes in pH will shift the H<sub>2</sub>CO<sub>3</sub>/HCO<sub>3</sub><sup>-</sup>/CO<sub>3</sub><sup>2-</sup> equilibrium leading to increased/decreased CO<sub>2</sub> concentrations in the headspace, depending on decreasing/increasing pH. This problem was discovered too late to measure pH of the samples during the measurement procedure and we regarded the CO<sub>2</sub> data measured by headspace technique not to be reliable. However, since the measurement of CO<sub>2</sub> concentrations by alkalinity and pH is an established method we did and do not see any problems in using it.

3 - The distinction between anthropogenic and natural CO<sub>2</sub> for hydroelectric reservoirs is still highly debatable in our opinion. While it can be argued, that CO<sub>2</sub> produced from allochthonous particles can not be attributed to the reservoir, it is not certain, that these particles would have produced CO<sub>2</sub> without the presence of the reservoir, but instead would have been flushed into the ocean and be sequestered there. The situation is further complicated by the practice of flushing reservoirs every few years to remove sediments and maintain the volume of the reservoir, as it is done in Swiss reservoirs. Because of this there will be no long-term carbon sequestration in those reservoirs.

4 - We mentioned the connection between CO<sub>2</sub> emissions and pH in the paragraph with the statistics. But we will remove the remark and the correlation.

5 - The correlation was not done to test for differences between reservoirs, but to look for possible connections between reservoirs emissions and a second parameter, in our case we tried to check for possible decreasing emissions with increasing elevation and decreasing emissions from spring to summer/autumn. But we will redo the whole statistics part.

7 - This remark is similar to remark 3 and was not part of this study.

8 - We do not quite understand this remark. However, as stated above, the release of

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methane after passage of the turbine will be better explained.

9 - All reservoirs, except Lake Gruyère at the bottom are completely oxic in the water column and there is no zone of methane oxidation where the Raleigh model could be applied. As our time resolution is several weeks and during that among other things time reservoir filling stage changed we can not correlate measured concentrations between the sampling dates. Additionally, water from the inflows (and thus methane) mixes with reservoir water, obscuring any isotope signal that methane oxidation might eventually have left.

Anonymous referee #1 We appreciate the suggestions for figures, the classification of the reservoirs and the mass balance. The classification we used will be changed in a way, that we will describe three typical types of profiles found in Swiss reservoirs and compare them to profiles from other regions and include hydrographic data in the figures. This should make our arguments more comprehensible. The mass balance will be changed to fit our available data. We will combine methane inflow, outflow and loss by diffusive surface flux and assume the imbalance has to be compensated by methane input from the sediment. This way we can compare the importance of inflow and input from the sediment. Emissions calculated by using different relationships for transfer velocities will be compared in a figure.

The remaining specific comments of the anonymous referees #1, #3, #4, and #5 will be integrated, if possible, into a revised manuscript.

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