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Redistribution of methane emission hot spots under drawdown conditions☆

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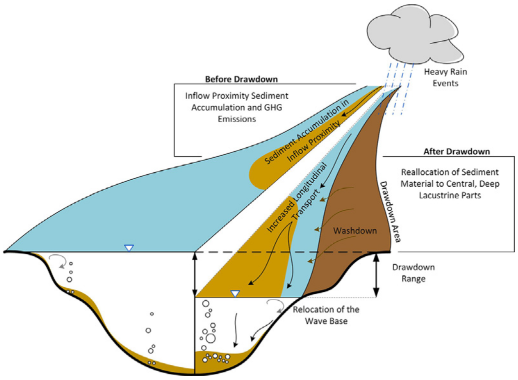
HIGHLIGHTS

- Emission hot spots within reservoirs will significantly shift after drawdown events.
- Historic water level fluctuations are important for emission extrapolations.
- No simplified relations between depth and methane emissions
- Future climate- and management-related level fluctuation will lead to different emission patterns.

GRAPHICAL ABSTRACT



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ABSTRACT

In the context of reservoirs, sediment trapping, and aquatic greenhouse gas (GHG) production, knowledge about the distribution of hot and low spots is essential for improved measurement strategies. It is also a key to a precise assessment of the GHG emissions of each reservoir. Large numbers of reservoirs are used mainly for hydroelectric power generation and, hence, affected by strong changes in water level. Drawdown events may lead to significant changes in spatial sediment and organic carbon distribution and, consequently, strongly alter the GHG emission patterns of the water body. We combined hydroacoustic sediment classification, sediment magnitude detection, and ebullition flux assessment with in-situ pore water investigations and sediment coring to detect ebullition distribution patterns after strong reservoir drawdown. The research was conducted in the Capivari Reservoir in the southeast of Brazil, which was affected by up to 15 m of drawdown within the last 10 years.

Results show severe changes in sediment accumulation and composition. The focusing of sediment divides the reservoir in extreme hot and low spots. Methane pore water concentrations are highly correlated with acoustic backscatter values ($r^2 = 0.97$) as well as with the organic carbon content ($r^2 = 0.55$) and allow for a precise detection of the newly created emission patterns. Highly productive sediment could be acoustically distinguished from non-productive areas. Only 23.6% of the reservoir surface produced 64% of the detected bubbles. An organic carbon content in the sediment of 2.4% was found to be a prerequisite for the formation of GHG emission hot spots. These findings may help to complement the still insufficient knowledge of methane ebullition fluxes from reservoirs with changing water levels.

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1. Introduction

Many studies have confirmed the relevance of greenhouse gas (GHG) emissions from reservoirs and inundated areas all over the world (Abril et al., 2005; Aselmann and Crutzen, 1989; Barros et al., 2011; Bastviken et al., 2004; Bastviken et al., 2011; Beaulieu et al., 2014; Cao et al., 1998; Maeck et al., 2013; Ometto et al., 2013; Roland et al., 2010; Wilkinson et al., 2015). Recent studies show that reservoirs and dammed areas of rivers in humid climates are able to produce equivalent amounts of GHG per area independently of the climate zone (DelSontro et al., 2010; Maeck et al., 2013; Wilkinson et al., 2015). The fact that CH_4 and CO_2 from reservoirs represent relevant sources of GHG has been known for some decades, but the reliability of the measurements and, hence, the calculated fluxes into the atmosphere are still unknown (Wik et al., 2016). Although innovative measurement methods have been developed (DelSontro et al., 2011; Maeck et al., 2013; Ostrovsky, 2003, 2009a), the general problem of high spatial emission variability prevails, especially for the ebullition pathway (Sollberger et al., 2014). Spatial variability of the emissions of methane (Beaulieu et al., 2016; Cardoso et al., 2013; Mendonça et al., 2016) from reservoirs and the discussed existence of methane hot spots become even more relevant when transferred to the relatively large reservoirs in the tropics and subtropics. Brazil features extensive reservoirs of above-average size with the corresponding extremely large inundated areas compared to other countries. Nearly all techniques for the measurement of GHG emissions from reservoirs have the disadvantage of limited sampling areas (~1 m^2), statistical uncertainties within large reservoirs are enormous. As shown by DelSontro et al., 2011, Sikar et al., 2012 and Sollberger et al., 2014, the spatial and temporal variability can be extremely high. Consequently, it is difficult to extrapolate the emissions from one point over large distances to the next measurement point. Many relevant studies include only a limited number of measurement points as a basis for spatial interpolation (Bastviken et al., 2004; Beaulieu et al., 2014; Chen et al., 2011; Gonzalez-Valencia et al., 2014; Musenze et al., 2014; Sturm et al., 2014). For diffuse fluxes, this calculation approach may be statistically sufficient due to lower horizontal gradients. For the ebullition pathway, however, this approach may lead to erroneous overall results when extrapolating to the entire reservoir. The production of GHGs is mainly coupled to the amount of accumulated sediment, the share of organic carbon (OC), and the availability of the carbon for microbial processes (Grinham et al., 2018; Maeck et al., 2013; Sobek et al., 2012). The sediment as a time- and, with some limitations also, a space-integrating entity may serve as a good variable to increase the understanding of GHG production in reservoirs (Mendonça et al., 2016; Sobek et al., 2012). Ebullition strongly depends on sediment accumulation and sediment properties and, hence, is characterized by high heterogeneities in space (DelSontro et al., 2011; DelSontro et al., 2015; Maeck et al., 2013; Sobek et al., 2012).

Results from fresh water systems as well as the marine realm have shown that acoustic techniques are a promising tool to detect sediment properties, including the presence of free gas in the sediment (Cukur et al., 2013; Freitas et al., 2008; Gopinath, 2000; Laier and Jensen, 2007; Martinez and Anderson, 2013; Tóth et al., 2014; Tóth et al., 2015).

A complex morphometry as a primary condition for sediment distribution may lead to distinct spatial heterogeneities (Blais and Kalff, 1995; Hilgert and Fuchs, 2015; Morris and Fan, 1998), which may clearly differ from simplified sedimentation patterns.

Beaulieu et al. (2016) found that in the complex shaped Harsha Lake (Ohio, USA) 42% of the total CH_4 emissions could be associated with tributary areas. Ebullition rates were 7.2 times higher in the tributaries than in open water areas. The areas below tributary inflows were found to be emission hot spots by several researchers (Grinham et al., 2011; Harrison et al., 2017; Musenze et al., 2014; Sturm et al., 2014; Tušer et al., 2017). Transferred to the Capivari Reservoir, this means that the proximal area (Fig. 3) was expected to have the highest overall emission potential, while the deeper areas (central and profundal) were to exhibit very low emissions.

Reservoir management as an anthropogenic factor causing water level fluctuations with high vertical drawdown amplitudes fundamentally changes the patterns of sediment distribution within reservoirs (Furey et al., 2004).

Drawdown behavior may lead to resuspension in the littoral and internal reallocation of large amounts of sediment (up to 96%, Effler et al., 1998). Receiving areas in the lacustrine zone (profundal) may reach significant amounts of sediment with 10 to 50 times the sedimentation rate compared to lacking drawdown (de Cesare et al., 2001; Effler et al., 1998). For this reason, GHG production might differ from general expectations. Complex shaped morphology of reservoirs may lead to small-scale intra-reservoir changes in sediment magnitude and composition of the sediment (Blais and Kalff, 1995; Gilbert, 2003; Hilgert and Fuchs, 2015; Mackay et al., 2012). Still, overall gradients like the river – dam gradient as well as lateral patterns may cause a general sediment zonation within a reservoir. Examples of the "zonation theory" of sediments in reservoirs or lakes are presented in Abraham et al., 1999; Effler et al., 1998, DelSontro et al., 2011 and Sollberger et al., 2014. Beaulieu et al., 2016 emphasize the importance of the riverine-lacustrine transition zones as hot spots of methane emission. However, the special situation of frequently changing water levels either in hydroelectric reservoirs or in reservoirs storing water for irrigation or drinking water supply under strong seasonal changes in usage and inflow volume may look very different in terms of sediment distribution and emission schemes.

Until now, only a limited attention was paid to these consequences of water level changes in the context of methane emissions (Harrison et al., 2017; Serça et al., 2016).

This study aims at a better understanding of reallocation processes of sediment during strong drawdown (> 30% relative depth) and, as a consequence, the creation of new emission hot spots. This may result in a more precise definition of methane production zones within reservoirs in order to improve measurement strategies and the quality of emission calculations. The goal not only is to detect the "hot spots," but also to be aware of the "low spots" in a reservoir. Zones with no or low and high potential methane production are determined for an exemplary reservoir under drawdown influence.

Echo sounding technology was used to assess the bathymetry and to derive the slope of the reservoir bed. Furthermore, the hydroacoustic data were analyzed for sediment classification based on various sediment parameters (organic carbon, wet bulk density, share of silt and clay fraction). The sediment magnitude was assessed following the approach of Hilgert and Fuchs (2015). Additionally, the echo sounder was used to detect rising bubbles in the water column (DelSontro et al., 2011; DelSontro et al., 2015; Ostrovsky, 2009b). For ground truthing, the sediment was investigated using gravity corers and a self-constructed placement system for dialysis pore water samplers (DPS) (Hilgert et al., 2014). DPS may provide insight into the local in-situ gas composition in the pore water.

We combined the resulting information to derive a spatial zonation of the reservoir, the objective being to estimate the local methane emission potential rather than flux.

2. Material and methods

2.1. Study site

Located 40 km northeast of the city of Curitiba in the state of Paraná, Brazil, the Capivari Reservoir l is situated at a latitude of about 25°S. To the east, the reservoir verges on the Sierra do Mar mountain range that separates it geographically from the Atlantic Ocean. The Reservoir was constructed in 1970 for the operation of the Governador Parigot de Souza Hydroelectric Power Station (Borges et al., 2008). The general characteristics of the reservoir are listed in Table 1. The Capivari River