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Effect of weir impoundments on methane dynamics in a river

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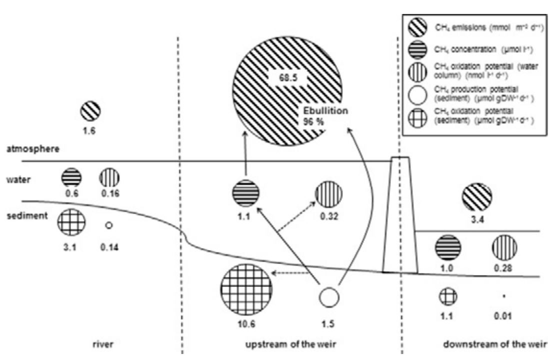
HIGHLIGHTS

- CH_4 emissions were higher upstream of the weirs compared to river reaches.
- Sediments upstream of the weirs resemble many previous observations for lake systems.
- Small impoundments significantly affect the CH_4 cycle in a river.

GRAPHICAL ABSTRACT



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ABSTRACT

We measured CH_4 concentration, CH_4 oxidation in the water column and total CH_4 emissions to the atmosphere (diffusion and ebullition) in three weir impoundments and river reaches between them, in order to understand their role in river methane (CH_4) dynamics. Sediment samples were also collected to determine CH_4 consumption and production potentials together with the contribution of individual methanogenic pathways. The CH_4 surface water concentration increased 7.5 times in the 16 km long river stretch. Microbial CH_4 oxidation in the water column reached values ranging from 51 to 403 nmol l^{-1} d^{-1} and substantially contributed to the CH_4 removal from surface water, together with CH_4 emissions. The total CH_4 emissions to the atmosphere varied between 0.8 and 207.1 mmol CH_4 m^{-2} d^{-1} with the highest values observed upstream of the weirs (mean 68.5 $\pm$ 29.9 mmol CH_4 m^{-2} d^{-1}). Most of the CH_4 was transported through the air-water interface by ebullition upstream of the weirs, while the ebullition accounted for 95.8 $\pm$ 2.0% of the total CH_4 emissions. Both CH_4 production and oxidation potential of sediments were higher upstream of the weirs compared to downstream of the weirs. The contribution of hydrogenotrophic methanogenesis to total CH_4 sediment production was 36.7–89.4% and prevailed upstream of the weirs. Our findings indicate that weirs might influence river CH_4 dynamics, especially by increased CH_4 production and consumption by sediments, followed by increasing CH_4 emissions to the atmosphere.

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1. Introduction

Methane (CH_4) emissions from inland freshwater ecosystems (lakes, reservoirs and rivers) are believed to be to important contributions to global CH_4 flux (Ciais et al., 2013; Bastviken et al., 2011). It has been estimated that CH_4 effluxes from lakes or wetlands are equivalent to ca. 20–50% of global CH_4 emission, but fluvial systems are one of the least studied freshwater types (Stanley et al., 2016). The controlling factors of CH_4 fluxes from rivers and the characteristics of their spatial and temporal heterogeneity are still poorly understood (Saarnio et al., 2009; Ortiz-Llorente and Alvarez-Cobelas, 2012).

One major factor affecting the CH_4 dynamic in rivers is the presence of dams. In general, impoundments can cause significant changes to river habitats, morphology, sediment transport and physicochemical properties of the water (Ogbeibu and Oribhabor, 2002; Rickard et al., 2003; Gao et al., 2013; Kattel et al., 2016) and is also known to be important in greenhouse gas dynamics (Louis et al., 2000; Sobek et al., 2012). Impoundments in central Europe are environments with a high organic carbon burial rate; with smaller impoundments having greater deposition and accumulation rates per unit area (Downing et al., 2008). There is a high contribution of small impoundments to the total area of impoundments, making it obvious that small aquatic bodies can play an important role in the global carbon cycles (Downing et al., 2006; Holgerson and Raymond, 2016).

The microbial processes related to CH_4 production occur to a large extent in the hyporheic zone of streams and rivers. Here anaerobic carbon cycling is the prevailing process and CH_4 is one of the major components of interstitial dissolved organic carbon (Dahm et al., 1991; Baker et al., 1999; Fischer et al., 2005).

Generally, H_2/CO_2 and acetate have been recognized as the two dominant substrates for methanogenic Archaea in freshwater ecosystems. When carbohydrates are anaerobically degraded to CH_4 and CO_2, acetoclastic methanogenesis (using acetate) would theoretically contribute 67% of CH_4 production following the stoichiometry of the degradation, while the contribution of hydrogenotrophic methanogenesis (using H_2/CO_2 as substrate) would contribute the remaining 33%. This holds true for rice field soils (Conrad et al., 2002; Fey et al., 2004; Scavino et al., 2013), but recent studies from numerous freshwater ecosystems show various contributions of the two dominating methanogenic pathways. Low contributions of hydrogenotrophic methanogenesis (using H_2/CO_2) have been reported for rivers – 18–45% (Avery and Martens, 1999; Mach et al., 2015). Much higher contributions of hydrogenotrophic methanogenesis have been frequently reported for lakes – 50–90% (Murase and Sugimuto, 2001; Conrad et al., 2011; Conrad et al., 2014) and peatlands – 46–89% (Galand et al., 2005; Galand et al., 2010). Nevertheless, very few data are available concerning spatial variations of methanogenic pathways in freshwater sediments, particularly those from rivers.

Damming reduces the flow velocity of the water, which in turn decreases the oxygen availability. Hence CH_4 produced in the sediment is less likely to be oxidised in the sediment and the water column. This has two consequences: (1) the increased production and reduced oxidation of CH_4 results in a supersaturation and increased ebullition events and (2) the supersaturated water increases the CH_4 concentration in downstream water sections.

Sites with increased sedimentation and CH_4 concentration are thus considered to be 'hot spots' of CH_4 ebullition (Sobek et al., 2012; Maeck et al., 2013). Bubble release is a frequent transportation pathway of CH_4 from lakes and reservoirs (Bastviken et al., 2004; DelSontro et al., 2010), while it is considered to be less important in natural streams and rivers, where most of the emission measurements have focused on transport through the air-water interface by diffusion (Striegl et al., 2012; Yang et al., 2012; Silvennoinen et al., 2008). There is now good evidence however, that bubble-mediated fluxes are an important CH_4 emission mechanism in running waters (Baulch et al., 2011; Crawford et al., 2014; Sawakuchi et al., 2014).

The aim of this study was to quantify the effect of three weirs and weir impoundments on individual components of the CH_4 dynamic in a 16 km river reach. Our hypotheses were that impoundments cause changes in sediment composition that leads to increased rate of CH_4 production and reduced rate of CH_4 consumption; these changes lead to increased CH_4 emissions to the atmosphere. We examined 1) changes in river CH_4 concentrations, 2) emissions to the atmosphere (diffusion and ebullition), 3) methanotrophic activity in water column and 4) CH_4 production and consumption by sediments including the determination of methanogenic pathways using stable carbon isotope values.

2. Material and methods

2.1. Study site

The study river was the Morava (Czech Republic), where it flows through Olomouc city (from 49°36.8″ N, 17°15.2″ E to 49°29.7″ N, 17°16.7″ E). The Morava is a second-order tributary of the Danube with a mean annual discharge of 26.4 $m^3\ s^{-1}$ at our study site. The Morava river catchment is characterised by the development of the relief features on the marginal West-European platform, young Carpathian folded mountain ranges and of the Pannonian basin. The present georelief has been characterised by alternating period of quiet development and by periods of abrupt changes. About 54% of the catchment area is agricultural land (45% arable), 34% is covered by forest, 1.5% urbanized areas and 1.4% is covered by water. The main sources of nutrients are municipalities and agricultural activities. Coniferous forests prevail in the upper part of the catchment. The river upstream from the study area meanders through the floodplain forests of the Protected Landscape Area Litovelské Pomoraví, however our study reach of Morava River is straightened, its cross section is modified and its river banks are stabilized.

Three weirs are situated in this 16 km stretch of the river (Table 1), constructed for stabilization of the vertical alignment and of the riverbed, energy production using small hydropower plants, and retention of surface water for water supply. Nine sampling points were chosen along the river (Fig. 1). Three sites were located in river parts unaffected by impoundments, between the weirs (R 1–3); three sites were directly in impoundments upstream of the weirs (UW 1–3) and three sites were situated just downstream of the weirs (DW 1–3). All samples were collected twice in the summer months of 2014, one week, in mid-July and one in mid-August. Measurements of all parameters were performed simultaneously for each sampling site. Data from both sampling periods are presented together.

2.2. Sediment samples and incubation experiments

Triplicate samples of surface sediment layer (0–10 cm) from each site were collected in July 2014 by scuba diving. Sediments were then sieved through a 1-mm sieve and stored at 4 °C until subsequent analyses and laboratory experiments. Sediments for the granulometric analysis were sieved through a system of ten sieves of decreasing mesh sizes. All separate parts of the sediment were weighted and grain median size was analyzed using the software Gradistat (version 8.0) (Blott and Pye, 2001). The dry weight of the sample was determined gravimetrically. The carbon content of the sediments was quantified on a CHNS-

Table 1
Basic parameters of weirs.

Weir	Backwater length (m)	Volume of reservoir (m^3)	Weir length at overflow edge (m)	Maximum water depth (m)	Height of weir(m)
W1	2600	139,000	40.8	3.2	2.7
W2	2000	160,000	40.0	4.1	2.4
W3	5290	450,000	50.6	2.7	3.7