Interactive comment on* "Methane emissions from a sediment-deposited island in a Lancang-Mekong reservoir"** ***by Wenqing Shi et al.

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Referee # 1

The paper deals with CH_4 dynamics in relation with methanotrophic and methanogenic bacteria abundance in the sediment/soils following topography from the shore line to the top of an island located in a hydroelectric reservoir.

This is a very original study with unexpected outcomes: -negative CH_4 fluxes at the water or sediment interface, never observed in aquatic systems and moist soils-maximum abundance of methanotrophs in the water saturated and organic soils/sediments of the shoreline, an environment supposed to be ideal for methanogens –maximum abundance of methanogens at the top of the highland which is more often uncovered with water and which therefore might favor oxygen diffusion and occurrence of methanotrophs.

Major comments

(1) In the community studying greenhouse gas emissions from hydroelectric reservoir, the littoral zone and the area undergoing the water level variations is called the drawdown area. Some reference listed at the end of the review might be considered for improving the description of the research context of this study and some comparison with those results could be interesting and more papers can be found on this topic.

- Many thanks for the valuable suggestions. We have carefully studied the listed references and improved the description of the research context of this study. Please see line19, 21 on page 2, line 57, 66, 67 on page 4, line 222 on page 11, line 249 on page 12, line 250, 252, 254 on page 13, line 288 on page 14, line 298, 303, 305, 306, 310 on page 15, line 318 on page 16 in the revised manuscript.

- According to the suggestions, we have added the comparison between the results of this study with others on this topic. Please see line 295-300 on page 15 in the revised manuscript.

(2) The sketch of the chamber in Supplementary material (S.5) did not show any vent for preventing an increase of the pressure in the chamber during the installation resulting from the decrease of the chamber volume when the edge of the chamber penetrates either in the water or the soils/sediment. Overpressure generate bias to the flux measurement by increasing the solubility of CH_4 in the surface water or interstitial water. Such phenomenon could explain some of the negative fluxes and might have influence all CH_4 fluxes measurements.

- During the chamber installation, the outlet of the chamber was open (**Fig. 1**), and was left to stand for 20 min to equilibrate with ambient pressure outside. Then, a drop of water was filled into the outlet to test whether the pressure inside was equilibrated or not before the outlet was closed. Based on our results of previous chambers (Fig. 2), we did not design another outlet for equilibrating pressure in order to increase the gas tightness of this chamber. We have updated the descriptions to make it clearer, and please see line 145-147 on page 8 in the revised manuscript.

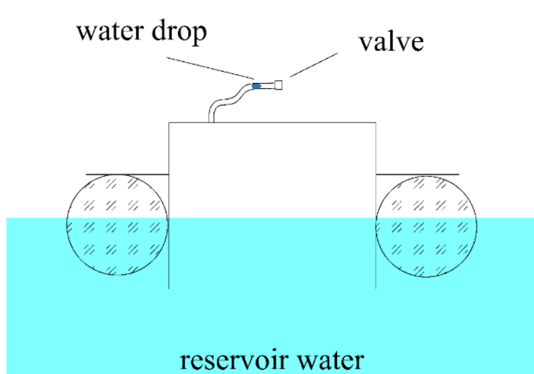

Fig. 1 The gas collection chamber for gas fluxes across the air-water interfaces in this study

Fig. 2 The gas collection chamber for gas fluxes across the air-water interfaces in our previous studies

(3) No information is given in the manuscript for air-soil flux measurements (L148). Again, the design of the chamber calls into doubt the validity of the soil fluxes (See supplementary material S.5)). Usually, soil flux measurements are performed with chambers with collar, which allows the installation of the collar a few hours before the flux measurement in order to avoid measuring a flux that might mostly result from the perturbation associated with the penetration of the chamber or collar edges in the soil/sediment. This might have increased significantly the soil fluxes.

- We are really sorry for having not described the air-soil flux measurements. We fully agree with the referee that soil flux measurements should be performed with chambers with collar. We had planned to set up perpetual collars in the study area; however, the frequent water level fluctuation often filled the collar with water in our preliminary tests. According to Schindlbacher et al. (2012), the chamber was carefully inserted 5 cm deep into the sediment, leaving 15 cm above the sediment surface. The outlet of the chamber was open during the chamber deployment, and was left to stand for 90 min to equilibrate before sample collection. The information has been updated in line 147-151 on page 8 in the revised manuscript. For the accurate estimation of CH_4 emissions in this special area, further studies are needed in future using the method of noncontact measurements, such as Eddy Covariance Measurement Systems.

Schindlbacher, A., Wunderlich, S., Borken, W., Kitzler, B., Zechmeister - Boltenstern, S., & Jandl, R. (2012). Soil respiration under climate change: prolonged summer drought offsets soil warming effects. *Global Change Biology*, 18(7), 2270-2279.

(4) Sediment sampling strategy (L116) is not ideal if one wants to link fluxes at the air-water interface or air soil interface with bacterial abundance and functions. Fluxes are controlled by the balance between methanogenesis and methanotroph, the former being mostly active in “deep” anoxic horizons (10 cm in soils, sediments...) and the latter above the oxic-anoxic interface (typically in the first mm at the air soil interface). Therefore, a bulk sample of the first ten cm in the sediment might fail at describing the expected vertical structure of the bacterial community involved in the CH_4 cycle. Cores might have been more adapted

- Yes, in natural aquatic ecosystems, methanogenesis is mostly active in “deep” anoxic horizons (10 cm in soils, sediments...) and methanotroph mainly occurs above the oxic-anoxic interface. In this study, frequent reservoir operation induced lateral hyporheic exchange and created oxygen gradients along the hyporheic flow path across the island (Fig. 3), regulating microbes for CH_4 emissions. Our interests focus on the horizontal heterogeneity of microbial abundance here to clarify spatial patterns of CH_4 emission. Sediment was collected from 10 cm below the surface in order to avoid the disturbances of oxygen penetration from air. For the vertical heterogeneity of bacterial community structure, we can design and conduct further studies using a core system according to the referee’s suggestions.

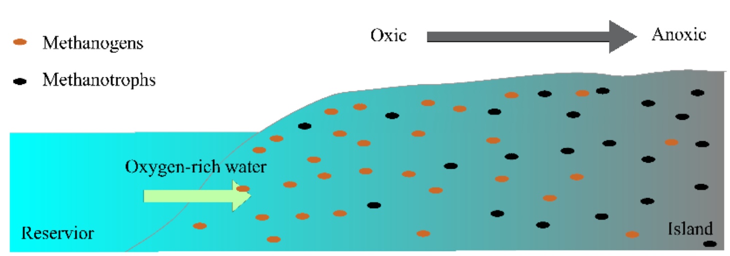

Fig. 3 The horizontal heterogeneity in the interior of island under reservoir operation.

(5) 16S rDNA can be used for the detection of active bacteria and biogeochemical pathways in combination with isotopic labelling. Without labelling, DNA prove the presence of the bacteria (since it is very stable in natural environment) but it does not clearly demonstrate they are active. RNA might have been more adapted because of its shorter life time. Relationships between the CH_4 fluxes and the bacterial abundance based on DNA must therefore be considered with care.

- Thanks for the valuable comments. Methane emissions may not only rely on bacterial abundance but also bacterial activity (Schwarz et al., 2008). Some other molecular biology techniques need to be used in future studies according to the referee's suggestions. The information has been updated to make the discussion appropriate in this study. Please refer to line 277-280 on page 14 in the revised manuscript.

Schwarz, J. I. K., Eckert, W., Conrad, R. Response of the methanogenic microbial community of a profundal lake sediment (Lake Kinneret, Israel) to algal deposition. *Limnology and Oceanography*, 2008, 53(1), 113-121.

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Chen, H., X. Yuan, Z. Chen, Y. Wu, X. Liu, D. Zhu, N. Wu, Q. a. Zhu, C. Peng and W. Li (2011). "Methane emissions from the surface of the Three Gorges Reservoir." J. Geophys. Res. 116(D21): D21306.

Chen, H., Y. Wu, X. Yuan, Y. Gao, N. Wu and D. Zhu (2009). "Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir." J. Geophys. Res. 114: D18301.

Li, Z., Z. Zhang, C. Lin, Y. Chen, A. Wen and F. Fang (2016). "Soil–air greenhouse gas fluxes influenced by farming practices in reservoir drawdown area: A case at the Three Gorges Reservoir in China." Journal of Environmental Management 181: 64-73.

Serça, D., C. Deshmukh, S. Pighini, P. Oudone, A. Vongkhamsao, P. Guédant, W. Rode, A. Godon, V. Chanudet, S. Descloux and F. Guérin (2016). "Nam Theun 2 Reservoir four years after commissioning: significance of drawdown methane emissions and other pathways." Hydroécol. Appl. 19: 119-146.

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Methane emissions from a sediment-deposited island in a Lancang-Mekong reservoir: Spatial heterogeneity and mechanisms

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Abstract

In dammed rivers, sediment accumulation creates potential methane emission hotspots, which have been extensively studied in forebays. However, methane emissions from sidebays remain poorly understood. We investigated methane emissions from a sediment-deposited island situated in the sidebay of the Manwan Reservoir, Lancang-Mekong River. High methane emissions (maximum 10.4 mg $h^{-1}m^{-2}$) were observed at the island center, while a ring-like zone of low-to-negative methane emission was discovered at the drawdown area around the island edge, whose flux varied between -0.2–1.6 mg $h^{-1}m^{-2}$. The ring-like zone accounted for 89.1 % of the island area, of which 9.1 % was a methane sink zone. Microbial processes in the drawdown area, regulated by hydrological variations, were responsible for the low methane flux in this area. Under reservoir operation, frequent water level fluctuations enhanced hyporheic exchange and created oxygen gradients along the hyporheic flow path. Dissolved oxygen in hyporheic water decreased from 4.80 mg L^{-1} at the island bank edge to 0.43 mg L^{-1} at the center, which in turn decreased methanogen abundance for methane production and increased methanotroph abundance for methane oxidation at the ring-like zone. This study quantified the methane emissions from sediment deposited islands in the reservoir and helps to evaluate the global warming effects of hydropower systems.

1 Introduction

Natural rivers form continuous ecosystems, in which physical and chemical factors drive biological processes from headwaters to river deltas (Butman and Raymond, 2011; Wilkinson et al., 2015). Along this continuum, rivers receive terrestrial organic carbon (OC) and deliver it to the ocean at a global average rate of approximately 400–900 Tg OC per year (Butturini et al., 2016; Seitzinger et al., 2005; Ran et al., 2013). In the past two decades, many rivers have become intensively regulated by dams for a variety of purposes, including improved navigation, water supply, flood control, and hydropower production (Maavara et al., 2015). These engineering works decrease water velocity, converting rivers into a series of lentic reservoirs, where sediment accumulates in forebays and sidebay islands (Maeck et al., 2013). Globally, the sediment accumulation process has reduced the river-to-ocean flux of terrestrial OC by 26 % (Syvitski et al., 2005).

Methane is the second most important greenhouse gas, contributing approximately 18 % to total global warming effects (Smith et al., 2013; Wuebbles and Hayhoe, 2002). Inland waters (lakes, rivers, and reservoirs) are significant sources of atmospheric methane, which is mainly released from anoxic sediment (Bastviken et al., 2011; Sobek et al., 2012). After river damming, settling particles aggregate to form cohesive sediment layers, which often become anoxic after oxygen is consumed but not replenished through diffusive exchange (Rubol et al., 2013; Maeck et al., 2013). Subsequently, large amounts of methane may be produced and released into the atmosphere (Thornton et al., 1990; Maeck et al., 2013; Wilkinson et al., 2015), thereby reducing the green credentials of hydropower. This issue has received considerable attention in dammed rivers (Giles, 2006; Hu and Cheng, 2013). Maeck et al. (2013) identified reservoirs as methane emission hotspots by comparing reservoir and riverine reaches, and estimated that global methane emissions have increased by 7 % due to sedimentation in dammed rivers. In sidebays, the deposited sediments often created the drawdown area under water level fluctuations, where water, heat, nutrients and chemicals are exchanged and many biogeochemical reactions preferentially occur (Tonina and Buffington, 2011; Cardenas and Markowski, 2010), potentially emitting large amounts of greenhouse gases. Previous studies have mainly focused on methane emissions from dam forebays (Yang et al., 2013; DelSontro et al., 2010; DelSontro et al., 2011), while the understandings of methane emissions from sediments deposited in sidebays remain poor.

In reservoirs, frequent water level fluctuations often occur following hydropower production demands, which enhances hyporheic exchange by driving water flow in and out of the drawdown area (Tonina and Buffington, 2011; Hucks Sawyer et al., 2009). This may lead to changes of oxygen conditions in the interior of the drawdown area. Zarnetske found a redox gradient along the hyporheic flow paths in a third-order stream in the Willamette River basin, USA (Zarnetske et al., 2011a). Methane from sediments is mainly produced by anaerobic methanogens, and is consumed by aerobic methanotrophs (Borrel et al., 2011). We suppose the shift in oxygen conditions in sediments may affect the microbial processes, thereby altering the methane emission scheme.

In this study, methane emissions from a sediment-deposited island were investigated in the sidebay of Manwan Reservoir, Lancang-Mekong River. Monitoring wells were established to probe hyporheic exchange and oxygen gradients across the island. Methanogen and methanotroph abundances in the sediment were analyzed using quantitative polymerase chain reaction (qPCR) to reveal the associated molecular mechanism. The objective of this study was to explore methane emissions from sediment-deposited zones in a sidebay of a dammed river, with the goal to guide future thorough assessments on the global warming effects of hydropower development.

2 Methods

2.1 Study area

The Lancang-Mekong River, a trans-boundary river in Southeast Asia, originates from the Tibetan Plateau and discharges into the South China Sea. It has a length of 4909 km, a watershed area of 760,000 km^2, and a mean annual runoff of 457 km^3 at a discharge of 14,500 $m^3 s^{-1}$ (Li et al., 2013). The Lancang-Mekong Basin can be divided into two parts: the "upper basin" in China, and the "lower basin" from Yunnan in China to the Southeast Asia. Until 2016, seven dams have been built for hydropower production in the upper Lancang-Mekong River in China, including Miaowei, Gongguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu and Jinghong. The locations and main features of these dams were shown in Fig. 1 and Table S1 in the Supplements, respectively.

After impoundment, several different types of islands formed in the reservoir (Fig.

S1). This study selected a typical island for investigation (182 m in length, 90 m in width), which is located at the convex bank (24°43′44″ N, 100°23′5″ E) in the sidebay of Manwan reservoir, 30 km away from the dam (Fig. 1). Manwan has a subtropical plateau monsoon climate, featuring no distinct seasons. Under reservoir operation, the island bank is frequently flooded (Fig. S2).

2.2 Monitoring wells

Ten monitoring wells were installed in the island bank at 0.5 (W1), 1.5 (W2), 3.5 (W3), 6.5 (W4), 10.5 (W5), 15.5 (W6) 20.5 (W7), 25.5 (W8), 30.5 (W9), and 35.5 m (W10) from the waterline, respectively (Fig. S2). The wells were 90-mm diameter perforated polyvinylchloride pipes, reaching a depth of 2.0 m below the ground surface. To prevent flooding, the wells were extended 2.0 m aboveground. Due to hydropower production, the reservoir runs in a pseudo-periodic hydrological regime with cyclic water level fluctuations. Here, we monitored a complete cycle of water level fluctuation within 115 h. Water levels were measured every 10 min from 11 to 16 September 2016 using automated water level recorders (U2000101, OneSetHoBo, USA), which were mounted at the bottom of W5, W7, W10, and the reservoir (Fig. S3).

Instantaneous lateral fluid fluxes (q) across the island bank per unit length were calculated following the Darcy Eq. (1) (Gerecht et al., 2011; Hucks Sawyer et al., 2009):

$$q(t) = -Kb \cdot \left[\frac{\vartheta h(x,t)}{\vartheta x}\right] \quad (1)$$

where Kb is sediment transmissivity, m d^{-1}; h is hydraulic head, m; x is distance, m; and t is time, d. A positive q value indicates flow from the reservoir to the island. The island Kb was 0.99 m d^{-1}, which was measured according to Philip (1993).

2.3 Sampling and physicochemical analysis

After water level receded at the monitoring time of 100 h, groundwater (100 ml) was carefully sampled in triplicate from each monitoring well with a portable peristaltic pump (SC-1/253Yx, Chongqing Jieheng Peristaltic Pump Co., Ltd., China), and then filtered *in situ* using portable syringe filters for water DOC analysis. Sediment (5 g) was synchronously collected in triplicate from 10 cm below the surface adjacent to each well using a hand shovel, and then homogenized before the storage for the analyses of sediment OC and microbe. At a reservoir site adjacent to W1, water and surface sediment samples were also collected in triplicate using a stainless-steel bucket and an Ekman grab sampler, respectively. The collected water and sediment samples were kept frozen in an ice box (-5 ℃–-10 ℃) and transported to the laboratory for analysis within three days.

Dissolved oxygen (DO) at each well was measured *in situ* using a multi-sensor probe (YSI 6600, Yellow Springs Instruments, USA). Analysis of dissolved organic carbon (DOC) in the water was conducted on filtered samples (Whatman GF/F, UK) using a total organic carbon analyzer (Liqui TOC II, Elementar Inc., Germany). Sediment OC was determined using a vario MACRO cube elementar (Elementar Inc., Germany). Fresh sediment was freeze-dried and ground before analysis. Approximately 30 mg of each sample was weighed in a tin cup and acidified with two drops of 8 % H_3PO_4 to remove inorganic carbonates before OC analysis.

2.4 Methane flux analysis

Methane fluxes from the reservoir (eight sampling sites) and island (seventeen sampling sites) were analyzed using bifunctional chambers according to the static chamber method (Duchemin et al., 1999). The sampling sites are shown in Fig. S4. The plexiglass bifunctional chamber consisted of a 6.28-L cylinder (20 cm in diameter, 20 cm in height) and a removable Styrofoam collar. During gas collection in the reservoir, the chamber was fitted with the Styrofoam collar, which maintained the upper closed portion of the chamber about 10 cm above the water surface (Fig. S5). The outlet of the chamber was open during the chamber deployment, and was left to stand for 20 min to equilibrate with ambient pressure outside before sample collection. During gas collection on the island, the chamber was carefully inserted 5 cm deep into the sediment, leaving 15 cm above the sediment surface. The outlet of the chamber was also open during the chamber deployment, and was left to stand for 90 min to equilibrate before sample collection. Gas samples (20 ml) were collected every 10 min over a 40-min period using a 25-ml polypropylene syringe and injected into a 12-ml pre-evacuated Exetainer® vial (839 W, Labco, UK) for storage until analysis using a gas chromatograph (7890B, Agilent Technologies, USA). Gas fluxes were calculated using linear regression based on the concentration changes of five samples over time. Linear regression correlation coefficients of less than 0.95 were not accepted for further calculations (Duchemin et al., 1999). Methane fluxes at each site were measured in triplicate by placing three individual chambers. Simple spline interpolation was used to interpolate the methane emissions from the sampling sites into space in the reservoir and island separately (Immerzeel et al., 2009), and the range of the uncertain was 0.05 mg h^{-1} m^{-2}. Methane emission areas at eight different categories were also calculated in the island.

2.5 Microbial abundance analysis

After being transported to the laboratory, the frozen sediment samples were stored immediately at -80 ℃ for further molecular analysis. The sediment methanogens and methanotrophs adjacent to each monitoring well across the island (ten sediment samples) were quantified using qPCR. DNA extraction was undertaken using a FastDNA Power-Max Soil DNA Isolation Kit (MP Biomedical, USA) according to the manufacturer's instructions. The qPCR assay was performed using primers targeting methanogenic archaeal 16S rDNA (primer set, 1106F/1378R) and methanotrophic *pmoA* genes (primer set, A189F/M661R) (Watanabe et al., 2007; Ma and Lu, 2011). Gene copies were amplified and quantified in a Bio-Rad cycler equipped with the iQ5 real-time fluorescence detection system and software (version 2.0, Bio-Rad, USA). All reactions were completed in a total volume of 20 μL containing 10 μL SYBR® *Premix Ex Taq*™ (Toyobo, Japan), 0.5 mM of each primer, 0.8 μL of BSA (3 mg mL^{-1}, Sigma, USA), ddH_2O, and template DNA. The qPCR program mainly depends on the sequence and length of functional genes and primers used, and different qPCR programs for archaeal 16S rDNA and *pomA* were applied in this study. The qPCR program for archaeal 16S rDNA was as follows: 95 ℃ for 60 s, followed by 40 cycles of 95 ℃ for 25 s, 57 ℃ for 30 s, and 72 ℃ for 60 s, and the qPCR program for *pomA* referred to: 95 ℃ for 60 s, followed by 40 cycles of 95 ℃ for 25 s, 53 ℃ for 30 s, and 72 ℃ for 60 s. A standard curve was established by serial dilution (10^{-2}–10^{-8}) of known concentration plasmid DNA with the target fragment. All PCRs were run in triplicate on 96-well plates (Bio-

Rad, USA) sealed with optical-quality sealing tape (Bio-Rad, USA). Three negative controls without the DNA template were included for each PCR run.

2.6 Data analysis

One-way analysis of variance (ANOVA) was employed to test the statistical significance of differences between sampling sites. Post-hoc multiple comparisons of treatment means were performed using the Tukey's least significant difference procedure. All statistical calculations were performed using the SPSS (v22.0) statistical package for personal computers. The level of significance was $P < 0.05$ for all tests.

3 Results

3.1 Physicochemical characteristics

As shown in Fig. 2, the island groundwater had lower DO but higher DOC, compared with that of the bulk reservoir water. Lateral gradients of groundwater DO and DOC were observed in the island. From the island edge to the center, DO and DOC decreased significantly from 4.80 ± 0.19 to 0.43 ± 0.09 mg L^{-1} and 7.30 ± 0.54 to 1.70 ± 0.39 mg L^{-1}, respectively ($P < 0.05$) (Fig. 2a,b). In general, sediment OC was higher near the island edge, decreasing from 6.37 ± 0.69 mg g^{-1} at the edge to 2.42 ± 0.60 mg g^{-1} at the center of the island. Sediment OC in the reservoir was 6.63 ± 0.09 mg g^{-1} (Fig. 2c).

3.2 Water level fluctuation and hyporheic exchange

The reservoir stage fluctuated frequently during the field survey, showing three distinct peaks, with a maximum of 3.80 m in the first 37 h and gradual decline to below 1.30 m in the next 60 h, yielding a maximum oscillation of 2.54 m. Similar oscillations were observed in the island water table, but were damped and lagged relatively to the reservoir stage fluctuations (Fig. 3a). In W5, W7, and W10, the water levels reached 3.27, 3.41, and 3.33 m, then fell to 1.74, 2.09, and 2.01 m, for a maximum oscillation of 1.53, 1.33, and 1.32 m, respectively. Data from the automated water level recorders indicated that the water level responses in W5, W7, and W10 lagged the reservoir stage by 20, 25, and 30 min, respectively. Lateral hyporheic exchanges across the island bank were calculated according to the Darcy Law, showing that the flux was largest at the island edge and decreased from the edge to the center. The water exchange across the 0–10.5 m island edge zone was 1.2 and 4.7 times higher than those across the 10.5–20.5 m and 20.5–35.5 m zones, respectively. The flow rates at the reservoir-W5, W5-W7, and W7-W10 zones were relatively consistent at -0.55–1.35, -0.89–0.28, and -0.39–0.17 m^2 d^{-1} (Fig. 3b), resulting in a water exchange volume of 2.61, 2.26, and 0.56 m^3, respectively, over the 115-h observation period.

3.3 Methane emissions

High methane emission rates were observed at the island sites, with a maximum of 10.4 mg $h^{-1}m^{-2}$ at the center. However, a large ring-like low methane emission zone appeared at the drawdown area around the island edge, where the methane flux was maintained at -0.2–1.6 mg $h^{-1}m^{-2}$ (Fig. 4a). The negative flux values also suggest the occurrence of a methane sink at the island edge. The ring-like zone accounted for 89.1 % of the island area, of which 9.1 % accounted for the methane sink zone (Fig. 4b). Compared with the island, the methane flux from the adjacent reservoir was moderate at 0.4–5.5 mg $h^{-1}m^{-2}$ (Fig. 4a).

3.4 Methanogen and methanotroph abundances

Methanogens and methanotrophs were distributed non-uniformly across the island. In general, methanogen counts were low at the island edge but high at the center, whereas methanotrophs were abundant at the island edge but scarce in the center. From the island edge to the center, the methanogenic archaeal 16S rDNA gene increased from 0.12×10^5 to 5.34×10^5 copies g^{-1}, and the methanotrophic *pmoA* gene decreased from 1.57×10^6 to 0.64×10^6 copies g^{-1} (Fig. 5a). The ratio of methanogen to methanotroph abundance increased from 0.01 at the island edge to 0.83 at the center (Fig. 5b).

4 Discussion

4.1 Hyporheic exchange and oxygen gradients

In hydropower reservoirs, the release of water pulses is often employed to increase power production and meet daily electricity peak demand (Bonalumi et al., 2012; Toffolon et al., 2010). Such hydropeaking creates daily water level fluctuations in the reservoir. In this study, frequent water level fluctuations were observed within the 115-h observation period, with a maximum of 3.80 m (Fig. 3a). A hysteretic response occurred in the island bank water table (Fig. 3a), driving water exchange between the reservoir and island (Fig. 3b). The water exchange flux was largest close to the island edge and decreased from the edge to the center, as water table fluctuations were attenuated (Fig. 3a).

During a storage-release cycle, the island switched from water gaining to losing at daily or hourly scales, creating a ring-like drawdown area of enhanced hyporheic exchange around the island. The drawdown area extended tens of meters into the island bank (Fig. 3b). If the river system was unregulated, however, hydrodynamics within the drawdown area would likely exhibit seasonal or annual patterns, or keep pace with snowmelt and rainstorm events, under a natural base flow-fed regime. In this case, the drawdown area may be limited or altogether absent (Boano et al., 2008; Cardenas and Wilson, 2007).

Exchange across the sediment-water interface involves mixing of surface water and groundwater through hyporheic flow (Hester et al., 2013; Naranjo et al., 2015). In this study, when the reservoir water entered the hyporheic flow path, it was typically rich in oxygen (Fig. 2d). As oxygen was consumed through aerobic respiration, other terminal electron acceptors were utilized (Klupfel et al., 2014), creating an oxygen gradient along the hyporheic flow path (Fig. 2d). Changes in sediment moisture can speed up the mineralization of organic matter (Wang et al., 2010; Rubol et al., 2014). Groundwater DOC showed a general decrease from the island edge to center (Fig. 2e). This hyporheic exchange clearly affected biogeochemical processes, and had important effects on hyporheic microbial communities, especially oxygen-sensitive species. For example, we detected poor methanogen abundance at the island edge, but rich abundance at the center, with methanotrophs showing the opposite pattern (Fig. 5).

4.2 Spatial heterogeneity of methane emissions

In dammed rivers, riverbed sediment accumulation creates potential methane emission hotspots. In this study, however, high methane emissions were only observed at the island center, with a ring-like low methane emission zone or even methane sink appearing around the island edge (Fig. 4a). This was attributed to the spatial heterogeneity of methanogens and methanotrophs across the island (Fig. 5), leading to an increase in methane production and a decrease in methane consumption from the island edge to the center. The methane sink at the island edge (Fig. 4) was mainly attributed to the strong oxidation by methanotrophs, which may consume methane to below equilibrium with the atmosphere. Methane emissions may not only rely on bacterial abundance but also bacterial activity (Schwarz et al., 2008). This deserves further studies using other molecular biology techniques, such as DNA/RNA-based stable isotope probing (Dumont and Murrell, 2005).

Groundwater DOC and sediment OC at the island edge, which are carbon sources for methane emission, were higher than that at the island center (Fig. 2b,c), suggesting that both sediment heterogeneity and dilution effects of hyporheic exchange had limited contribution to the spatial pattern of methane emissions in the island. Hyporheic exchange effectively shifted oxygen gradients across the island, resulting in substantial mitigation of potential methane emissions. In this study, only 0.2 % of the island area maintained a high methane flux (9.6–11.2 mg $h^{-1}m^{-2}$) (Fig. 4b), suggesting that methane emissions across the small island were attenuated, but only in the drawdown area where hyporheic exchange occurred.

4.3 Implications

Greenhouse gas emissions significantly detract from the green credentials of hydropower, and have thus received considerable research attention (Giles, 2006; Hu and Cheng, 2013). Previous studies have revealed that damming causes significant retention of carbon and creates deep, anoxic sediment strata, fueling methanogenesis and net water-air methane flux (Maeck et al., 2013). This study demonstrated that methane emissions at the most area of the sediment-deposited island were generally lower than the adjacent reservoir under reservoir operation (Fig. 4a), but higher than the drawdown area at other reservoir bank, such as Three Gorge Reservoir (Chen et al., 2011). This was mainly due to the deep sediment strata (about 60 m in depth) in the island. Given the widely distributed sediment-deposited islands in reservoirs, it should be of concern in future estimations of greenhouse gas emissions from dammed rivers. Prospective studies should assess the quantitative relationship between methane emissions from the drawdown area and hydropower operation scenarios.

Until now, few studies have concentrated on organic carbon mineralization in the drawdown area in reservoirs, with most focusing on the process of denitrification (Zarnetske et al., 2011b). Carbon emissions in the drawdown area are poorly understood, especially in regulated and dammed rivers. This study fills the knowledge gap and adds to our understanding of the ecological impacts of hydropower exploitation. Under reservoir operation, variable oxygen conditions and methane production may also affect the mercury cycle in the drawdown area and thereby the release of methylmercury (a bioaccumulative environmental toxicant) to the river (Marvin-DiPasquale et al., 2009), a subject deserving of further study.

5 Conclusions

In dammed rivers, sediment deposited islands are widely distributed in sidebays and are potential hotspots of methane emission to the atmosphere. In this study, high methane fluxes were only observed at the island center, while a ring-like zone of low methane emission or even sink was found in the drawdown area around the island edge. We attribute this spatial heterogeneity of methane emissions to hyporheic exchange between the reservoir and island. Under reservoir operation, frequent water level fluctuations drove hyporheic exchange, creating oxygen gradients along the hyporheic flowpath. These oxygen gradients affected the microbial communities associated with methane production and consumption, producing the spatial heterogeneity in methane emissions across sediment-deposited islands. This study will help us to evaluate the global warming effects of hydropower systems.

Data availability

The data presented here can be obtained upon request to Wenqing Shi (wqshi@nhri.cn).

Author contribution

Qiuwen Chen designed the research; Wenqing Shi, Yuyu Ji and Yuchen Chen performed the research; Cheng Chen and Juhua Yu contributed new reagents/analytic tools; Qiuwen Chen and Wenqing Shi analyzed the data; Jianyun Zhang and Bryce R. Van Dam contributed significant discussions and inputs; Wenqing Shi and Qiuwen Chen wrote the paper with input from all authors.

Competing interests

The authors declare that they have no conflict of interest.

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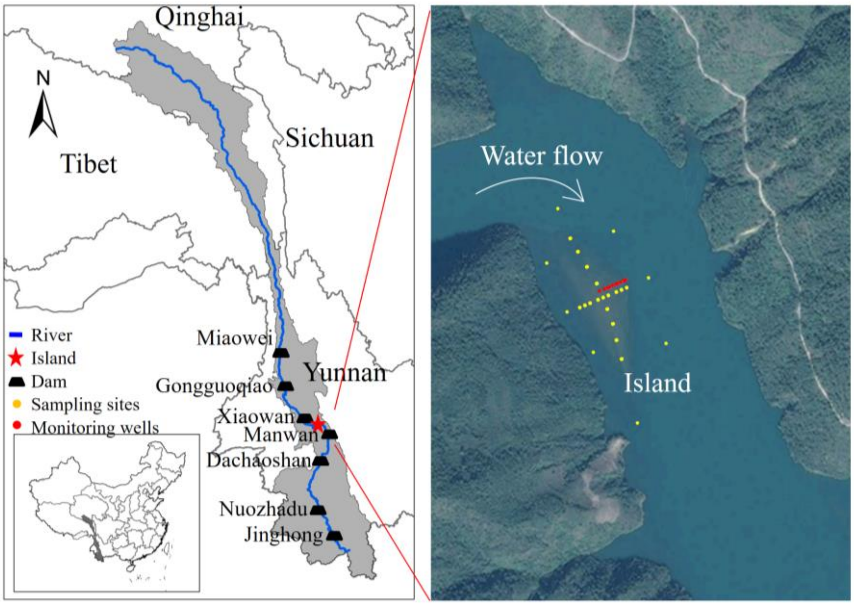

Fig. 1 Map of the studied island in Manwan reservoir, Lancang-Mekong River.

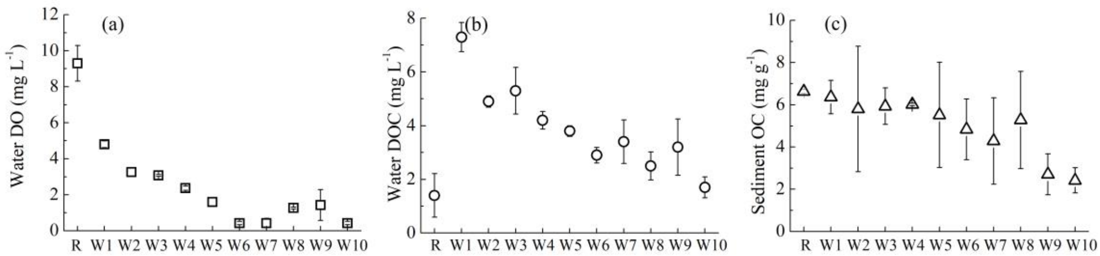

Fig. 2 Physicochemical properties of the island and reservoir, including water (a) DO, (b) DOC, and (c) sediment OC. DO = dissolved oxygen, DOC = dissolved oxygen carbon, OC = organic carbon, R = reservoir, W = monitoring wells. Error bars indicate standard deviations.

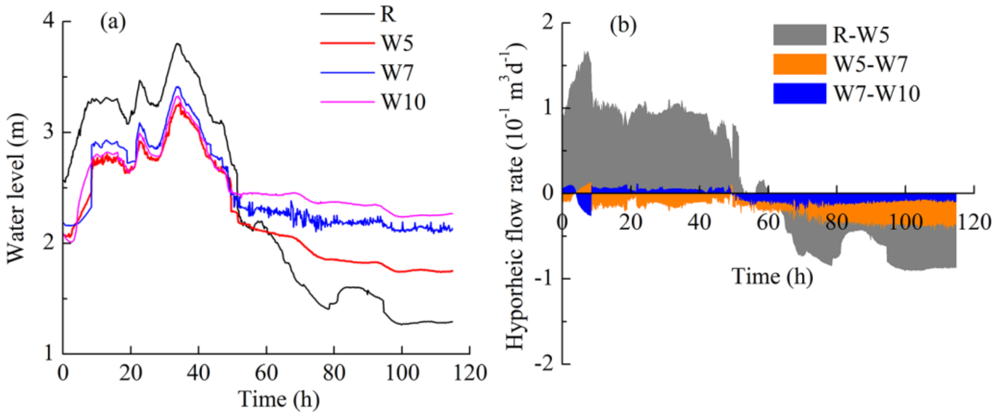

Fig. 3 Vertical water level fluctuation (a) and horizontal hyporheic flow rate (b). R = reservoir, W = monitoring wells. Positive fluxes indicate net flow from the reservoir to island, whereas negative values indicate net flow from the island to reservoir.

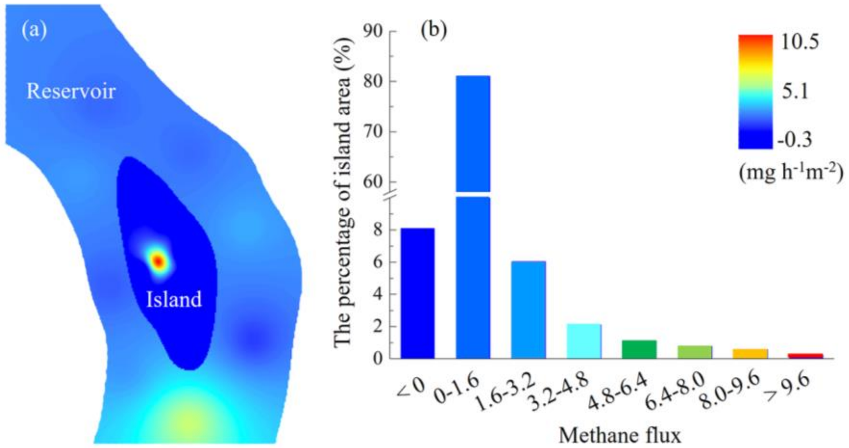

Fig. 4 Methane emissions from the island and reservoir. (a) Spatial pattern of methane emissions; (b) Percentage of the island area emitting methane at a certain flux. Methane fluxes were interpolated separately for the island and reservoir.

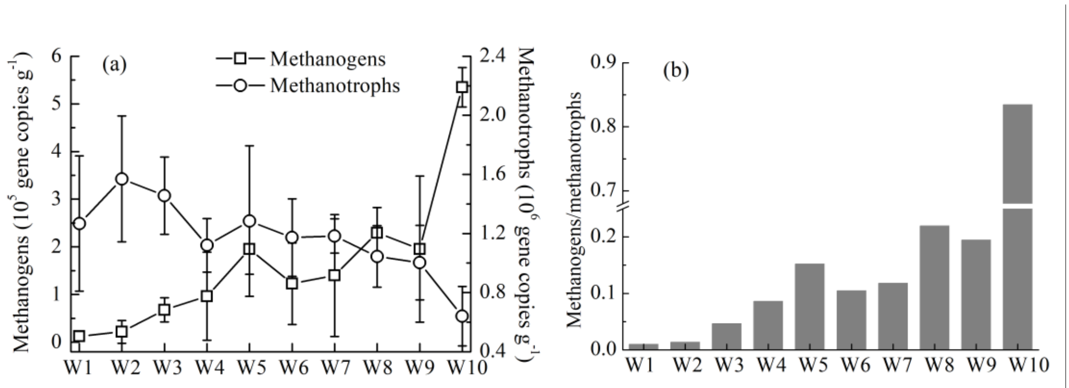

Fig. 5 Abundances of sediment methanogens and methanotrophs in the island. (a) Spatial patterns of methanogen and methanotroph abundances across the island; (b) The ratio of methanogen to methanotroph abundance at each site. W= monitoring wells. Error bars indicate standard deviations.