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Original paper

Methane emissions from the shallow water zone of the Kuibyshev Reservoir: a floating chamber study

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ABSTRACT

Relevance. Freshwater ecosystems, including reservoirs, contribute significantly to the global emissions of the greenhouse gas methane (CH_4). Shallow-water reservoir zones are considered emission "hotspots"; however, their contribution to the carbon budget of large reservoirs, such as the Kuibyshev Reservoir, has not been sufficiently quantified. **Methods.** A quantitative assessment of specific CH_4 fluxes in the shallow-water zone of the Kuibyshev Reservoir was performed during the summer–autumn period of 2024 using the floating chamber method. CH_4 concentrations were determined using a Nexis GC-2030 gas chromatograph. Measurements were conducted at two contrasting stations: an open shallow-water area (Station 1) and a semi-enclosed channel with slow water exchange (Station 2). Hydrophysical and physicochemical parameters were recorded concurrently, and sediment samples were collected for particle size and organic matter analysis. **Results.** High spatial variability of CH_4 fluxes was revealed. The average emission at the open shallow-water station was 22.9 ± 3.5 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$, while in the semi-enclosed channel, it was an order of magnitude higher (231.8 ± 50.3 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$). The maximum values (up to 623.5 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) were recorded in July and are associated with ebullition against the background of near-bottom hypoxia (< 0.5 mg $O_2 \cdot dm^{-3}$). Shallow isolated bays, despite their small area, contribute disproportionately to the total CH_4 emissions from the reservoir surface. This phenomenon is driven by a combination of factors: specific morphometry promoting thermal and oxygen stratification, as well as accumulation of silty sediments enriched with organic matter. Accurate assessment of the carbon footprint of large reservoirs requires targeted monitoring of such "hotspots", which should be taken into account when developing regional and national carbon budgets.

KEYWORDS: greenhouse gases, emission, methane, CH_4, Kuibyshev Reservoir, floating chambers, shallow-water zone, ebullition, diffusive flux, carbon cycle, emission hotspots

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INTRODUCTION

Freshwater ecosystems make a significant and still being clarified contribution to global methane (CH_4) emissions [1]. According to current estimates, their emissions may exceed direct anthropogenic sources related to agriculture or the energy sector [2]. Reservoirs – artificial bodies created by regulating rivers – occupy a special place among freshwater systems. They are active centers of organic matter transformation, where anaerobic decomposition processes in bottom sediments lead to formation of CH_4 [3, 4]. Recent data show that lakes and reservoirs account for about 10 % of global CH_4 emissions, with the potential to increase by 24–91 % by the end of the century depending on the climate change scenario [5]; at the same time, the methanogenesis potential in reservoir sediments may be many times higher than that in lakes and rivers [6].

CH_4 emissions from reservoirs into the atmosphere occur through several main pathways: diffusive and ebullitive fluxes, degassing via turbines and dam spillways, as well as emissions mediated by aquatic plants [7]. In shallow-water zones, characterized by intense heating and organic matter input, the dominant mechanism is often ebullition, leading to significant spatial and temporal variability in fluxes [8]. While global experience in studying CH_4 emissions from reservoirs is extensive, in Russia, which has a significant number of such water bodies, data on CH_4 fluxes remain fragmentary [9] and insufficient for developing accurate regional and national estimates [10].

The Kuibyshev Reservoir, the largest in the cascade and one of the largest in the world, is a significant potential source of greenhouse gases in the region [11], especially given the observed climate changes in its basin [12]. Despite early synthesis studies of CH_4 emissions in the Volga reservoirs [13], quantitative estimates specific to the shallow-water zones of the Kuibyshev Reservoir and based on direct measurements remain few. The high spatial and temporal variability of fluxes characteristic of these areas requires more frequent observations to collect representative data. Research conducted within the Volga Carbon Polygon is aimed at filling this gap [14].

The aim of this study was to quantify the specific CH_4 fluxes from the shallow-water zone of the Kuibyshev Reservoir using the floating chamber method. The objectives included assessing the spatial and temporal dynamics of CH_4 fluxes at two stations, evaluating the influence of hydrophysical and hydrochemical parameters (temperature and dissolved oxygen concentration), and identifying potential CH_4 emission mechanisms (diffusive and ebullitive fluxes).

METHODS AND RESEARCH

The Kuibyshev Reservoir is located in the Middle Volga and the Lower Kama regions of European Russia (Fig. 1). It was formed in 1955–1957 following the construction of the Zhiguli Hydroelectric Power Plant (HPP) dam on the Volga River.

The reservoir has a complex configuration with a surface area of 5,900 km^2 and a total volume of 57.3 km^3, and is characterized by seasonal discharge regulation. The shallow-water zone of the reservoir is highly dynamic [15].

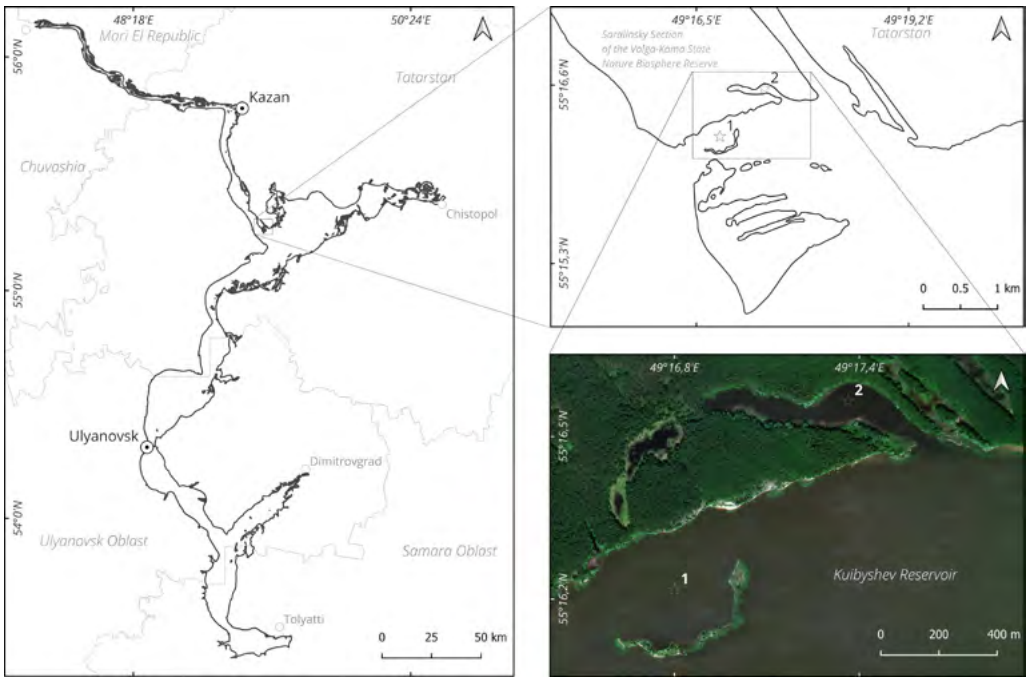


Fig. 1. Map showing the monitoring stations in the shallow-water zone of the Kuibyshev Reservoir: (a) overview of the region; (b) water area of the Volga Carbon Polygon. Station numbers: 1 – open shallow water; 2 – semi-enclosed channel.

The research was conducted from June to September 2024 at two stations within the water area of the Volga Carbon Polygon (Fig. 1). Station 1 (55°16′12″N, 49°16′52″E) is located in an open shallow water zone (depth 2–4 m), exposed to wind and wave action. Station 2 (55°16′34″N, 49°17′21″E) is located in a semi-enclosed channel (depth 1–4 m), with banks completely covered by macrophytes.

To characterize the sediments, surface layer samples were collected using a Zabolotsky rod sampler, while deep-water areas were sampled with a DAK-250 box corer. Particle size distribution was determined using a Bluewave analyzer (Microtrac, USA). The organic matter content was estimated by loss on ignition (LOI, %). A total of 46 samples were collected during the study period: 12 at Station 1 and 34 at Station 2.

Specific CH_4 fluxes were determined using the floating chamber method [16, 17]. At each station, three to ten chambers were deployed monthly, evenly distributed across the water area. Measurements were conducted from a boat during day-

light hours (10:00 to 15:00 local time, UTC+3). The floating plastic chambers had a volume of 0.008 m^3 and an enclosed surface area of 0.075 m^2 (Fig. 2). Buoyancy and stability were provided by a foamed polyethylene float around the chamber perimeter; upon deployment, the chamber edges were submerged 2 cm below the water level. To prevent solar heating, the chambers were shielded with aluminum foil. Each chamber was equipped with a sampling port with a rubber stopper and a protective filter, connected to a 50-cm PVC tube (4 mm outer diameter) and a Luer-lock stopcock.

Before the exposure began, the entire sampling line was purged with ambient air to remove residual gases. Each chamber was held in place by an individual anchor via a separate float, which served as a buffer and stabilizer. This design eliminated the direct mechanical impact of the anchor on the sediments in the measurement zone, preventing the artificial emission of methane bubbles into the chamber.

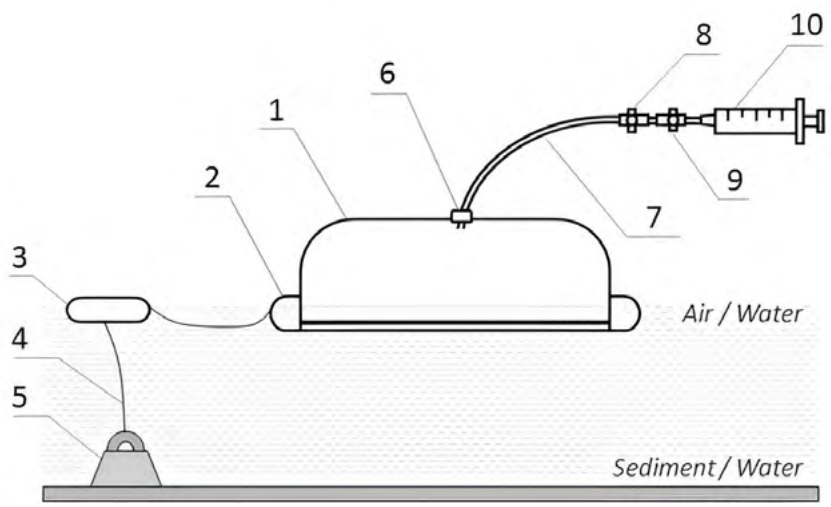


Fig. 2. Floating chamber design for CH_4 flux measurement: 1 – floating chamber body; 2 – peripheral float; 3 – additional float; 4 – connecting line; 5 – anchor; 6 – rubber seal; 7 – PVC tube; 8 and 9 – three-way stopcock with a Luer-lock connection; 10 – polypropylene syringe for headspace gas sampling (not to scale).

At each station, the chambers were deployed simultaneously for 30–60 min. Gas samples (100 mL) were collected at the beginning (t_0) and end (t_1) of the exposure using 150-mL polypropylene syringes equipped with a three-way stopcock. Before collecting the final sample, the headspace air was homogenized by pumping it five times through the attached syringe.

Concurrently with gas sampling, we recorded coordinates and depth at the deployment points (Humminbird 597cxi HD DI Combo echo sounder/chartplotter, USA), as well as temperature and dissolved oxygen (DO) concentration in the surface and near-bottom water layers (MARK-303E oximeter, Russia). Meteorological data were obtained from the nearest weather station.

CH_4 analysis was performed within 24 h of collection using a Nexis GC-2030 gas chromatograph (Shimadzu, Japan) equipped with an HS-20 headspace sampler and LabSolutions software. Gas samples were transferred from the sampling syringes into 20-mL glass chromatographic vials (sealed with butyl rubber stoppers and aluminum crimp caps) by water displacement in a vessel filled with degassed distilled water.

Components were separated on an Rt-Q-BOND PLOT capillary column (Restek, USA; 30 m × 0.53 mm ID × 20 μm film thickness). The CH_4 concentration (ppm) was detected using a flame ionization detector (FID). Helium (99.9999 % purity) was used as the carrier gas at a flow rate of 10 mL·min^{-1}. The sample injection volume was 10 μL, with a total analysis time of 5 min per sample.

The specific CH_4 flux (F_{CH4}, mg CH_4·m^{-2}·day^{-1}) was calculated based on the change in its concentration in the chamber during exposure using the formula:

$$F_{CH_4} = \frac{\Delta C \times V \times P \times M}{\Delta t \times A \times R \times T},$$

where $\Delta C/\Delta t$ is the rate of CH_4 concentration change in the chamber (ppm·h^{-1});
V is the volume of the chamber (0.008 m^3);
A is the enclosed water surface area (0.075 m^2);
P is the atmospheric pressure (Pa);
M is the molar mass of CH_4 (16.04 g·mol^{-1});
R is the universal gas constant (8.3145 m^3·Pa·K^{-1}·mol^{-1});
T is the air temperature (K).

The formula includes the following coefficients: 10^{-6} to convert ppm into dimensionless units, 24 to convert the hourly fluxes to the daily values, and 1,000 to express the results in milligrams. A total of 41 chamber experiments were conducted during the study period.

Statistical analysis was performed using Statistica 10 (StatSoft, USA), including Spearman's rank correlation (r_S). Results with $p < 0.05$ were considered statistically significant. Unless otherwise specified, data are presented as mean ± standard error (SE). By convention, positive flux values represent CH_4 emission from the water into the atmosphere.

RESULTS AND DISCUSSION

The results demonstrate high spatial and temporal variability of CH_4 emissions in the shallow-water zone of the Kuibyshev Reservoir (Table). At Station 1, located in the open shallow-water zone, the CH_4 specific flux ranged from 0 to 74.1 mg CH_4·m^{-2}·day^{-1}, averaging 22.9 ± 3.5 mg CH_4·m^{-2}·day^{-1} over the entire study period. In contrast, at Station 2, in the semi-enclosed vegetated channel, the average CH_4 specific flux was an order of magnitude higher (231.8 ± 50.3 mg CH_4·m^{-2}·day^{-1}) and varied over a wider range, from 10.2 to 623.5 mg CH_4·m^{-2}·day^{-1}.

Table. Specific CH_4 fluxes (mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) at the monitoring stations in the shallow-water zone of the Kuibyshev Reservoir

Station (*n*)	Sampling date	Mean	Median	Range	SD	SE
2 (9) *	30.06.2024	76.9	61.5	10.2–190.9	72.1	24.0
1 (3)	10.07.2024	41.1	30.7	18.6–74.1	29.2	16.8
2 (4)	10.07.2024	573.8	576.5	518.8–623.5	51.7	25.9
1 (10)	20.08.2024	21.1	15.0	8.4–40.1	13.8	4.4
2 (5)	20.08.2024	236.9	266.5	122.1–368.9	99.4	44.5
1 (8)	27.09.2024	18.4	18.3	0.0–29.4	9.7	3.4
1 (21)	10.07–27.09	22.9	18.6	0.0–74.1	16.2	3.5
2 (18)	30.06–20.08	231.8	172.6	10.2–623.5	213.2	50.3
1–2 (39)	30.06–27.09	119.3	33.8	0.0–623.5	177.8	28.5

Note: *n* is the number of chambers. * – in June, chambers at Station 2 were installed in the littoral zone within macrophyte stands; in subsequent months, measurements were conducted in the channel water area at a distance from the shore. Station 1 was located in the open shallow-water zone at all study stages. For periods (e.g., 10.07–27.09), statistics include all measurements. SD – standard deviation; SE – standard error of the mean.

Parallel measurements revealed significant differences in environmental conditions at the stations, which coincided with the periods of peak CH_4 emissions. In July, when peak fluxes were recorded, the water surface temperature at the stations reached 26.5–27.2 °C; thermal and oxygen stratification was observed at Station 2. The bottom water temperature (depth 4 m) dropped to 19.9 °C, while dissolved oxygen concentration was only 0.2 $mg \cdot dm^{-3}$, creating near-bottom anaerobic conditions conducive to methanogenesis. At the same time, at Station 1, the oxygen regime at a similar depth was significantly more favorable; with DO concentrations being 9.6 $mg \cdot dm^{-3}$ at the surface and 5.7 $mg \cdot dm^{-3}$ at the bottom.

To determine the driving factors of CH_4 emissions, a correlation analysis was performed. At Station 2, statistically significant strong correlations were found: CH_4 flux showed a positive correlation with depth ($r_S = 0.743$, $p < 0.001$) and surface DO concentration ($r_S = 0.798$, $p < 0.001$), as well as a strong negative correlation with bottom DO concentration ($r_S = -0.818$, $p < 0.001$). No significant correlations with hydrophysical and hydrochemical parameters were found at Station 1. For the combined sample ($n = 39$), a significant negative correlation of CH_4 flux with bottom DO concentration was confirmed ($r_S = -0.692$, $p < 0.001$).

The maximum emission values at both stations were recorded in July. During this period, the absolute maximum of the series was observed at Station 2: 623.5 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$. During the study period, two abnormally high flux values were also recorded, which were not taken into account when calculating the average values in

the Table due to their extreme and stochastic nature: 271.6 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$ at Station 1 in July and 4.82 g $CH_4 \cdot m^{-2} \cdot day^{-1}$ at Station 2 in August. Both cases were probably related to ebullition episodes.

Differences in the emission regime between the stations were also confirmed by direct field observations. At Station 2, along with high and extreme flux values, the release of gas bubbles at the water surface was regularly observed visually, providing direct evidence of a significant contribution from ebullition. No such phenomena were observed at Station 1, which corresponds to the lower and more stable fluxes characteristics of diffusive transport.

Any reservoir is a complex natural-anthropogenic system in which the processes of greenhouse gas emission and sink depend on the interaction of multiple factors. The hydrological, physicochemical, and biological characteristics of a reservoir significantly impact gas exchange, forming spatiotemporal patterns of greenhouse gas fluxes. These patterns reflect the complex interaction of ecosystem processes, including water-level fluctuations, temperature gradients, and biological productivity [18, 19]. Among these factors, the morphometric features of the reservoir, thermal and oxygen regimes, as well as its trophic status, are of particular importance [20]. The combined effect of these parameters controls fundamental carbon cycle processes: organic matter decomposition (including anaerobic methanogenesis) and CH_4 oxidation (mainly aerobic methanotrophy), and diffusive and turbulent gas transfer across the air–water interface. Their effect can be both direct, such as the stimulation of methanogenesis under oxygen deficiency, and indirect, mediated by changes in related physicochemical and biological processes.

The study revealed significant spatial and temporal variability in CH_4 emissions in the shallow-water zone of the Kuibyshev Reservoir. The observed patterns are shaped by local environmental conditions and are generally consistent with data on reservoirs of the Volga-Kama Cascade [13] and temperate water bodies in general [2].

The significant difference in fluxes between the stations is due to a complex of factors, the key of which is likely the DO regime. This finds direct statistical support: at Station 2, CH_4 flux showed a strong negative correlation with bottom DO concentration ($r_S = -0.814$, $p < 0.001$); for the combined sample at both stations, this relationship also remained significant and strong ($r_S = -0.715$, $p < 0.001$). The pronounced near-bottom hypoxia (≤ 0.5 $mg \cdot dm^{-3}$) at Station 2 created favorable conditions for methanogenesis, which is fully consistent with the established role of anoxia in intensifying methanogenesis [21]; combined with water heating, this led to peak emission values. Summer warming not only reduces CH_4 solubility but also directly stimulates CH_4 production in sediments [22], creating a dual effect. In contrast, a more favorable DO regime at Station 1 (5.7 $mg \cdot dm^{-3}$ at the bottom) not only acted as a natural limiter of methanogenic archaea activity, but also promoted aerobic oxidation of CH_4 in the water column. This process, during which methanotrophic mi-

croorganisms effectively reduce CH_4 emissions by oxidizing it to CO_2 [23], plays a crucial role in reducing net CH_4 emissions in shallow waters bodies [24].

Thus, the DO regime, acting as the main limiting factor, directly regulates the composition and function of the microbial community and ultimately determines the balance between CH_4 production and oxidation in the water column [25]. The existing gradient of conditions clearly demonstrates how local features can form neighboring "hotspots" and zones of moderate emissions within the same water area.

The morphometric features of the sites, which predetermine differences in their hydrodynamic and trophic regimes, played a significant role in the observed contrast. The semi-enclosed channel at Station 2, representing a flooded inter-ridge depression of the floodplain protected by woody vegetation from wind and wave action, contributes to the accumulation of silty sediments rich in organic matter. The positive correlation between CH_4 flux and depth at Station 2 (r_S = 0.743, p < 0.001) indirectly indicates the role of morphometry, reflecting increased stratification and anoxia in the deeper parts of the channel. Limited water exchange with the main part of the reservoir and reduced water circulation under such morphological conditions favor the development of stable stratification and near-bottom oxygen deficiency [16], thereby creating a set of prerequisites for intensive methanogenesis. Moreover, the accumulation of organic matter, serving as a substrate, forms a positive feedback: its decomposition under anaerobic conditions enhances CH_4 emissions [3, 26].

In contrast, the open water area of Station 1 is subject to wind-driven mixing and characterized by a flushing regime, intensive aeration, and sandy sediments. As shown in studies of the Volga-Kama Cascade reservoirs, under conditions of constant water mixing, aerobic CH_4 oxidation proceed stably, almost independently of fluctuations in the DO regime [27]. These conditions do not favor the accumulation of organic matter and, importantly, contribute to aerobic CH_4 oxidation both in the water column and in the sediments [24] effectively reducing emissions. Consequently, the morphometry of reservoir areas acts as an important factor influencing CH_4 emission through its control over organic matter accumulation and the formation of local DO regime.

The influence of morphometry on organic matter accumulation is confirmed by sediment survey results. At Station 2, silty sediments prevailed, with a high organic matter content (LOI: 1.2–16.3 %, median 8.5 %) and a significant proportion of the pelitic fraction (< 0.01 mm), averaging 11.5 ± 6 %. In the near-shore zone of this station, sediments were additionally enriched with leaf litter and undecomposed macrophyte remains. This is fully consistent with the relationship established for the Kuibyshev Reservoir, according to which organic matter content naturally increases in the "sand → silty sand → silt" series, with the main part of organic carbon concentrated in fine-grained fractions [28]. Such silty, organically enriched sediments are zones of maximum potential methanogenic activity in the Volga-Kama Cascade

reservoirs [3]. In our case, sand and silty sand with a low organic matter content prevailed at Station 1 (LOI: 1.0–9.6 %, median 1.4 %), which is typical for the open-water areas of the reservoir and leads to a predominantly diffusive emission pathway.

Special attention should be paid to the potential contribution of aquatic vegetation to the total emission at Station 2. The rather high flux recorded in June in the littoral zone overgrown with reeds (*Phragmites australis* (Cav.) Trin. ex Steud.) may be associated not only with ebullition and diffusion from the water column, but also with additional methane input mediated by plants. Although the technique used does not allow directly quantifying these pathways, positioning the chambers near macrophyte stands theoretically made it possible to capture the integrated flux, which could include both methane diffusion from underwater plants parts and, potentially, direct emission near the stem bases. In addition to this possible direct effect, the presence of vegetation could indirectly increase emissions by creating an additional substrate for methanogenesis via root exudates and detritus [29], as well as by trapping and accumulating allochthonous organic matter from the catchment area in the near-shore zone [4].

In reservoirs of the Volga-Kama Cascade, the mass die-off of macrophytes in late summer leads to a pronounced peak in methanogenesis within the sediments of the vegetated littoral zone [27]. It should be noted that labile organic matter of this type, in contrast to recalcitrant leaf litter from terrestrial trees, is considered a main factor stimulating the activity of methanogenic archaea in sediments [30]. Moreover, studies show that reeds can actively transport gases internally (via so-called pressurized flow), which may make them a particularly effective conduit for methane transfer from sediments to the atmosphere [31]. Thus, macrophytes are potentially significant factor that can influence emissions through a complex of direct and indirect mechanisms, highlighting the need for targeted study in future research on the gas balance of reservoir shallow waters.

The differences revealed in hydrophysical, physicochemical, and morphometric conditions predetermine the dominance of various emission mechanisms at the sampling sites. A combination of several independent indicators – significantly higher and more variable fluxes, visually observed bubble release, and extreme point emissions (up to 4.82 g $CH_4 \cdot m^{-2} \cdot day^{-1}$) – clearly indicates the predominance of ebullition at Station 2. Our data clearly illustrate the concept that most of the ebullitive flux is provided by a small number of large, stochastic events [32]. This highlights the high risk of underestimating emissions under insufficient sampling frequency, since the inadvertent exclusion of such "hotspots" can lead to a significant underestimation of total emissions. At Station 1, where the fluxes were moderate and stable, the CH_4 diffusive pathway most likely prevailed.

Our data are consistent with the emission patterns typical of both the main water area (1.5–71.3 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) and the floodplain areas and bays (up to 304–651 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) of the Kuibyshev Reservoir [13]. The maximum fluxes

observed at Station 2 (~624 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) are close to the values recorded in the Cheremshansky Bay, which is also characterized by summer hypoxia caused by density stratification. This confirms that shallow, isolated, and stratified areas can be key sources of spatial variability and likely make a significant contribution to the overall CH_4 emission budget. Moreover, the morphology of Station 2 (a semi-enclosed channel/bay) is typical of the reservoir shoreline, where isolated bays formed by the flooding of erosional landforms are widespread [3]. The similarity of the emission regimes between Station 2 and other isolated basins suggests that shallow embayments subject to seasonal stratification represent a widespread type of "hotspots", and the revealed "stratification – hypoxia – methanogenesis" relationship may be universal for such systems.

The flux ranges for the Kuibyshev Reservoir (0–623.5 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) correspond to global data [2] for mesotrophic (4.3–392.0 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) and eutrophic (6.4–2296.5 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$) reservoirs. At the same time, the maximum emission values, probably associated with ebullitive transport, fall well within the range typical for ebullition in eutrophic reservoirs (0.0–734.3 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$). This makes it possible to consider the CH_4 emission regime of the Kuibyshev Reservoir typical of reservoirs in its class.

Comparability of data obtained by fundamentally different methods provides important confirmation of the reliability of emission estimates [1]. For instance, eddy covariance measurements conducted at Station 1 (mean ± standard deviation) showed average fluxes of 52.84 ± 22.49 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$ in August and 47.53 ± 27.06 $CH_4 \cdot m^{-2} \cdot day^{-1}$ in September 2024 [11]. These data agree well with the results recorded using the floating chamber method during the same months (up to 40.1 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$). The consistency between the point-based chamber method and integrative eddy covariance approach confirms the validity of our findings.

CONCLUSION

The floating chamber study allowed for the quantification of CH_4 emissions in the shallow-water zone of the Kuibyshev Reservoir and the identification of their key controlling factors. The study confirmed the hypothesis of extremely high spatial heterogeneity in CH_4 fluxes. The presence within a single water area of sites with emissions differing by an order of magnitude (from ~23 to ~232 mg $CH_4 \cdot m^{-2} \cdot day^{-1}$ on average) demonstrates the impossibility of simple extrapolation of point measurements to the entire reservoir without taking into account the biotope type.

The dominant factor determining emission intensity is the DO regime, which, in turn, is closely related to the morphometry and hydrodynamics of the site. Isolated, stratified, and organically enriched shallow waters (such as channels and bays) are "hotspots" of CH_4 emission where ebullition dominates. Our data confirm that to accurately assess the carbon footprint of large lowland reservoirs, in addition to the

main water area, it is necessary to conduct targeted monitoring of shallow-water zones, especially areas with signs of stratification and hypoxia.

Future research should include diel measurement dynamics, the quantitative partitioning of emission pathways (diffusion, ebullition, and transport via vascular plants), and the scaling of findings using GIS technologies and remote sensing to build a more accurate CH_4 emission map for the entire reservoir area.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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