



Groundwater Discharge: A Major Driver of Global Methane Emissions from Aquatic Environments

Rea Camile Maglaya¹ · Mahmood Sadat-Noori¹ · Martin S. Andersen²

Received: 23 May 2025 / Revised: 8 August 2025 / Accepted: 14 August 2025
© The Author(s) 2025

Abstract

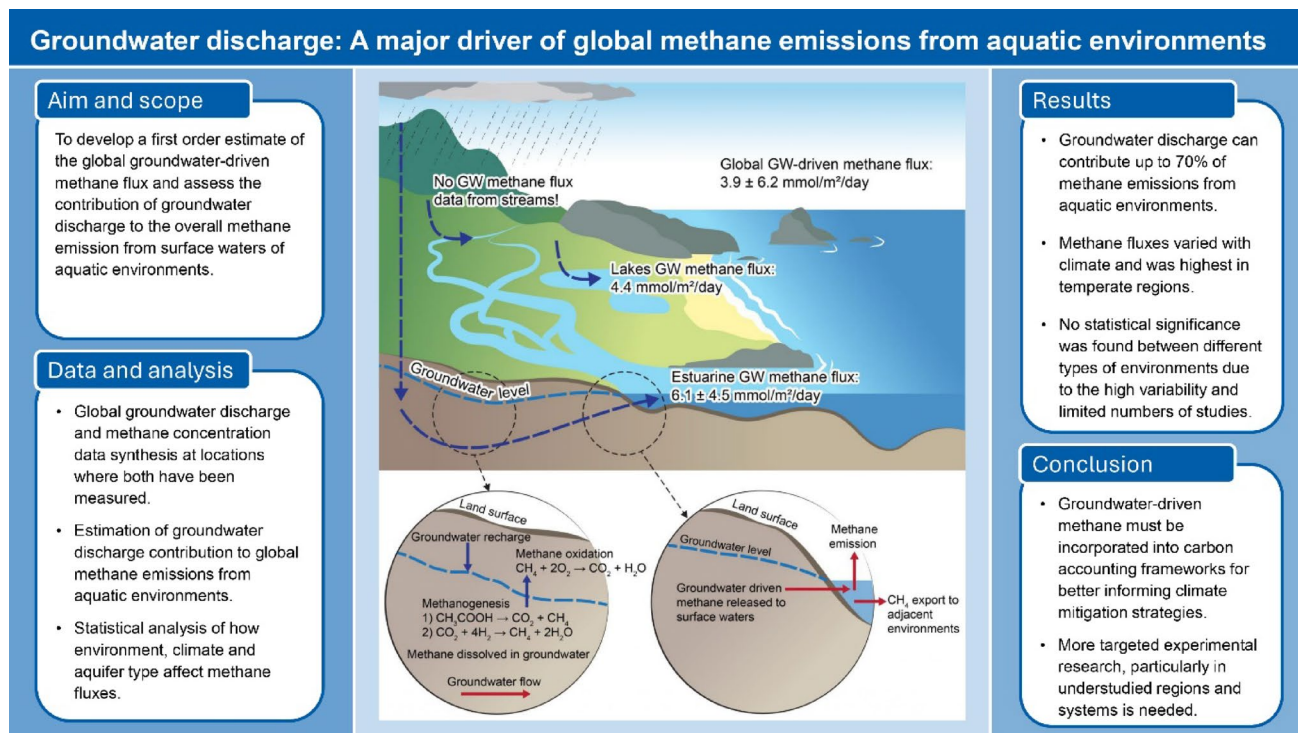
Methane is a potent greenhouse gas, and aquatic environments such as wetlands, lakes, rivers, and estuaries are recognized as significant natural sources of methane emissions. However, a major gap in current methane budgets is the limited understanding of methane contributions from groundwater–surface water interactions. Groundwater discharge has often been overlooked in methane budgets due to the difficulty of detecting and quantifying both discharge rates and the associated methane fluxes. This study addresses this gap by synthesizing global literature to estimate groundwater methane concentrations and fluxes across various aquatic environments. A systematic review of peer-reviewed literature from 2011 to 2023 was conducted, synthesizing data on groundwater methane concentrations, discharge rates, and environmental factors across diverse aquatic environments. These data were subsequently integrated with global groundwater discharge estimates to quantify methane fluxes, thereby advancing current understanding of groundwater contributions to aquatic methane emissions and their potential role in the global carbon cycle. The main findings are as follows: (1) The average global groundwater methane concentration was 0.31 ± 0.47 mmol/L. (2) The global average groundwater-driven methane flux was estimated to be 3.9 ± 6.2 mmol/m²/day. (3) When extrapolated globally using existing estimates of groundwater discharge, these fluxes suggest that groundwater may account for up to 70% of methane emissions from surface waters in aquatic systems. (4) In some environments, groundwater-driven methane fluxes exceed direct surface water–atmosphere methane emissions by several fold, particularly in subarctic and temperate regions. This significant groundwater contribution has been largely unrecognized in global methane budgets and climate models. Findings indicate a lack of studies quantifying groundwater-driven methane fluxes (or providing concurrent data on groundwater methane concentrations and groundwater discharge), particularly in streams. Incorporating groundwater-driven methane into carbon accounting frameworks is essential for improving the accuracy of methane emission estimates and for better informing climate mitigation strategies. Further empirical studies are needed to reduce uncertainty and address current data gaps across geographic regions and aquifer types.

✉ Mahmood Sadat-Noori
mahmood.sadatnoori@jcu.edu.au

¹ College of Science and Engineering, James Cook University, Townsville, QLD 4810, Australia

² Water Research Laboratory, School of Civil & Environmental Engineering, UNSW, Sydney, NSW 2052, Australia

Graphical Abstract



Methane, a potent greenhouse gas, is emitted directly to the atmosphere from aquatic environments like wetlands, lakes, rivers, and estuaries, yet the contribution from groundwater discharge to these emissions remain poorly understood, a gap this study addresses. The graphical abstract illustrates the formation of methane in anaerobic groundwater systems, followed by its discharge into aquatic environments, and release to the atmosphere. Arrows link these hydrogeological and biogeochemical processes. This study, synthesizing global literature from 2011 to 2023, estimates groundwater methane concentrations and fluxes, revealing a global average groundwater methane concentration of 0.31 ± 0.47 mmol/L and a global groundwater driven methane flux of 3.9 ± 6.2 mmol/m²/day. A key finding is that groundwater discharge may contribute up to 70% of methane emissions from aquatic environments, with fluxes exceeding surface water emissions by up to 6 times, especially in subarctic and temperate regions. The role of groundwater discharge in methane budgets has been largely unrecognized, while this study clearly shows the need for its integration into carbon accounting frameworks.

Highlights

- Groundwater discharge may contribute up to 70% of methane emissions from aquatic environments.
- Estimated global groundwater-driven methane flux to coastal environments is 3.9 ± 6.2 mmol/m²/day.
- Methane flux from groundwater can exceed surface water emissions by up to 6 times.
- Sediment type and climate potentially influence groundwater methane flux and concentration.
- Data on groundwater-derived methane fluxes in aquatic environments remain scarce, with streams being particularly underrepresented.

Keywords Greenhouse gases · Carbon cycling · Submarine groundwater discharge · Carbon budget

1 Introduction

Understanding the sources and processes that lead to greenhouse gas emissions is essential for addressing challenges related climate change. Methane (CH₄), the second most prevalent greenhouse gas in the Earth's atmosphere after

carbon dioxide, plays a significant role in shaping our planet's climate (Montzka et al. 2011; Shindell et al. 2009). Methane emissions stem from both human-induced activities and natural processes (Saunio et al. 2020). Burning fossil fuels emits 9.9 ± 0.5 Gt C yr⁻¹ into the atmosphere (Friedlingstein et al. 2023). Among the natural sources of methane, aquatic environments such as wetlands, lakes,

streams, and estuaries play an important role in the global methane emissions to the atmosphere (Saunio et al. 2020). For instance, wetlands and inland waters significantly contribute to the global methane budget releasing approximately 248 Tg CH₄ yr⁻¹ (248 million tonnes CH₄ yr⁻¹) (Saunio et al. 2020, 2024). The Intergovernmental Panel on Climate Change recognises methane emissions from wetlands as the largest global source of methane to the atmosphere (IPCC 2014) and wetland emissions have shown to dominate the interannual variability of methane sources (Bousquet et al. 2006).

Groundwater discharge represents the connection between groundwater and surface water and therefore, controls the transport of dissolved solids and gasses, such as methane. Despite its importance, groundwater discharge remains an overlooked contributor to global carbon emissions to the atmosphere (Friedlingstein et al. 2023). Many aquatic environments are sustained, at least in part, by groundwater discharge (Rohde et al. 2024). This interaction suggest that groundwater discharge may increase methane concentrations in surface waters, which are subsequently released into the atmosphere (Schutte et al. 2020). Estimating groundwater discharge is therefore essential for reliable and accurate carbon budgeting and the effective management of coastal environments (Alongi 2020; Sanders et al. 2015; Wang et al. 2022).

Methanogenesis, the microbial process of methane production, occurs for conditions depleted in terminal electron acceptors (e.g., dissolved oxygen, nitrate, sulfate, etc.), such as those found in organic rich groundwater environments (Torres-Alvarado et al. 2005). Groundwater, a key component of wetland environments, exhibits these anaerobic characteristics as the saturated conditions, high organic matter content and typically high microbial respiration effectively eliminates oxygen. However, groundwater discharge has often been overlooked in developing carbon (and methane) budgets, in aquatic environments due to its hidden and complex nature (Sadat-Noori et al. 2021a). Unlike surface water flows, which are visible and more straightforward to quantify, groundwater discharge is challenging to quantify because it occurs diffusely and is influenced by heterogeneity in sediment properties and various subsurface processes like hydraulic gradient dynamics, permeability variability, geochemical reactions, and tidal effects (Burnett et al. 2006). This has led to its underrepresentation in many studies attempting to develop carbon budgets. This neglect is further exacerbated by the perception that groundwater inputs are less significant compared to surface water sources, despite evidence suggesting that they can play a crucial role in transporting dissolved carbon, including methane, and other nutrients to aquatic systems (Luijendijk et al. 2020; Santos et al. 2021). While the volumes of

groundwater discharge can be small compared to surface water flows for a particular system the higher concentrations of solutes in groundwater compared to surface waters, means that the contributions can still be significant (Sadat-Noori et al. 2016b). As a result, carbon fluxes from wetlands, estuaries, and coastal waters may be underestimated and thus potentially misrepresenting the broader environmental and biogeochemical processes.

In this study, available data from the literature is synthesized to develop a first order estimate of the global groundwater-driven methane flux and assess the contribution of groundwater discharge to the overall methane emission from surface waters of aquatic environments. This study explores the global influence of groundwater on methane emissions, providing insight on the implications of this overlooked process for methane transport and budget development and its role in climate change. By determining where groundwater discharge constitutes a notable source of atmospheric methane and examining how groundwater flow influences the carbon cycle through methane fluxes, this study aims to advance our understating of groundwaters role in shaping the global methane budget. The study is novel in that it provides the first global synthesis and estimate of groundwater-driven methane fluxes across aquatic environments, while earlier studies have focused on groundwater discharge and methane fluxes from localized systems. This paper therefore, addresses a major gap in methane budgets by quantifying a previously underrepresented source at a global scale.

2 Methodology

2.1 Literature Synthesis

A systematic literature review was conducted using academic search engines, with Google Scholar as the primary focus, to identify relevant scholarly articles published between the year 2011 to 2023. Keywords including “submarine groundwater discharge”, “groundwater discharge”, and “methane flux”, were selected and used to retrieve articles. Some studies refer to groundwater discharge as “pore water exchange” and “sediment to water exchange” thus these were also used as a search terms. Critical information, including ecosystem type, aquifer or sediment type, groundwater methane concentration, groundwater-driven methane flux, and surface water to atmospheric methane flux, was extracted from the identified research articles. In addition, supplementary data, such as geographic location, climate of the region, and surface water methane concentrations were retrieved. ArcGIS Pro was utilised for mapping. Maps were created to illustrate the concentration of

groundwater methane across various types of environments, and the groundwater-driven methane flux variation in different types of environments based on the corresponding aquifer material or sediment type.

2.2 Estimation of Groundwater-Driven Methane Flux

Generally, groundwater-driven methane flux is estimated by multiplying the methane concentration in the discharging groundwater by the groundwater flow rate, represented by Eq. 1 below (Sadat-Noori et al. 2015):

$$F = Q \cdot C \quad (1)$$

Where F is the groundwater-driven methane flux, Q is the groundwater discharge rate, C is the average methane concentration in groundwater. The flux is influenced by several factors, including hydrogeological conditions and methane concentrations resulting from sedimentary methane production (Paytan et al. 2015). However, uncertainties arise due to the challenges of measuring discharge and concentration simultaneously, as these parameters can vary significantly over time and space. Assumptions made in the synthesis, such as steady-state flow conditions and uniform methane distribution, may oversimplify the complex interactions between hydrological and biogeochemical processes. These factors should be considered when interpreting the results. In this study, the result of the synthesised groundwater driven methane flux from the metadata will be referred to as the “Complied Groundwater-Driven Methane Flux” and the average will be referred to as the “Global Average Groundwater-Driven Methane Flux”.

3 Results and Discussion

3.1 Spatial Distribution of Groundwater Discharge Data

The studies found in the published literature are summarised in Table 1. Of the global studies, 43% were carried out in the USA, 18% in Australia, and the remaining divided among China, Sweden, Germany, Brazil and India. The studied environments were estuaries, lakes, lagoons and rivers, with 46% of the studies conducted in estuaries, 34% in rivers, 12% lakes and 8% in lagoons. The majority of the studies were conducted in subtropical regions, accounting for 42%, while 23% in temperate regions, 19% in subarctic, followed by 16% in the tropics. With regards to sediment type, 46% of the studies were in a location with mix sediments (sandy, muddy and rocky), 35% in sandy and 15% in

muddy sediments. 4% were in fractured consolidated rocks. Most of the studies reported concentrations of methane in adjacent groundwater, while only a small number of studies reported the groundwater discharge rate and the methane concentration in this discharging groundwater.

3.2 Groundwater Methane Concentration

The global dataset showed an average groundwater methane concentration of 0.31 ± 0.47 mmol/L. The dataset also revealed that the average concentration of methane in groundwater varied between different environments. The average groundwater concentration of methane in estuaries was 0.647 ± 0.568 mmol/L, 0.099 ± 0.119 mmol/L for lakes, 0.00006 ± 01 mmol/L for lagoons and 0.00019 ± 01 mmol/L for rivers. Groundwater methane concentration adjacent to rivers was small, ranging from 0.303 nmol/L to 548 nmol/L. Estuarine environments showed the highest concentration of methane in groundwater, with concentrations reaching up to 1.7 mmol/L. Studies conducted in the subarctic Landing Lake in the USA and the Torneträsk catchment in Sweden show high groundwater methane concentration with an average of 0.37 mmol/L and 0.16 mmol/L, respectively (Dabrowski et al. 2020a; Olid et al. 2022). However, a similar subarctic lake, Toolik Lake (Paytan et al. 2015) had a lower average methane concentration of 0.021 mmol/L. Lakes in tropical and subtropical places had very low values of groundwater methane concentrations except for Tian-E-Zhou, Yangtze River in China (Jiang et al. 2023) in which the groundwater concentration was 0.098 mmol/L. Although estuarine environments exhibited the highest average groundwater methane concentrations in our dataset, statistical analysis (Table 2; $p=0.55$) indicates that differences among ecosystem types are not statistically significant. This suggests that observed patterns may be influenced by sampling bias or site-specific conditions rather than consistent ecosystem-level effects. The lack of statistical significance is also a function of the limited number of studies, and more studies and data are needed for more robust statistical tests.

Groundwater methane concentrations vary significantly across climatic regions. Temperate regions exhibit elevated average concentrations (0.938 ± 0.048 mmol/L), likely due to favorable conditions for methanogenesis (Lecher et al. 2017). In contrast, tropical regions show notably low concentrations (0.0007 ± 0.00008 mmol/L), while subtropical regions have an intermediate average concentration (0.116 ± 0.260 mmol/L), consistent with relatively higher temperatures. Subarctic regions display similar average concentrations (0.138 ± 0.147 mmol/L) to subtropical areas. In the Arctic region however, elevated methane concentrations are linked to permafrost thaw and the abundance of carbon-rich substrates (Dabrowski et al. 2020a; Paytan et al.

Table 1 Previous studies in the literature reporting groundwater-driven and water – air CH₄ flux

Location	Country	Climate	Type of Environment	Aquifer material	GW-CH ₄ Conc. (mmol/L)	GW-driven CH ₄ Flux (mmol/m ² /d)	Water - air CH ₄ Flux (mmol/m ² /d)	GW contribution to atmospheric CH ₄ emissions (%)	References
Okatee Estuary	USA	Subtropical	Estuary	Muddy	0.8	0.8	–	–	(Porubsky et al. 2014)
Tootlik Lake	USA	Subarctic	Lake	Sandy	0.021	0.4	0.26	154	(Paytan et al. 2015)
Elson Lagoon	USA	Subarctic	Lagoon	Mix	0.0000617	0.7347	–	–	(Lecher et al. 2015)
Yukon Delta National Wildlife Refuge	USA	Subarctic	Lake	Mix	0.37	16	2.4	667	(Dabrowski et al. 2020b)
Sapelo Island, Georgia	USA	Subtropical	Estuary	Sandy	9.90E-04	0.613	–	–	(Schutte et al. 2020)
Queen's Creek York River	USA	Temperate	Estuary	Sandy	0.98	–	–	–	(Borges and Abril 2011)
Long Island Sound (US NY/ Connecticut)	USA	Temperate	Estuary	Sandy	1	–	–	–	(Borges and Abril 2011)
Cape Lookout Bight	USA	Temperate	Estuary	Sandy	1.7	–	–	–	(Borges and Abril 2011)
White Oak River	USA	Temperate	Estuary	Mix	1	–	–	–	(Borges and Abril 2011)
White Oak River	USA	Temperate	Estuary	Mix	0.75	17.1	–	–	(Borges and Abril 2011)
Gulf of Mexico	USA	Subtropical	Estuary	Mix	0.061	0.0302	0.0072	420	(Bugna, et al., 1996)
Kangaroo Island	Australia	Subtropical	Estuary	Mix	0.015462	–	0.214	–	(Call et al. 2015)
Chowder Bay	Australia	Subtropical	Estuary	Mix	0.000064	0.0057	0.0013	23	(Sadat-Noori et al. 2017)
Heron Island	Australia	Subtropical	Lagoon	Rocky	0.000056	0.0108	0.0034	318	(O'Reilly et al. 2015)
Korogoro Creek	Australia	Subtropical	Estuary	Mix	0.027	12	25.8	47	(Sadat-Noori et al. 2016b)
Tweed River Flood plain	Australia	Subtropical	River	Mix	0.000548	–	–	–	(Webb et al. 2016)
Manly Dam	Australia	Subtropical	Lake	Mix	0.000238	0.04	0.3	13	(Sadat-Noori et al. 2021b)
Rio Negro (Black Water River)	Brazil	Tropical	River	Muddy	0.0000313	–	–	–	(Call et al. 2018)
Rio Negro (Black Water Lake)	Brazil	Tropical	Lake	Muddy	0.00004956	–	–	–	(Call et al. 2018)
Tapajos (Clear Water)	Brazil	Tropical	River	Mix	0.000000303	–	–	–	(Call et al. 2018)
Tapajos (Clear Water)	Brazil	Tropical	Lake	Mix	0.00019049	–	–	–	(Call et al. 2018)
Tornetråsk catchment	Sweden	Subarctic	Lake	Mix	0.15	4.625	–	35	(Olid et al. 2022)
Tornetråsk catchment	Sweden	Subarctic	Lake	Mix	0.15	0.13	–	35	(Olid et al. 2022)
Tian-E-Zhou, Yangtze River	China	Subtropical	Lake	Sandy	0.09804	(1.48–7.84)	–	–	(Jiang et al. 2023)
Sundarbans Mangrove, Bay of Bengal	India	Subtropical	Estuary	Sandy	0.09804	7.84	–	–	(Borges and Abril 2011)
Tidal Flat Janssen, Wadden Sea	Germany	Temperate	Estuary	Sandy	0.09804	1.48	–	–	(Borges and Abril 2011)
Average					0.31±0.47	3.90±6.25			

Table 2 Summary of statistical results examining the influence of environment, climate and of aquifer type on groundwater methane concentration

Description	Frequency	Mean	Standard Deviation	df	Mean squares	F	p
Climate	11	0.09	±0.24	3	1.13	13.68	<0.001
Subtropical	6	0.94	±0.48				
Temperate	5	0.14	±0.15				
Subarctic	4	–	–				
Tropical							
Type of Environment	12	0.54	±0.57	3	0.5	2.96	0.055
Estuary	9	0.1	±0.12				
Lake	3	–	–				
River	2	–	–				
Lagoon							
Type of Aquifer	12	0.21	0.34	–	–	–	–
Mix	9	0.46	0.62				
Sandy	4	0.20	0.4				
Muddy	1	–	Nan				
Rocky							

2015). These observations suggest that while temperature influences methane production, it is not a sole predictor, as local geochemical and climatic factors play critical roles. Table 2 shows that the p-value for climate type is 0.001, which is below the significance threshold of 0.05, revealing that the type of climate has a statistically significant effect on the groundwater methane concentration.

Sediment type and its content and quality of organic matter can also influence groundwater methane concentration. The average groundwater methane concentration in mixed sedimentary material was 0.2 ± 0.4 mmol/L, while sandy sediments had 0.585 ± 0.65 mmol/L, and muddy sediments had an 0.2 ± 0.4 mmol/L. There was only one study for a consolidated rock aquifer which reported a groundwater methane concentration of 0.00006 mmol/L. Interestingly, the sandy aquifers had the highest groundwater methane concentration amongst the studied environments. The high methane concentration is likely to be controlled by the amount of labile organic matter (Gonsalves et al. 2011) which was not reported for any of the studies.

3.3 Groundwater-Driven Methane Flux

Figure 1 shows a conceptual diagram of groundwater flow transporting methane to surface waters and, surface water methane atmospheric emission (Sadat-Noori et al. 2021a). Groundwater-driven fluxes of methane remain relatively understudied, with few investigations reporting both methane concentrations and associated groundwater discharge rates, i.e., allowing direct methane flux calculations. However, available studies, mostly from regions such as the USA and Australia, highlight the substantial contribution of groundwater-driven methane fluxes to the overall methane budget of aquatic environments. From the dataset, the global average groundwater-driven methane flux was determined to be 3.9 ± 6.2 mmol/m²/day.

Figure 2 shows the groundwater-driven methane flux from the available studies in the literature (average = 3.9 ± 6.2 mol/m²/d). Alternatively, we estimated the global groundwater-driven methane flux by multiplying the global average groundwater methane concentration (0.31 ± 0.47 mmol/L) taken from the synthesised dataset, by the global groundwater discharge rate, estimated at $12 \pm 6 \times 10^{13}$ m³ yr⁻¹ (Kwon et al. 2014). This produced a global annual groundwater-driven methane flux of $3.7 \pm 5.3 \times 10^{13}$ mol/yr (or $5.9 \pm 9.5 \times 10^{14}$ g/yr). It is important to acknowledge uncertainties in the estimated global groundwater-driven methane flux, given the large geospatial variation of both groundwater methane concentration and discharge.

The calculation of methane flux as a product of groundwater methane concentration and discharge rate is highly uncertain when the methane concentration used represents the general groundwater concentration rather than being directly measured in discharging groundwater. This uncertainty is due to two key reasons: (1) sediments near discharge zones often exhibit steep redox gradients, driven by an abundance of fresh labile organic matter, which can result in higher methane concentrations compared to those in aquifer in general, potentially leading to an underestimation of methane fluxes (Rissanen et al. 2023). (2) In environments with significant mixing, such as tidal zones, suppression of methanogenesis by sulfate reduction and substantial methane reoxidation may occur, potentially causing an overestimation of methane fluxes (Andersen et al. 2005; Huang et al. 2019).

With respect to regional climate, temperate areas exhibited a groundwater-driven methane flux of 17 mmol/m²/day which is the highest average groundwater methane-flux among all the regions, followed by subarctic regions with an average groundwater methane flux of 4.38 ± 6.75 . During thaw periods in arctic regions, the snowmelt may lead to an increase in groundwater recharge which can translate

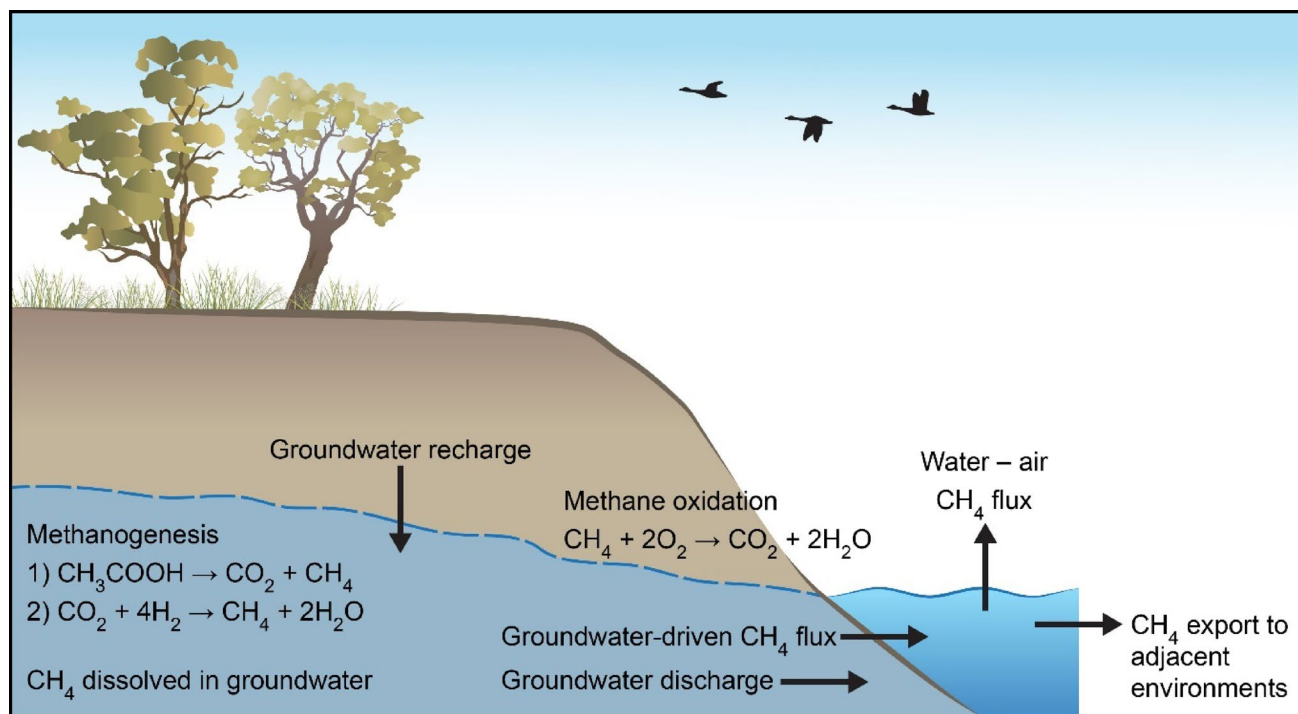


Fig. 1 Conceptual figure illustrating methanogenesis and groundwater flow as a pathway for transporting CH_4 to surface waters and ultimately to the atmosphere through water-air flux

to higher groundwater discharge into surface waters (Jiang et al. 2023) and hence, increased flux of methane. Subarctic regions also showed a high groundwater methane concentration. This may be due to methane produced during warmer climatic periods and trapped in frozen soil of the subarctic and subsequently released upon global warming and increased seasonal thaw (Dean et al. 2018; Walvoord and Kurylyk 2016).

Although subtropical regions were found to have a higher groundwater methane concentration compared to Arctic regions, the groundwater-driven methane flux in subtropical climates was found to be 2.82 ± 4.54 mmol/m²/day, which is lower than that in Arctic regions. In the subtropics, biogeochemical processes, particularly groundwater redox conditions, are influenced by seasonal rainfall (Jiang et al. 2023). Jiang et al. (2023) reported that during wet periods, increased rainfall led to more oxygenated recharge, which altered redox conditions by supplying terminal electron acceptors such as dissolved oxygen and nitrate. The increased rainfall regulates methanogenesis by increasing the availability of electron acceptors, such as dissolved oxygen, sulfate or nitrate, which inhibits methane production and hence, the methane flux (Chapelle 2000; Serrano-Silva et al. 2014).

Seasonal rainfall also affects groundwater recharge, which can induce spatial and temporal variability in redox gradients. These changes influence the mobilization and

dilution of labile organic matter, such as DOC, a key substrate for methanogens (Jasechko et al. 2014; McDonough et al. 2020a; Sela-Adler et al. 2017). McDonough et al. (2020b) showed that an increase in precipitation decreased groundwater dissolved organic carbon probably due to dilution of soil DOC. We speculate that this together with an increased influx of electron acceptors may increase the redox state and lower methanogenesis in wet tropics and subtropics.

Estuarine environments had the largest groundwater-driven methane flux of 6.07 ± 4.54 mmol/m²/day, followed by lakes at 4.36 mmol/m²/day, and lagoons at 0.37 mmol/m²/day. The higher methane flux observed in estuaries may be attributed to the disproportionate focus on estuarine environments in the literature, with over 50% of studies examining such environments. The observed lower methane flux in subtropical regions compared to Arctic regions may also result from variability in sampling and limited datasets, as well as natural heterogeneity in methane concentrations and groundwater discharge rates. In contrast, no studies as of 2024 have reported groundwater-driven methane flux from tropical regions. Low sample numbers, combined with high variability in groundwater methane concentration and groundwater discharge rate, remain a significant limitation in understanding methane fluxes across these regions.

The average groundwater-driven flux from wetlands in mixed aquifer material was 7.23 mmol/m²/day.

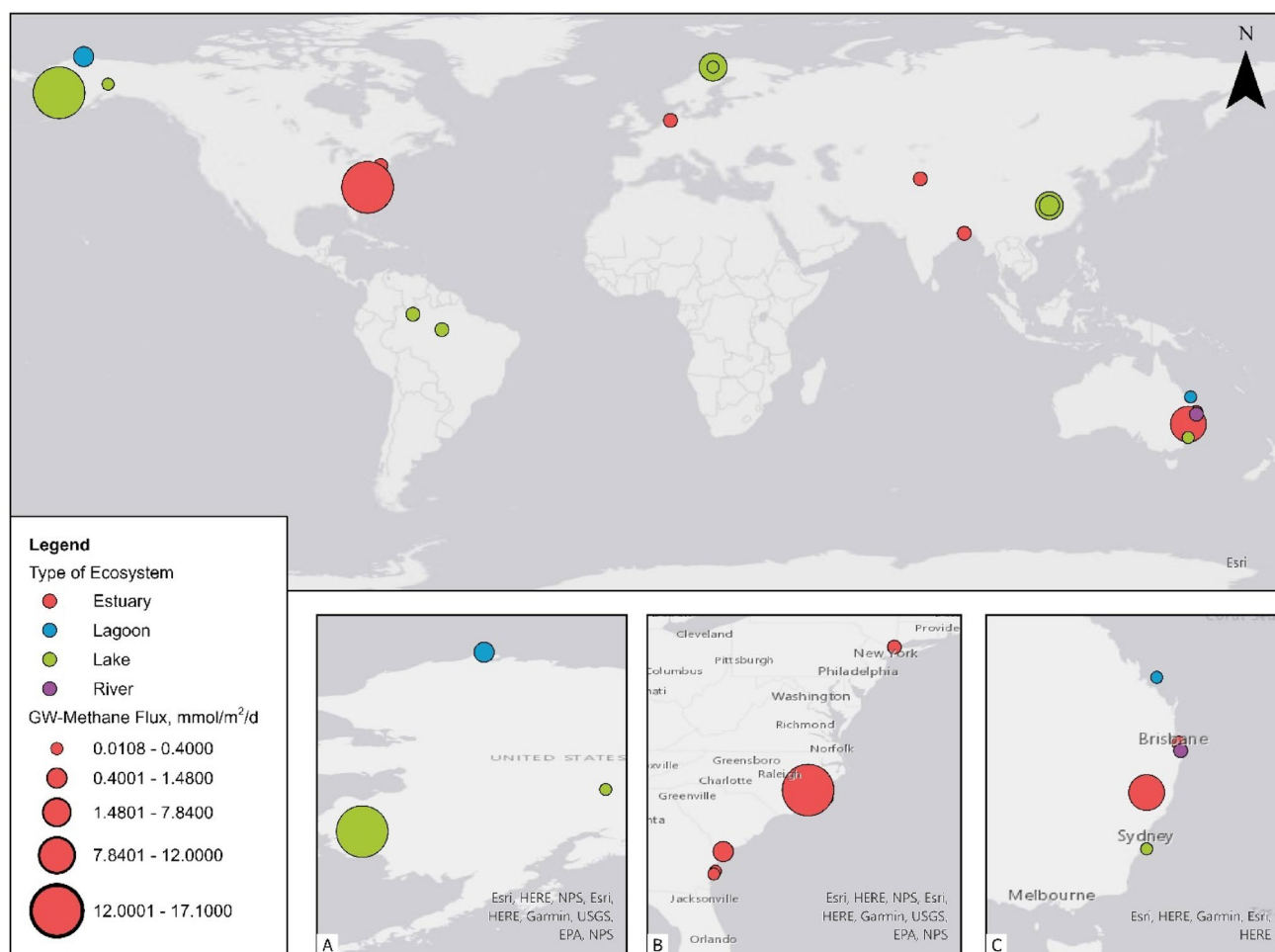


Fig. 2 Global distribution of groundwater-driven methane flux ($\text{mmol/m}^2/\text{day}$) across different aquatic environments, based on available literature. Circle size represents flux magnitude, with colors indicating ecosystem type: red (estuaries), green (lakes), purple (rivers), and

blue (lagoons). Panels highlight key regions: USA-Alaska (A), USA-Southeastern coast (B), and Australia (C). Data points are overlaid on a world map, with a legend indicating flux ranges ($\text{mmol/m}^2/\text{day}$)

Groundwater-driven methane flux for rocky aquifer material has only been reported from a single study, which was $0.0108 \text{ mmol/m}^2/\text{day}$. Average groundwater-driven methane flux from muddy aquifer material was $0.8 \text{ mmol/m}^2/\text{day}$ and the average groundwater-driven methane flux for sandy aquifer material was $2.04 \text{ mmol/m}^2/\text{day}$. Methane emissions from aquatic environments can occur through a variety of pathways, including diffusion, ebullition, and plant-mediated transport (Bridgham et al. 2013). While groundwater-driven flux is recognized as a significant contributor to methane release in aquatic environments (Olid et al. 2022), understanding the factors influencing this flux is crucial, given its variability due to groundwater discharge magnitude and methane concentration.

3.4 Groundwater Contribution To Global Methane Emissions

Only a limited number of studies have reported the contribution of groundwater discharge to water-air methane emissions (e.g., reported on both surface water emissions and the contribution of groundwater). The contribution of groundwater-driven methane to water-air methane emissions is calculated as the percentage of groundwater-driven methane flux relative to the surface water-to-atmosphere methane flux. In some cases, this contribution exceeds 100%, indicating that groundwater delivers more methane to surface waters than is emitted to the atmosphere. The excess methane may be oxidized by methanotrophic bacteria, exported to adjacent environments (e.g., coastal waters), or stored in surface waters or sediments (Dabrowski et al. 2020b; Sadat-Noori et al. 2024; Schutte et al. 2020; Segarra et al. 2013; Sela-Adler et al. 2017).



Fig. 3 Groundwater driven methane flux contribution to atmospheric methane emissions: USA-Alaska (A); Australia (B)

Based on our synthesized dataset, groundwater-driven methane contributed between 13% and 667% of the water to atmosphere methane emissions, with an average of 123% in mixed aquifer material (calculated as the percentage of groundwater-driven methane flux to the surface water methane emission). Based on the single study conducted in a rocky aquifer (O'Reilly et al. 2015), it was found that groundwater-driven methane can contribute >100% of atmospheric emissions, in such systems, indicating the dominance of groundwater-driven methane to the surface water emission. Clearly more studies are needed from rocky aquifers to confirm these findings.

Studies undertaken in subarctic lakes in the United States, such as Landing Lake and Toolik Lake, have shown that groundwater-driven methane flux contributes far more methane than surface water emissions. In these cases, groundwater-driven methane emissions were found to be 1.5 and 6 times greater than those from surface water, respectively. The subarctic region groundwater-driven methane contribution to atmospheric emissions ranges from 355 to

667%, with an average of 182%. This implies that groundwater-driven methane contributes significantly to methane emissions in subarctic wetlands. Furthermore, groundwater-driven methane flux contributed significantly to atmospheric emissions in Subtropical regions, ranging from 13 to 318% with an average of 106%. There was no data available on the temperate and tropical regions' that report groundwater-driven methane contribution to the atmospheric emissions (Fig 3). Mix aquifer material in the subarctic appear to have the greatest groundwater-driven methane to the atmosphere exceeding 100%. Additionally, groundwater-driven methane contribution to the emission is less than 100% in sub-tropical areas but is still significant. Groundwater-driven methane in rocky and sandy aquifer material appears to have a significant contribution in the surface water methane emissions also exceeding 100%.

Multiple studies have emphasized the substantial role of groundwater driven methane in contributing to surface water methane emissions. For example, a study in Heron Island, Australia, found that groundwater methane flux

were three times higher than those from surface water to the atmosphere (O'Reilly et al. 2015). Groundwater-driven methane flux was measured at $0.0108 \text{ mmol/m}^2/\text{day}$, while surface water emissions were measured at $0.0034 \text{ mmol/m}^2/\text{day}$. The authors concluded that groundwater was the main source of methane from the Heron Island Lagoon.

Here, results show that groundwater methane flux can be much higher than surface water methane atmospheric fluxes, contributing 1 to 6 times that of the surface water methane emission. Nevertheless, it is important to consider that in addition to methane atmospheric fluxes, methane can be exported by surface waters to neighboring environments. For example, groundwater contribution to CH_4 export from an estuary in Hat Head, Australia, to coastal waters was estimated to be $>100\%$ (Sadat-Noori et al. 2016a). Further, it is important to recognize that not all methane discharged via groundwater contributes directly to atmospheric emissions. Studies show that methanotrophic bacteria in sediments and oxic water columns in some cases, can oxidize between 50 and 90% of dissolved methane before it reaches the air–water interface (Cabrol et al. 2020; Morana et al. 2020). In addition, lateral hydrological transport from the waterbody, and sediment burial can also reduce the flux contributing to atmospheric emissions (Abril and Borges 2005; Sawakuchi et al. 2021; Treude et al. 2005). For example, in some subarctic lakes where measured groundwater-derived methane inputs exceeded measured atmospheric fluxes several-fold, microbial oxidation and downstream losses would likely explain these apparent discrepancies (Schenk et al. 2021). Therefore, our estimate of groundwater methane flux represents a potential maximum input to surface water, not necessarily the net emission to the atmosphere. Future efforts combining measurements of surface water methane oxidation rates, lateral hydrological export, and sediment sequestration are needed to constrain the actual net methane emissions originating from groundwater discharge.

Considering the compiled groundwater-driven methane flux of $3.9 \pm 6.2 \text{ mmol/m}^2/\text{day}$ based on the average taken from the synthesized dataset, and the calculated global average groundwater-driven methane flux of $6.72 \pm 10.88 \text{ mmol/m}^2/\text{day}$, these figures imply that groundwater discharge can be a significant source of methane to the atmosphere, through aquatic environments. A recent study by Saunois et al. (2024) examines methane emissions from wetlands using a bottom-up method. This study estimates global wetland emissions at $248 \pm 25 \text{ Tg CH}_4/\text{year}$ (bottom up), with a global wetland area of $7.9 \pm 1.6 \times 10^{12} \text{ m}^2$. This results in an average areal wetland methane emission rate of $5.37 \pm 1.20 \text{ mmol/m}^2/\text{day}$. When comparing the global average groundwater-driven methane flux to wetland emissions, it becomes evident that groundwater discharge is comparable to the emissions from wetland surface waters.

The average contribution of groundwater-driven methane to atmospheric emissions is approximately 73% of the total wetland emission. Considering the estimated global average groundwater-driven methane flux, groundwater could contribute as much as 125% of the wetland methane flux in some areas.

While this study provides a global estimate suggesting that groundwater discharge may contribute up to 70% of methane emissions from aquatic environments, we acknowledge that this value is subject to considerable uncertainty. The global average groundwater methane concentration ($0.31 \pm 0.47 \text{ mmol/L}$) and groundwater discharge rate ($12 \pm 6 \times 10^{13} \text{ m}^3/\text{year}$) used in our calculation are drawn from datasets that reflect broad spatial heterogeneity and temporal variability. Additionally, our approach assumes steady-state conditions, which does not take seasonal or tidal variation into account and uses a generalized methane distribution, which simplify the complex hydrogeological and biogeochemical processes governing methane dynamics. These assumptions inherently limit the precision of our estimate, and the resulting coefficient of variation exceeding 100% highlights the uncertainty.

It is important to note that the global dataset synthesized in this study exhibits a pronounced geographic bias, with 43% of the included studies originating from the USA and 18% from Australia. In contrast, regions such as Africa, large parts of Asia, and the tropics remain substantially underrepresented or entirely absent. This imbalance introduces uncertainty into our global extrapolations, particularly for tropical regions where no direct measurements of groundwater-driven methane fluxes are currently available. Nonetheless, these regions were included in our global estimates for a first pass global estimate, to avoid the current systemic exclusion of groundwater methane sources from carbon accounting and to emphasize the urgent need for targeted studies in the underrepresented regions.

Providing this high-level estimate is a critical first step toward recognizing and quantifying the role of groundwater in global methane budgets. It serves to draw attention to a generally ignored methane source and highlights the urgent need for more targeted experimental research, particularly in understudied regions and systems. Despite its limitations, this synthesis helps frame future work by identifying key data gaps and establishing a conceptual and quantitative foundation for refining methane emission estimates from groundwater–surface water interactions.

4 Conclusion

Groundwater was shown to potentially account for a substantial portion of methane emissions from aquatic environments, highlighting the importance of groundwater discharge as a pathway for transporting dissolved methane to surface waters and the atmosphere. Although this study provides insights into the impact of groundwater discharge on the global methane emissions, large uncertainties and information gaps remain. A significant restriction is a lack of studies measuring groundwater-driven methane fluxes, or studies where groundwater methane concentrations and groundwater discharge has been measured concurrently. Most existing research focus on either groundwater carbon dioxide dynamics or surface water methane emissions. This highlights the need for further investigations, particularly in stream and rivers and in regions like Asia and Africa where data is scarce. Further research is required to accurately quantify the contribution from groundwater discharge to atmospheric methane levels and to understand processes in the discharge zone that may modulate the methane emissions. These findings highlight the need to integrate groundwater-driven methane fluxes into global carbon budgets, potentially informing targeted mitigation strategies such as managing organic carbon inputs to aquifers. Future research leveraging isotopic tracing or high-resolution sensor networks could further refine such estimates, particularly in data-scarce regions.

Acknowledgements We are grateful to Anna Blacka for creating the graphical abstract and Fig. 1.

Author Contributions Rea Camile Maglaya: Data Gathering, Formal analysis, Investigation, Visualization, Writing - original draft. Mahmood Sadat-Noori: Conceptualization, Methodology, Formal analysis, Investigation, Supervision, Funding acquisition, Writing- review and editing. Martin S. Andersen: Investigation, Formal analysis, Supervision, Funding acquisition, Writing- review and editing.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. Authors acknowledge funding from a Hermon Slade Foundation Grant (HSF 22034), and support from James Cook University and UNSW, Sydney.

Declarations

Conflict of Interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not

included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abril G, Borges AV (2005) Carbon Dioxide and Methane Emissions from Estuaries. In: Tremblay A, Varfalvy L, Roehm C, Garneau M (eds) *Greenhouse Gas Emissions — Fluxes and Processes*. Environmental Science. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-26643-3_8
- Alongi DM (2020) Carbon cycling in the world's Mangrove ecosystems revisited: significance of non-steady state diagenesis and subsurface linkages between the forest floor and the coastal ocean. *Forests* 11:977
- Andersen MS, Nyvang V, Jakobsen R, Postma D (2005) Geochemical processes and solute transport at the seawater/freshwater interface of a sandy aquifer. *Geochim Cosmochim Acta* 69:3979–3994
- Borges AV, Abril G (2011) Carbon dioxide and methane dynamics in estuaries. *Treatise on Estuarine and Coastal Science*, pp 119–161
- Bousquet P, Ciais P, Miller J, Dlugokencky EJ, Hauglustaine D, Prigent C, Van der Werf G, Peylin P, Brunke E-G, Carouge C (2006) Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature* 443:439–443
- Bridgman SD, Cadillo-Quiroz H, Keller JK, Zhuang Q (2013) Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. *Glob Change Biol* 19:1325–1346
- Bugna G, Chanton JEFFREY, JAYE E, WILLIAM CABLE, PETER CBURNETT, H., CABLE (1996) The importance of groundwater discharge to the methane budgets of nearshore and continental shelf waters of the Northeastern Gulf of Mexico. *Geochim Cosmochim Acta* 60:4735–4746
- Burnett WC, Aggarwal PK, Bokuniewicz H, Cable JE, Charette MA, Kontar E, Krupa S, Kulkarni KM, Loveless A, Moore WS, Oberdorfer JA, Oliveira J, Ozyurt N, Povinec P, Privitera AMG, Rajar R, Ramessur RT, Scholten J, Stieglitz T, Taniguchi M, Turner JV (2006) Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Sci Total Environ* 367:498–543
- Cabrol L, Thalasso F, Gandois L, Sepulveda-Jauregui A, Martinez-Cruz K, Teisserenc R, Tananaev N, Tveit A, Svenning MM, Barret M (2020) Anaerobic oxidation of methane and associated microbiome in anoxic water of Northwestern Siberian lakes. *Sci Total Environ* 736:139588
- Call M, Maher D, Santos I, Ruiz-Halpern S, Mangion P, Sanders C, Erler D, Oakes J, Rosentreter J, Murray R (2015) Spatial and temporal variability of carbon dioxide and methane fluxes over semi-diurnal and spring-neap-spring timescales in a mangrove creek. *Geochim Cosmochim Acta*. <https://doi.org/10.1016/j.gca.2014.11.023>
- Call M, Sanders CJ, Enrich-Prast A, Sanders L, Marotta H, Santos IR, Maher DT (2018) Radon-traced pore-water as a potential source of CO₂ and CH₄ to receding black and clear water environments in the Amazon basin. *Limnol Oceanogr Lett* 3(5):375–383
- Chapelle FH (2000) The significance of microbial processes in hydrogeology and geochemistry. *Hydrogeol J* 8:41–46
- Dabrowski JS, Charette MA, Mann PJ, Ludwig SM, Natali SM, Holmes RM, Schade JD, Powell M, Henderson PB (2020a) Using radon to quantify groundwater discharge and methane fluxes to a shallow, tundra lake on the Yukon-Kuskokwim delta. *Alaska Biogeochemistry* 148:69–89

- Dabrowski JS, Charette MA, Mann PJ, Ludwig SM, Natali SM, Holmes RM, Schade JD, Powell M, Henderson PB (2020b) Using radon to quantify groundwater discharge and methane fluxes to a shallow, tundra lake on the Yukon-Kuskokwim delta. *Alaska Biogeochemistry* 148:69–89
- Dean JF, Middelburg JJ, Röckmann T, Aerts R, Blauw LG, Egger M, Jetten MS, de Jong AE, Meisel OH, Rasigraf O (2018) Methane feedbacks to the global climate system in a warmer world. *Rev Geophys* 56:207–250
- Friedlingstein P, O’Sullivan M, Jones MW, Andrew RM, Bakker DC, Hauck J, Landschützer P, Le Quééré C, Luijkx IT, Peters GP (2023) Global carbon budget 2023. *Earth Syst Sci Data* 15:5301–5369
- Gonsalves M-J, Fernandes CE, Fernandes SO, Kirchman DL, Bharathi PL (2011) Effects of composition of labile organic matter on biogenic production of methane in the coastal sediments of the Arabian Sea. *Environ Monit Assess* 182:385–395
- Huang J, Luo M, Liu Y, Zhang Y, Tan J (2019) Effects of tidal scenarios on the methane emission dynamics in the subtropical tidal marshes of the Min river estuary in Southeast China. *Int J Environ Res Public Health* 16:2790
- IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, p. 151 pp
- Jasechko S, Birks SJ, Gleeson T, Wada Y, Fawcett PJ, Sharp ZD, McDonnell JJ, Welker JM (2014) The pronounced seasonality of global groundwater recharge. *Water Resour Res* 50:8845–8867
- Jiang Y, Du Y, Sun X, Deng Y, Xu J, Tian H, Han P, Gan Y, Ma T, Wang Y (2023) Quantification of groundwater-borne greenhouse gases (CH₄, CO₂, N₂O) fluxes to an oxbow lake in a subtropical alluvial-lacustrine plain. *Appl Geochem* 155:105743
- Kwon EY, Kim G, Primeau F, Moore WS, Cho HM, DeVries T, Sarmiento JL, Charette MA, Cho YK (2014) Global estimate of submarine groundwater discharge based on an observationally constrained radium isotope model. *Geophys Res Lett* 41:8438–8444
- Lecher AL, Kessler J, Sparrow K, Garcia-Tigreros Kodovska F, Dimova N, Murray J, Tulaczyk S, Paytan A (2015) Methane transport through submarine groundwater discharge to the North Pacific and Arctic ocean at two Alaskan sites. *Limnology and Oceanography*
- Lecher AL, Chuang PC, Singleton M, Paytan A (2017) Sources of methane to an Arctic lake in Alaska: an isotopic investigation. *J Geophys Res: Biogeosciences* 122:753–766
- Luijendijk E, Gleeson T, Moosdorf N (2020) Fresh groundwater discharge insignificant for the world’s oceans but important for coastal ecosystems. *Nat Commun* 11:1–12
- McDonough LK, O’Carroll DM, Meredith K, Andersen MS, Brügger C, Huang H, Rutledge H, Behnke MI, Spencer RG, McKenna A (2020a) Changes in groundwater dissolved organic matter character in a coastal sand aquifer due to rainfall recharge. *Water Res* 169:115201
- McDonough LK, Santos IR, Andersen MS, O’Carroll DM, Rutledge H, Meredith K, Oudone P, Bridgeman J, Goody DC, Sorensen JP (2020b) Changes in global groundwater organic carbon driven by climate change and urbanization. *Nat Commun* 11:1–10
- Montzka SA, Dlugokencky EJ, Butler JH (2011) Non-CO₂ greenhouse gases and climate change. *Nature* 476:43–50
- Morana C, Bouillon S, Nolla-Ardévol V, Roland FA, Okello W, Descy J-P, Nankabirwa A, Nabafu E, Springael D, Borges AV (2020) Methane paradox in tropical lakes? Sedimentary fluxes rather than pelagic production in oxic conditions sustain methanotrophy and emissions to the atmosphere. *Biogeosciences* 17:5209–5221
- O’Reilly C, Santos IR, Cyronak T, McMahon A, Maher DT (2015) Nitrous oxide and methane dynamics in a coral reef lagoon driven by pore water exchange: insights from automated high-frequency observations. *Geophys Res Lett* 42:2885–2892
- Olid C, Rodellas V, Rocher-Ros G, Garcia-Orellana J, Diego-Feliu M, Alorda-Kleinglass A, Bastviken D, Karlsson J (2022) Groundwater discharge as a driver of methane emissions from Arctic lakes. *Nat Commun* 13:3667
- Paytan A, Lecher AL, Dimova N, Sparrow KJ, Kodovska FG-T, Murray J, Tulaczyk S, Kessler JD (2015) Methane transport from the active layer to lakes in the Arctic using Toolik Lake, Alaska, as a case study. *Proc Natl Acad Sci* 112:3636–3640
- Porubsky WP, Weston NB, Moore WS, Ruppel C, Joye SB (2014) Dynamics of submarine groundwater discharge and associated fluxes of dissolved nutrients, carbon, and trace gases to the coastal zone (Okatee river estuary, South Carolina). *Geochim Cosmochim Acta* 131:81–97
- Rissanen AJ, Jilbert T, Simojoki A, Mangayil R, Aalto SL, Khanongnuch R, Peura S, Jäntti H (2023) Organic matter lability modifies the vertical structure of methane-related microbial communities in lake sediments. *Microbiol Spectr* 11:e01955–e01923
- Rohde MM, Albano CM, Huggins X, Klausmeyer KR, Morton C, Sharman A, Zaveri E, Saito L, Freed Z, Howard JK (2024) Groundwater-dependent ecosystem map exposes global dryland protection needs. *Nature* 632:101–107
- Sadat-Noori M, Santos IR, Sanders CJ, Sanders LM, Maher DT (2015) Groundwater discharge into an estuary using spatially distributed radon time series and radium isotopes. *J Hydrol* 528:703–719
- Sadat-Noori M, Maher DT, Santos IR (2016a) Groundwater discharge as a source of dissolved carbon and greenhouse gases in a subtropical estuary. *Estuaries Coasts* 39:639–656
- Sadat-Noori M, Maher DT, Santos IR (2016b) Groundwater discharge as a source of dissolved carbon and greenhouse gases in a subtropical estuary. *Estuaries Coasts*. <https://doi.org/10.1007/s12237-015-0042-4>
- Sadat-Noori M, Tait DR, Maher DT, Holloway C, Santos IR (2017) Greenhouse gases and submarine groundwater discharge in a Sydney harbour embayment (Australia). *Estuarine, Coastal and Shelf Science*
- Sadat-Noori M, Rutledge H, Andersen MS, Glamore W (2021a) Quantifying groundwater carbon dioxide and methane fluxes to an urban freshwater lake using radon measurements. *Sci Total Environ* 797:149184
- Sadat-Noori M, Rutledge H, Andersen MS, Glamore W (2021b) Quantifying groundwater carbon dioxide and methane fluxes to an urban freshwater lake using radon measurements. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2021.149184>
- Sadat-Noori M, Andersen MS, Waddington K, Ruprecht J, Tucker TA, Glamore W (2024) Groundwater driven carbon fluxes in a restored coastal saltmarsh wetland: implications for coastal wetland restoration. *J Hydrol* 643:131997 <https://doi.org/10.1016/j.jhydrol.2024.131997>
- Sanders CJ, Santos IR, Maher DT, Sadat-Noori M, Schnetger B, Brumsack H-J (2015) Dissolved iron exports from an estuary surrounded by coastal wetlands: can small estuaries be a significant source of Fe to the ocean? *Mar Chem* 176:75–82
- Santos IR, Chen X, Lecher AL, Sawyer AH, Moosdorf N, Rodellas V, Tamborski J, Cho H-M, Dimova N, Sugimoto R (2021) Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nat Rev Earth Environ* 2:307–323
- Saunio M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK (2020) The global methane budget 2000–2017. *Earth Syst Sci Data* 12:1561–1623
- Saunio M, Martinez A, Poulter B, Zhang Z, Raymond P, Regnier P, Canadell JG, Jackson RB, Patra PK, Bousquet P (2024) Global Methane Budget 2000–2020. *Earth System Science Data Discussions* 2024, 1–147

- Sawakuchi HO, Bastviken D, Enrich-Prast A, Ward ND, Camargo PB, Richey JE (2021) Low diffusive methane emissions from the main channel of a large Amazonian run-of-the-river reservoir attributed to high methane oxidation. *Front Environ Sci* 9:655455
- Schenk J, Sawakuchi HO, Sieczko AK, Pajala G, Rudberg D, Hagberg E, Fors K, Laudon H, Karlsson J, Bastviken D (2021) Methane in lakes: variability in stable carbon isotopic composition and the potential importance of groundwater input. *Front Earth Sci* 9:722215
- Schutte CA, Moore WS, Wilson AM, Joye SB (2020) Groundwater-driven methane export reduces salt marsh blue carbon potential. *Glob Biogeochem Cycles* 34:e2020GB006587 <https://doi.org/10.1029/2020GB006587>
- Segarra KE, Comerford C, Slaughter J, Joye SB (2013) Impact of electron acceptor availability on the anaerobic oxidation of methane in coastal freshwater and brackish wetland sediments. *Geochim Cosmochim Acta* 115:15–30
- Sela-Adler M, Ronen Z, Herut B, Antler G, Vigderovich H, Eckert W, Sivan O (2017) Co-existence of methanogenesis and sulfate reduction with common substrates in sulfate-rich estuarine sediments. *Front Microbiol* 8:766
- Serrano-Silva N, Sarria-Guzmán Y, Dendooven L, Luna-Guido M (2014) Methanogenesis and methanotrophy in soil: a review. *Pedosphere* 24:291–307
- Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE (2009) Improved attribution of climate forcing to emissions. *Science* 326:716–718
- Torres-Alvarado R, Ramírez-Vives F, Fernández FJ, Barriga-Sosa I (2005) Methanogenesis and methane oxidation in wetlands: implications in the global carbon cycle. *Hidrobiologica* 15:327–349
- Treude T, Niggemann J, Kallmeyer J, Wintersteller P, Schubert CJ, Boetius A, Jørgensen BB (2005) Anaerobic oxidation of methane and sulfate reduction along the Chilean continental margin. *Geochim Cosmochim Acta* 69:2767–2779
- Walvoord MA, Kurylyk BL (2016) Hydrologic impacts of thawing permafrost—a review. *Vadose Zone J* 15(6):vzj2016.2001.0010
- Wang Z-l, Sadat-Noori M, Glamore W (2022) Groundwater discharge drives water quality and greenhouse gas emissions in a tidal wetland. *Water Sci Eng* 15:141–151
- Webb JR, Santos IR, Tait DR, Sippo JZ, Macdonald BCT, Robson B, Maher DT (2016) Divergent drivers of carbon dioxide and methane dynamics in an agricultural coastal floodplain: post-flood hydrological and biological drivers. *Chem Geol* 440:313–325

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.