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A first run-of-river hydropower plant development in a permafrost-rich subarctic Canadian region: short-term fate of mercury and carbon

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A first run-of-river power plant built in Nunavik (QC, Canada) lies in a continuous permafrost zone, a substantial carbon (C) rich mercury (Hg) reservoir. Its impoundment could promote permafrost thaw and remobilize Hg and lead to the enhanced production of highly toxic methylmercury (MeHg). To elucidate how RORs can influence C and Hg dynamics and transformations in a subarctic landscape, soils, water and benthic invertebrates were sampled shortly before and after the flooding. Soil Hg concentrations were higher in the organic active layer than in frozen ground. Three months after river impoundment, MeHg concentrations and proportions in the surface organic layer of flooded soils were seven and four times higher, respectively. A similar increase was observed in surface waters of the newly created bay, where MeHg concentration and proportion were, respectively, ~ 10 and four times higher. Biological MeHg concentrations increased in low trophic level organisms associated with this flooded environment, namely primary consumers ($\sim 4\times$) and omnivores ($\sim 3\times$). However, these rises were limited to the small ($<1\text{ km}^2$) newly created bay, highlighting spatial heterogeneity in the production and trophic transfer of MeHg at the river scale in response to recent impoundment.

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Environmental significance

Small hydropower plants account for more than 90% of global hydropower installed capacity but few studies have investigated their environmental impact even though it could be larger per megawatt produced than large hydroelectric dams. Mercury can be transformed to the neurotoxic methylmercury (MeHg) when soils are flooded by powerplant impoundments and can then be bioaccumulated and biomagnified in foodwebs. In the North, such flooding can occur in permafrost-rich areas with unknown consequences on Hg cycling. A first hydropower plant was recently built in the northern Canadian subarctic region to provide a sustainable energy source to an Inuit community. This study provides the first account of the environmental impact of subarctic powerplants on mercury cycling for communities consuming freshwater fish.

Introduction

Standing as a leading renewable energy source worldwide, hydropower is broadly supported by national incentives and policies aimed to mitigate global carbon (C) emissions.¹ Many parts of the world witness an unprecedented proliferation of small hydropower plants (SHP) (generally defined as $<10\text{ MW}$) like run-of-the-river (RORs) dams, notably to sustain isolated communities that rely solely on fossil fuels.^{2,3} While it is widely accepted that large reservoirs can impact mercury (Hg) and C cycling, less is known on

SHP impacts on the latter, let alone in remote northern landscapes featured with permafrost.^{4,5} Known environmental impacts of river damming include the flooding of terrestrial soils which creates niches for the microbial transformation of Hg into methylmercury (MeHg), a potent neurotoxin that bioaccumulates and biomagnifies along aquatic food chains.⁶ In northern regions, large boreal reservoir dams cause a temporary surge of MeHg in top predators that may persist up to 30 years before returning to pre-flooding levels.⁷ Data about Hg cycling in SHP is scarce despite the fact they account for 91.5% of global hydropower installed capacity.⁸ The few existing studies in southern rivers showed that RORs had little to no significant impact on Hg and MeHg levels in wildlife and water.^{9–11} In contrast, within a boreal watershed impacted by multiple disturbances affecting the mobilization of organic matter (OM) and mercury (Hg), elevated concentrations of methylmercury (MeHg) were detected in flooded areas upstream of two run-of-river (ROR) structures—across sediments, the water column, biofilms, and throughout the entire food web.^{12–14}

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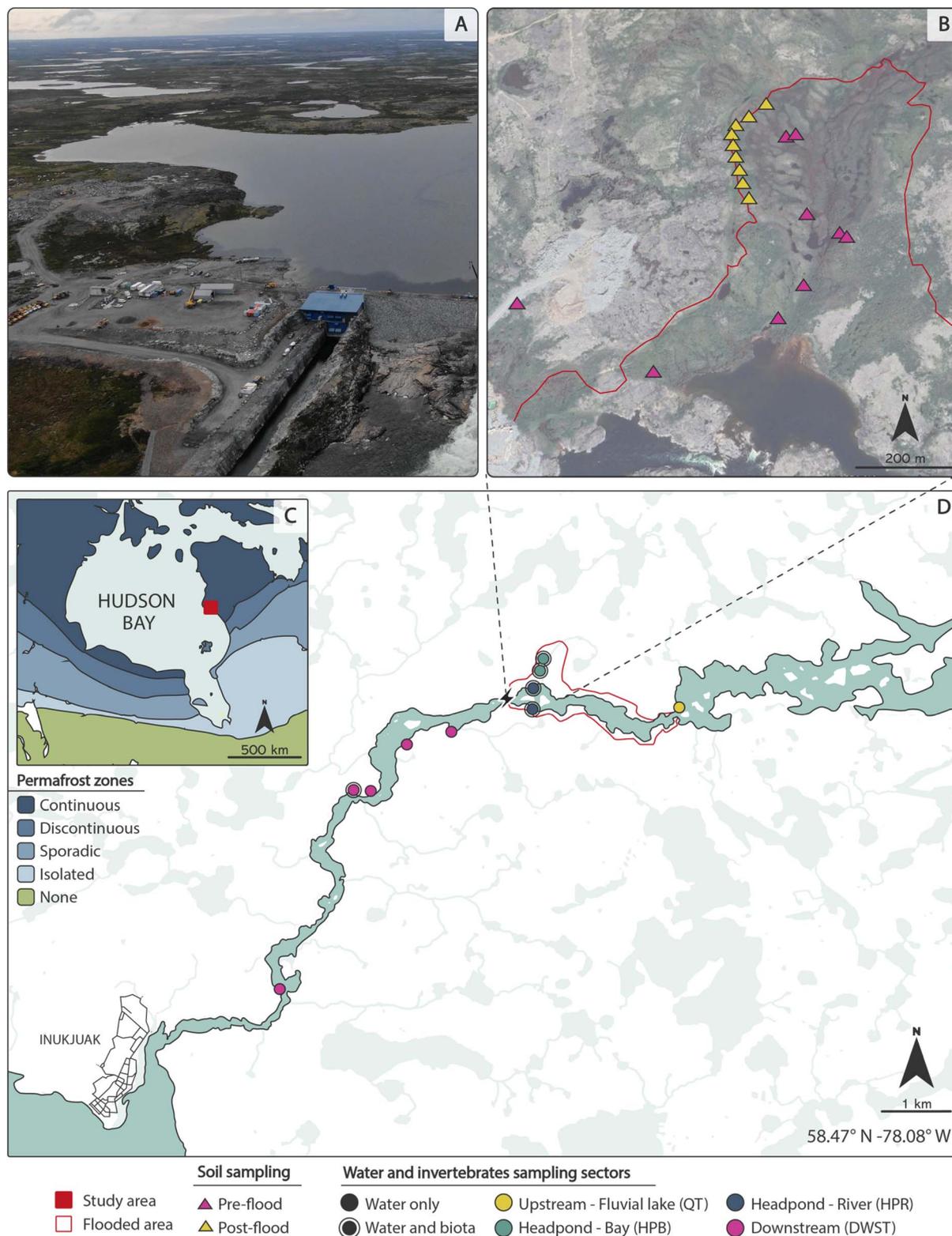


Fig. 1 Map of the study area with (A) the new flooded bay, (B) the sampling sites for soils in the new flooded bay, (C) the location of the study with regard to the permafrost zones³⁹ and (D) the sampling stations for water and biota.

Benthic invertebrates and small fishes (<10 cm) were collected in the sediments and overlying water with a kick net. All invertebrates were identified and sorted to the family rank apart from the sub-class Oligochaeta. A total of 12 families and

one sub-class of invertebrates were found, from primary consumers to predators (Table S1). Similar size organisms of a given taxon were pooled together to ensure enough biomass for analyses. All organisms were depurated of their gut content



Overall, our results suggest that soil THg mainly resides in the organic fraction of the active layer, indicating that even if the flooding destabilized the underlying permafrost, it would likely not result in the release of large quantities of ice-immobilized Hg. The near-surface active layer response to the flooding is restricted to a small area and should reflect locally on the overlaying water.

Timeline of the flooding event reveals minimal impacts on riverine mercury exports

Apart from the two sites sampled post-flood in the newly created bay, the river exhibited consistently low concentrations of unfiltered THg and MeHg, averaging $0.58 \pm 0.35 \text{ ng L}^{-1}$ and $0.099 \pm 0.178 \text{ ng L}^{-1}$, respectively. Bulk DOC averaged $2.90 \pm 0.23 \text{ mg L}^{-1}$, with the highest concentrations monitored in the new bay followed by the spring high-flow. It correlated well with THg (Spearman's $\rho = 0.61$, $p < 0.0001$) but not with MeHg (Spearman's $\rho = 0.03$, $p = 0.87$), which maintained concentrations close to the detection limit throughout the whole campaign, except for two extreme points in the newly flooded bay. Furthermore, dissolved organic matter (DOM) showed a prominence of terrestrial-derived humic-like material as highlighted by the five-component parallel factor analysis (PARAFAC) model. In non-flooded sites, DOM quality was a better predictor of dissolved THg than bulk DOC, with the strongest predictive power obtained with terrestrial-derived humic-like components C1, C2 and C4 (Table S4). However, when adding the two extreme points from the newly flooded bay, bulk DOC was the strongest predictor. Overall, concentrations of aqueous DOC and THg, primarily the dissolved fraction, roughly tracked the river seasonal discharge fluctuations (DOC: $R^2 = 0.83$, $p < 0.0001$; dissolved THg: $R^2 = 0.73$, $p <$

0.0001), as well as the discharge variations observed throughout the flooding event that spanned over several days, in the summer of 2023.

During the creation of the headpond, the initial increase in water level upstream from the plant decelerated the river flow until water surpassed the spillway, resulting in a rapid increase in the discharge downstream (Fig. 3). This surge was accompanied by about a doubling in terms of suspended particulate matter, from 1.3 to 2.6 mg L^{-1} , a short pulse that lasted for a day before decreasing to previous levels. In addition, the subsequent daily monitoring downstream from the spillway revealed a short-lived spike in THg and MeHg levels, especially apparent for the particulate fractions. The latter experienced the greatest variation within the first five days, with a relative standard deviation of 60% for particulate THg and 50% for particulate MeHg, before returning to prior levels within five days (Fig. 3). Moreover, the dissolved fractions peaked during the rising phase, while the maximal particulate THg concentration was measured during peak discharge, and interestingly particulate MeHg culminated during the falling discharge phase (Fig. 3).

All sampling campaigns combined, most of the dissolved C pool was characterized as modern with some samples exhibiting slightly older carbon, while all POC samples showed older radiocarbon age, ranging from 250 to 1130 years before present (BP). All records considered, the particulate fraction was slightly older ($\Delta^{14}\text{C} = -105 \pm 24\%$) than the dissolved one ($\Delta^{14}\text{C} = -20 \pm 34\%$), but no clear age-changing pattern could be established between surface water sampled before, during and after the flooding.

Riverine THg concentrations were in the lower range of previous data collected from large rivers in Nunavik,⁶⁴ whilst low MeHg concentrations are typical of arctic streams.⁶⁵ An alignment between stream discharge, terrestrial-derived DOM

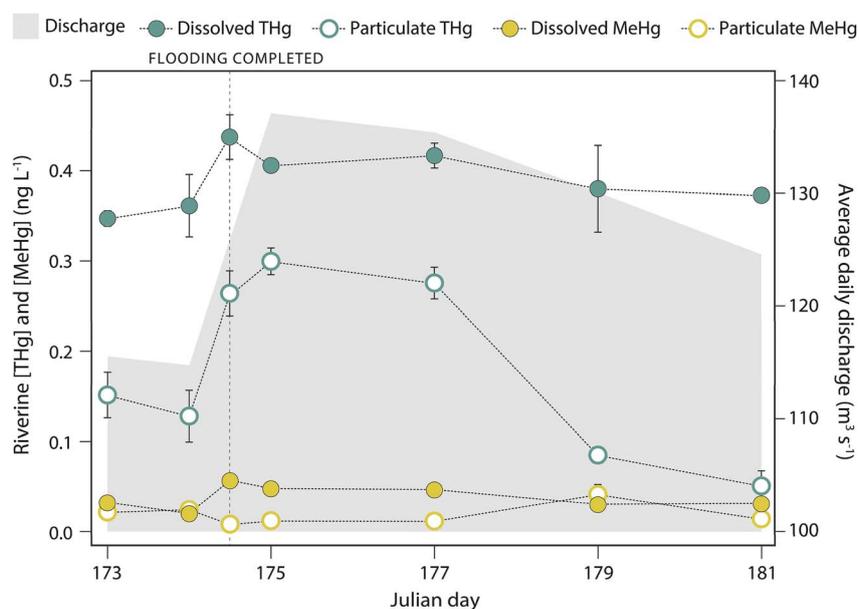


Fig. 3 Short term response of the dissolved (filled dots) and particulate (open dots) fractions of total mercury (green) and methylmercury (yellow) to the flooding event in June 2023 in contrast with the average daily flow rate (light grey).



Additionally, within primary consumers sampled post-impoundment, a clear gradient of MeHg concentrations as well as more depleted $\delta^{13}\text{C}$ signatures was seen from the

flooded bay to downstream. While $\delta^{13}\text{C}$, widely used to reconstruct dietary niches,⁸⁰ showed a significant negative relationship with MeHg concentrations (2022: $R^2 = 0.30$, $p <$

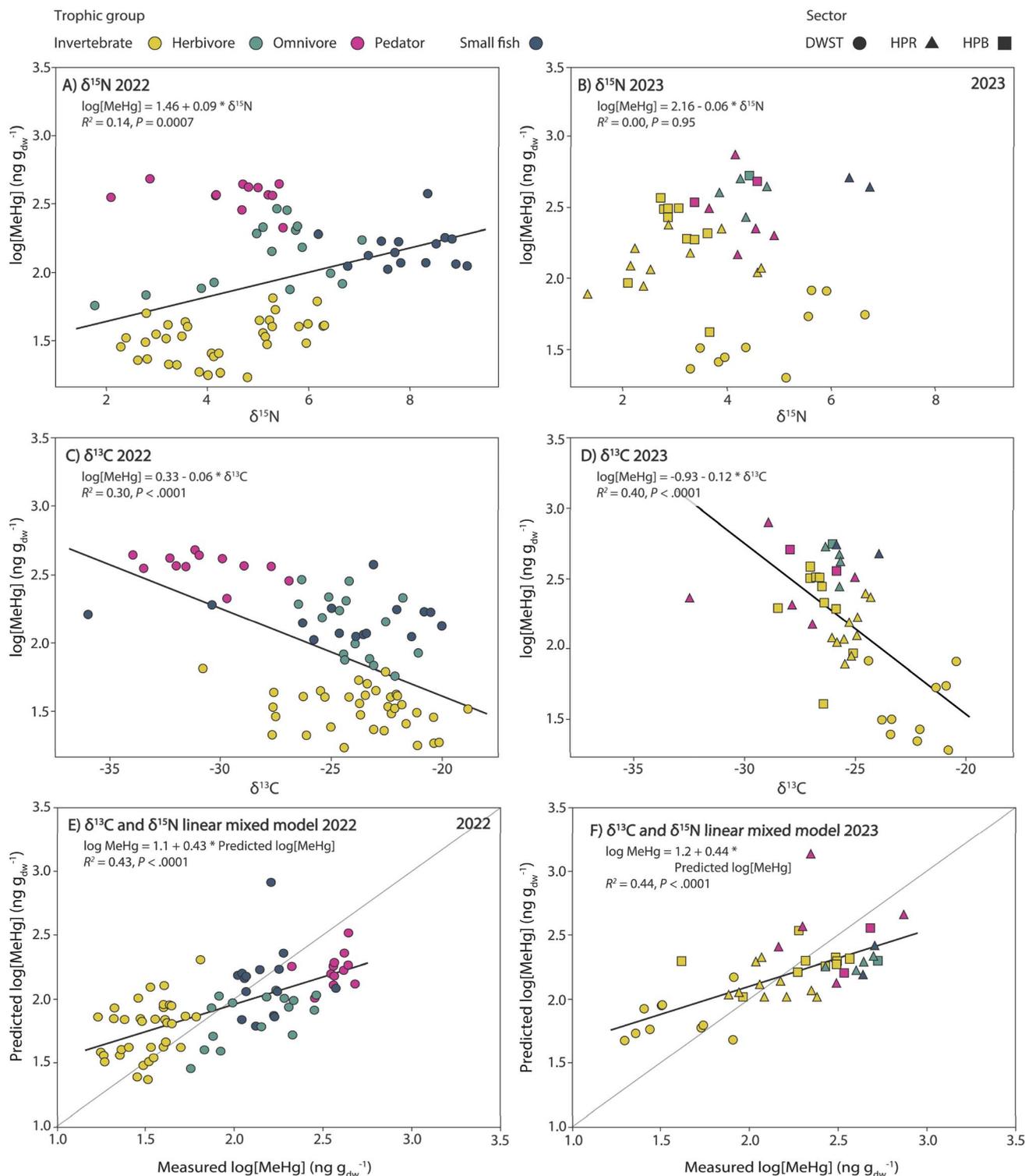


Fig. 5 Simple linear regressions of $\log[\text{MeHg}]$ ($\text{ng g}_{\text{dw}}^{-1}$) measured in biota plotted with $\delta^{15}\text{N}$ (‰) (A and B) and $\delta^{13}\text{C}$ (‰) (C and D)) in pre-flood conditions of 2022 (left panels) and three months post-flood in 2023 (right panels), and predicted $\log[\text{MeHg}]$ from the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ linear mixed model plotted with measured $\log[\text{MeHg}]$ ($\text{ng g}_{\text{dw}}^{-1}$) for 2022 (E) and 2023 (F). Trophic groups of invertebrates and small fishes are shown by the different colors while sampling sectors are highlighted by different shapes for the 2023 data only. A fit line is shown when the model is significant.



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