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Glacial bay as a local hot spot for retention and accumulation of heavy metals transported with glacier meltwater (Hornsund, Svalbard)

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Abstract

In this study, we aim to understand the influence of an underwater sill on the fate of suspended particulate material (SPM) discharged by a melting tidewater glacier in an Arctic glacial bay. We examined the potential significance of SPM retention for the bay's environment by analysing the fate of heavy metals introduced by glacier meltwater. Semi-enclosed bays with sills can not only limit water exchange but also act as effective traps for SPM and, consequently, for components, e.g., pollutants adsorbed onto these particles. Enhanced deposition of particulate pollutants can locally pose a threat to the ecosystem. We focus on Hansbukta, a glacial bay in Hornsund Fjord (Svalbard) that receives freshwater from the rapidly melting Hansbreen, a tidewater glacier. We analysed suspended particulate matter (SPM) concentrations and associated heavy metal content in six ablation seasons (2015–2020). Our results reveal seasonal variability in SPM and metal concentrations. In most months, over half of the analysed elements discharged with glacier meltwater remain in the bay. It was concluded that Hansbukta, which is isolated from the main fjord basin by an underwater sill, acts as a trap for metals and possibly other pollutants.

Keywords

Heavy metals; Pollutants; Melting glaciers; SPM; Glacial bays

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1. Introduction

Climate warming is significantly stronger in the Arctic, which has warmed nearly four times faster than the rest of the globe since 1979 (Rantanen et al., 2022). Increased glacier melting, permafrost thawing (Biskaborn et al., 2019), increased river runoff (McClelland et al., 2016), and stronger coastal erosion (Fritz et al., 2017) have significant impacts on the marine environment. Enhanced glacier melting induces higher discharges of freshwater and particulate matter directly into the sea via tidewater glacier outflows and indirectly via rivers fed by melting mountain glaciers. The main source of particles in a glacier's meltwaters is erosion of the bedrock under the glacier (Domack et al., 1994; Hallet et al., 1996). Glacier meltwater can be rich in particulates, mainly minerals, but also in petrogenic organic matter. Glacier meltwater can also include different compounds, e.g., pollutants that have been accumulated and stored in the glacier (e.g., Rudnicka-Kępa and Zaborska, 2021). Intense glacier melting increases the discharge of glacier meltwater to the glacial bays. Sediment-rich freshwater can be quickly spread and diluted, but it can also be retained in the enclosed system of the glacial bay.

Suspended particulate matter (SPM) is a fundamental component of marine ecosystems, exerting a profound influence on the physicochemical conditions within moving water masses (Blo et al., 2003; Cenci and Martin, 2004). The SPM discharged by glaciers acts as a crucial carrier for various substances. These include organic matter, nutrients, essential microelements, and pollutants, which can significantly affect the delicate balance of marine life. The transport mechanism of these particles plays a key role in the dispersion of adsorbed substances, especially heavy metals, within aquatic systems (Ardini et al., 2016; Bazzano et al., 2014, 2017; Zaborska et al., 2020). Glacier meltwaters can introduce accumulated pollutants into fjord waters, subsequently affecting the surrounding marine ecosystem (Cogley et al., 2011; Spolaor et al., 2021). In seawater, heavy metals are present in particulate or dissolved form. Particulate heavy metals are discharged to the sea already sorbed onto particulate material, and the sorption takes place in seawater. At the sudden salinity increase, dissolved metal ions transported by glacier freshwater are readily sorbed on the marine SPM (Park et al., 2014). Heavy metals persist in the environment and have the potential to bioaccumulate in marine organisms. As metals are potentially toxic, the studies of heavy metal discharge and fate in the Arctic are nowadays important.

Some tidewater glaciers discharge freshwater not to the open fjord but to glacial bays that are often enclosed by geographical and bathymetrical features. In such bays, limited water exchange can prevent further distribution of glacial freshwater. The bathymetric barriers preventing water exchange include underwater sills. Underwater sills can restrict the spread of freshwater discharged by the tidewater glacier, and also restrict the flow of open sea water (Zhao et al., 2021; Bao and Moffat, 2023). This process was observed in Hornsund (Jain et al., 2024).

Recent reports indicate that intense glacier melting can introduce previously deposited contaminants to the marine ecosystem (Kohler et al., 2007; Rudnicka-Kępa and Zaborska, 2021). Understanding the dynamics of glacier-derived SPM is of paramount importance in assessing the ecological consequences of pollutant discharge by glaciers to marine ecosystems. In addition, the analysis of the implications of particulate matter with absorbed pollutant deposition on the bottom, especially taking into account the role of bathymetry, is important. Sediment deposition on the bottom, resulting from the presence of a sill, affects the accumulation of pollutants in the marine environment, which is crucial for assessing the impact of contaminants on the benthic organisms living there. Heavy metals, even in low concentrations, can be poisonous to marine organisms. Marine sediments in fjords are affected by meltwater processes, iceberg calving effects, high sedimentation rates, seasonally stratified water masses, and glacier-controlled water currents (near the glacier), among others (Gilbert, 2000; Mackiewicz et al., 1984; Syvitski et al., 1987). Sedimentation rates in glacial fjords are usually high compared to the central parts of the fjord (Włodarska-Kowalczuk et al., 2019). Another important factor affecting the distribution of adsorbed contaminants on the suspension is sediment resuspension (Huang et al., 2012; Pourabadehei and Mulligan, 2016). The bottom of the bay around the sill consistently exhibits relatively high SPM concentrations throughout the year, e.g., because of this process (Syvitski et al., 1987; Moskalik et al., 2018).

The main goal of this article is to estimate the influence of specific bottom topography on the fate of suspended material and to study the consequences of SPM retention for the fate of pollutants discharged by the melting glacier. We hypothesise that the presence underwater sill creates a trap and enhances retention and accumulation of SPM and, in consequence, the pollutants absorbed onto SPM. It can be of particular importance as the Arctic receives additional discharges of different contaminants, e.g., heavy metals, due to glacier melting.

2. Material and methods

2.1 Study area

The Hornsund is located in the southern part of Spitsbergen, the largest island in the Svalbard archipelago. This fjord stretches approximately 35 km in length and spans a width of 2 to 12 km, covering an approximate area of 320 km^2 (Błaszczyk et al., 2013; Muckenhuber et al., 2016). Glaciers within Hornsund fjord occupy almost 70% of its total drainage area (Błaszczyk et al., 2009, 2013). Moreover, Hornsund hosts the most rapidly retreating glaciers as compared to other fjords of Svalbard (Grabiec et al., 2012; Błaszczyk et al., 2013, 2021).

Within the scope of this research, we focused our attention on Hansbukta (Figure 1), a bay hosting the tidewater glacier Hansbreen, with an ice cliff extending approximately 2 km in length. The bay covers an area of 6 km^2 and exhibits varying depths, reaching up to 80 m in the inner part and a maximum depth of 25 m in its outer region (Ćwiąkała et al., 2018). The glacial ablation is the primary source of freshwater in Hansbukta. The influx of freshwater into the fjord reaches its peak in July and August, as highlighted by Węsławski et al. (1995). The average summer and winter fluctuations are −125 m and 79 m, respectively (Błaszczyk et al., 2013, 2021). Interestingly, Ciepły et al. (2023) observed that the most substantial glacier calving took place in September, a trend that might be correlated with the intensified precipitation during that period, as suggested by Tęgowski et al. (2023). Such late-season glacier dynamics, prompted by heightened autumn rainfall, align with findings reported for other glaciers in Svalbard (Luckman et al., 2015; Schellenberger et al., 2015). The freshwater discharged by the glacier contains a high amount of suspended material (SPM). Its distribution within the glacial bay is mainly influenced by suspended particle size, flocculation, pycnocline, and the surface current, which results in the transport of SPM out of the bay (Szczuciński and Moskalik, 2017; Moskalik et al., 2018). Hansbukta's bathymetry enhances the accumulation of SPM at the bottom of the inner bay. SPM range 10–50 mg l^{-1}, and sedimentation rate range 100–5000 g m^2 d^{-1}, depending on distance from the glacier and season (Korhonen et al., 2024). As a result, accumulation rates are notably higher in the bay (0.84 cm yr^{-1}), even at the 1 km distance from the glacier front (Zaborska et al., 2017), as compared to the central fjord (0.2 cm yr^{-1}, Pawłowska et al., 2017; Zaborska et al., 2017). Accumulated sediments can play a crucial role in the distribution and retention of heavy metals, serving as sinks for contaminants transported by glacial meltwater. Hansbukta is separated from the main basin by a shallow sill at a depth of 15 m and is located about 2 km from the glacier front, originating from glacial deposits of moraine (Arntsen et al., 2019; Korhonen

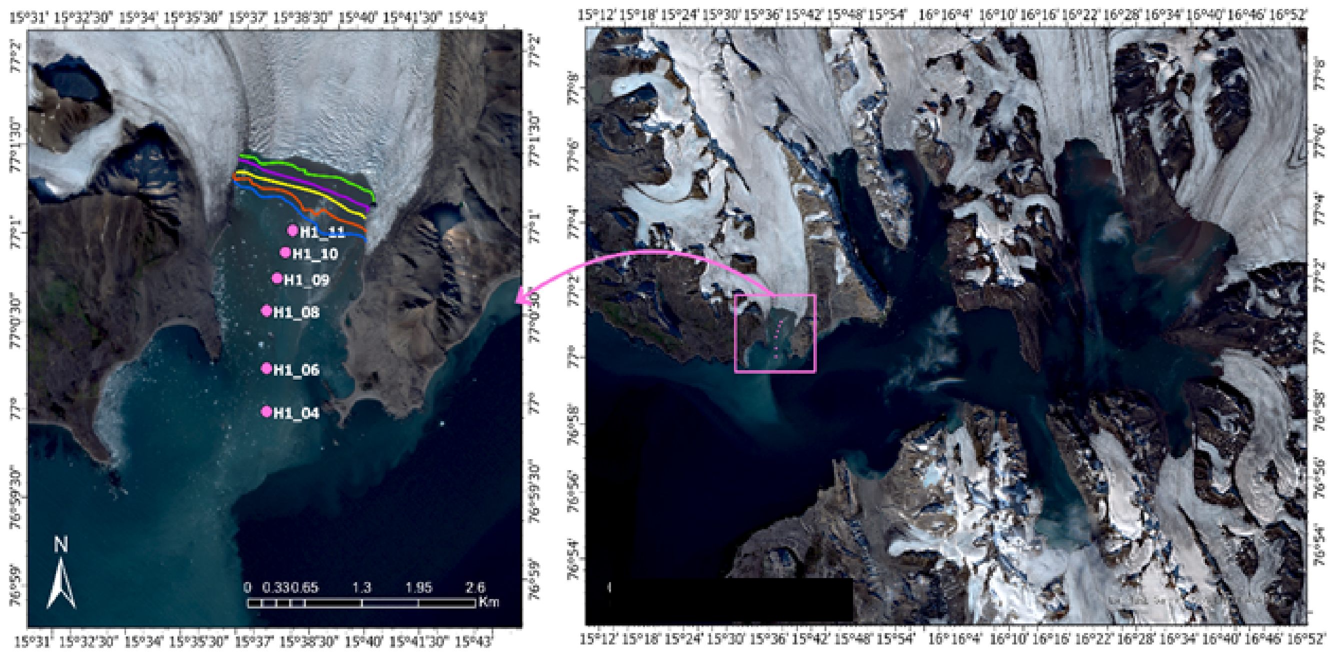

Figure 1. Location of the measurement stations in Hansbukta bay (blue line – ice cliff in 07.2015; orange line – 07.2016; yellow line – 07.2017; purple line – 07.2018; green line – 07.2019; satellite images from scihub.copernicus.eu/ (access date: 07.2023)).

et al., 2024). This sill limits water exchange between the bay and the main fjord basin, and in consequence, can act as a trap for SPM and heavy metals associated with SPM. The enhanced deposition and retention of heavy metals can be a threat to marine organisms inhabiting this region, especially less mobile benthic organisms.

2.2 Data and data analysis

Water samples for SPM concentration measurements were collected using a 1-litre Hydrobios Free Flow Niskin bottle at various depths. Each sample was filtered through pre-weighed Whatman GF/F filters (0.7 µm, 45 mm diameter). Filters were first dried at 200°C for 2 hours and then weighed with 0.001 g precision. After filtration, filters were dried again at 40°C for 24 hours and stored in a desiccator before final weighing. The amount of SPM was calculated by subtracting the initial filter weight from the final weight and dividing the result by the volume of filtered water (Korhonen et al., 2024). The data on heavy metals adsorbed onto suspended particulate matter were obtained from the study by Zaborska et al. (2020). Additionally, wave data (https://doi.org/10.1594/PANGAEA.954224; Świrad et al., 2023) as well as atmospheric precipitation and air temperature data (https://doi.org/10.1594/PANGAEA.921919; Wawrzyniak et al., 2020) were also used.

To ascertain the spatial distribution of SPM, we employed the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method, implemented using MATLAB software. This technique facilitated data interpolation for depth profiling and bridging gaps between profiles. The calculations were performed for each day with SPM investigations, analogously to the method used in the work of Moskalik et al. (2018).

The resulting interpolated SPM dataset was used to portray SPM distribution during the ablation season in the inner Hansbukta region, up to 2000 meters from the glacier where the underwater sill is located. The dataset was divided into two layers of water: above (depth 0–15 meters) and below (from 15 meters to the maximum depth) the sill. The main reason for this division is the role of the underwater sill in limiting the water exchange between the inner bay and the fjord. The SPM located in the layer above the threshold has the potential to be transported beyond the Hansbukta, while one located deeper will mostly be deposited at the bottom. The same is with heavy metals adsorbed on SPM. The number of measurement series in each season ranged from 3 to 9, while in each month, from 5 to 10 (Table S1). In total were 36 measurement series.

The data on heavy metals adsorbed onto SPM were obtained from a study by Zaborska et al. (2020). To determine the total mass of SPM and heavy metals adsorbed on them, we made calculations of the volume of water

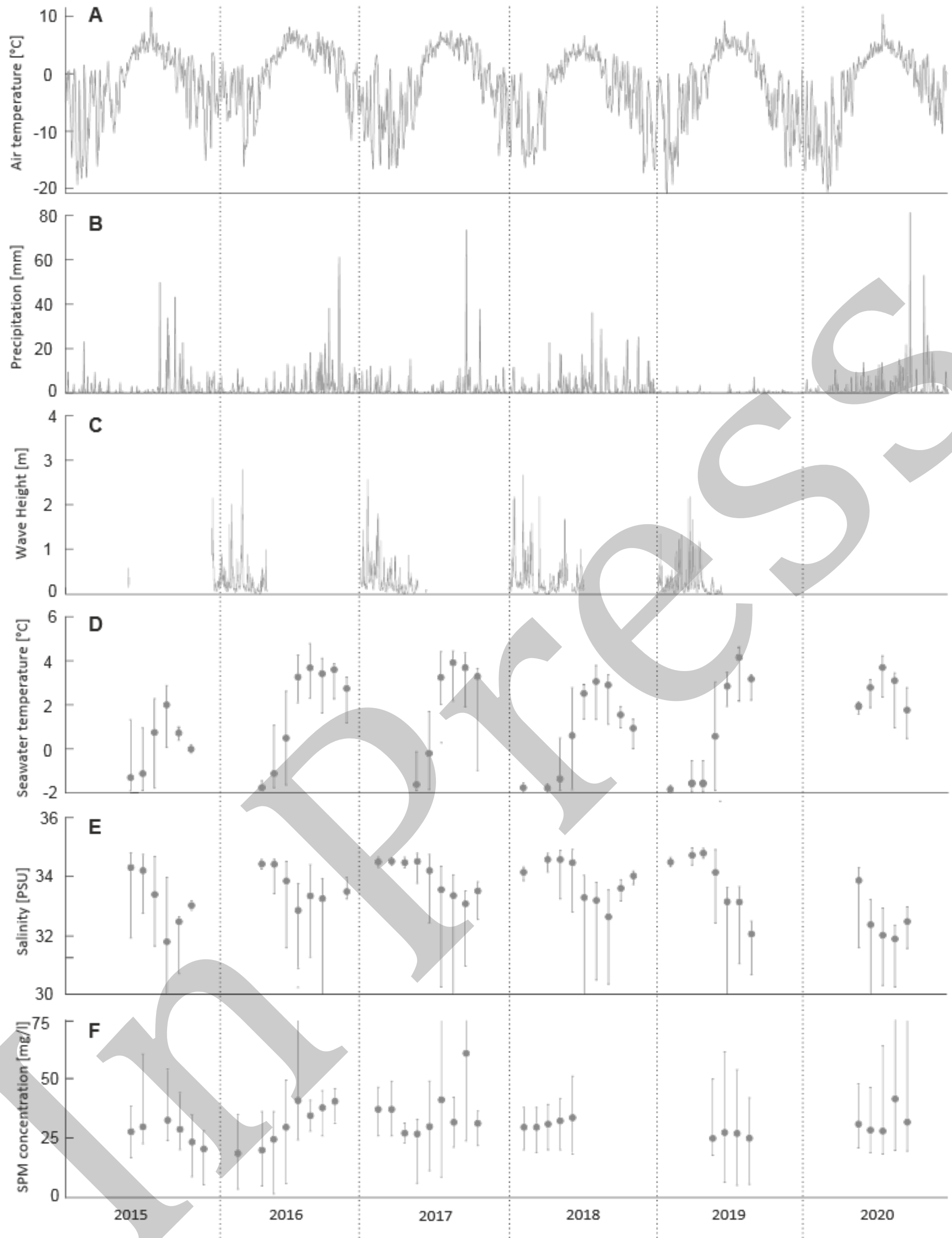

Figure 2. Annual meteorological conditions at the Polish Polar Station, including oceanographic conditions and SPM from all sampling stations (see Figure 1 for station locations). A) Mean daily air temperature (based on Wawrzyniak et al., 2020); B) daily precipitation (based on Wawrzyniak et al., 2020); C) significant wave height (Świrad et al., 2023); D) mean, minimum and maximum seawater temperatures; E) mean, minimum and maximum water salinity; F) mean, minimum and maximum SPM concentrations.

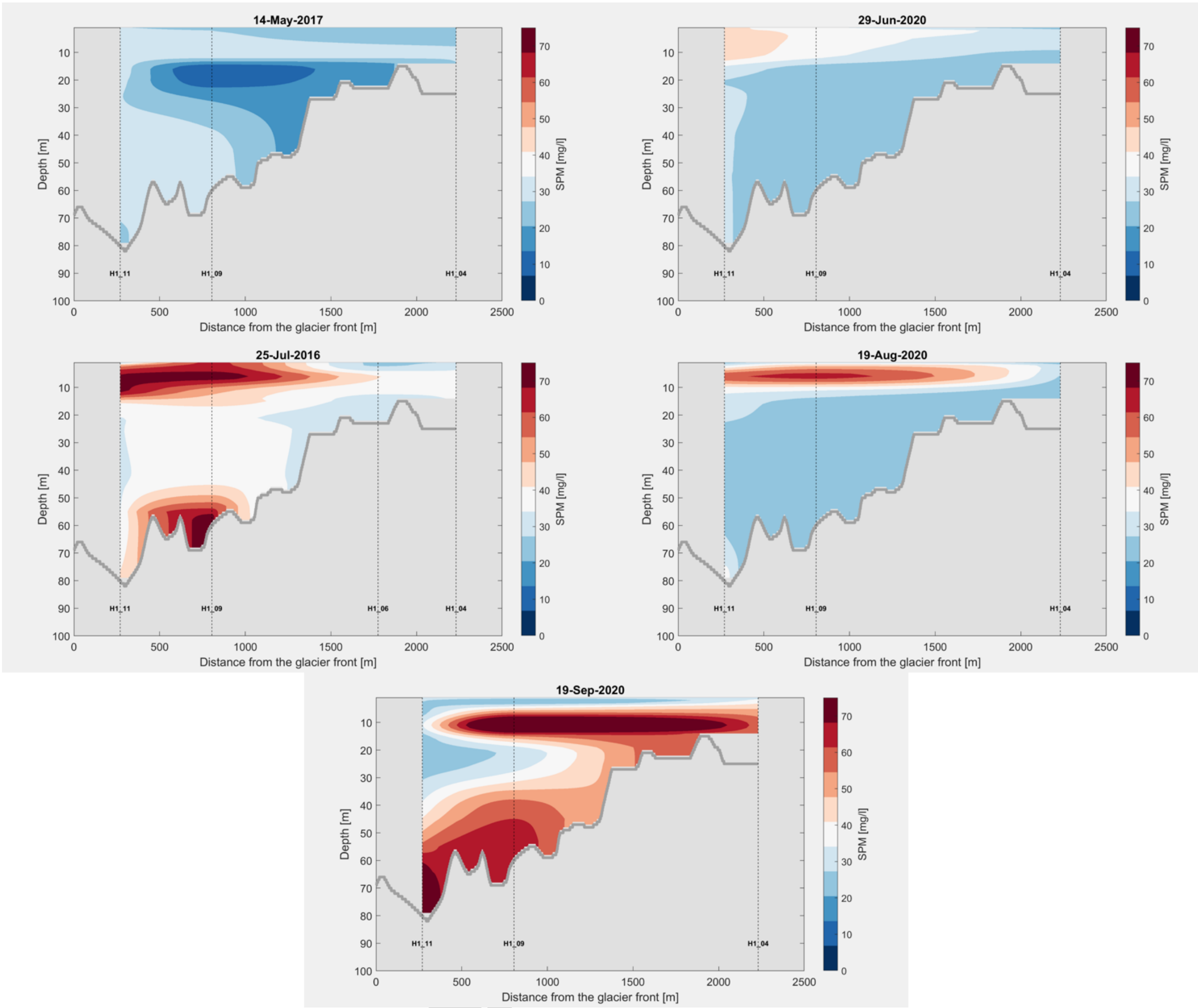

Figure 3. Vertical SPM distribution (mg/l) with distance from the glacier front – examples for different days.

in the bay. Hansbukta has an average depth of 39.2 m and an area of almost 3 km^2. The total volume of the bay was around 106,125,000 m^3, where part above the sill has 37,082,000 m^3 and below the sill: 69,043,000 m^3.

3. Results and discussion

3.1 Parameters influencing the spatial and temporal variability of SPM in Hansbukta Bay

The meteorological (air temperature and atmospheric precipitation) data for Hornsund are shown in Figure 2 (panels AB) together with the wave data (panel C). The CTD measurements and suspended particulate matter (SPM) concentration measurements in the Hansbukta are given in panels DEF (Figure 2).

During the period from May to September, significant changes in the concentration of suspended solids in the water column close to the Hansbreen glacier region are observed. The lowest SPM samples were measured during spring (2.3 mg/l on May 2016 at H1_09 on 0 m), while the highest were measured during summer (214.8 mg/l on July 2017 at H1_11 at surface) (Table S2).

The highest mean daily air temperature (11.5°C) was recorded in late July 2015, while the lowest (−10.4°C) was recorded in early May 2019 (Figure 2A). Higher air temperatures lead to increased ablation of glaciers, which increases the freshwater input with SPM into the bay.

Precipitation was low throughout the study period, but the highest daily precipitation occurred in September 2017 (Figure 2B). High rainfall can lead to increased freshwater inflow, which in turn can increase SPM (Figure 2B; Osuch and Wawrzyniak, 2016). Based on the wave height analysis, it can be seen that the highest values occurred in May 2015, while the lowest values were observed in May 2017 (Figure 2C). Waves, tidal currents, and water flows can play an important role in sediment redeposition, which also increases the concentration of suspended solids in the water. Water exchange processes between Hansbukta and the main part of Hornsund, driven by tides, Coriolis effect-induced circulation and freshwater inflow

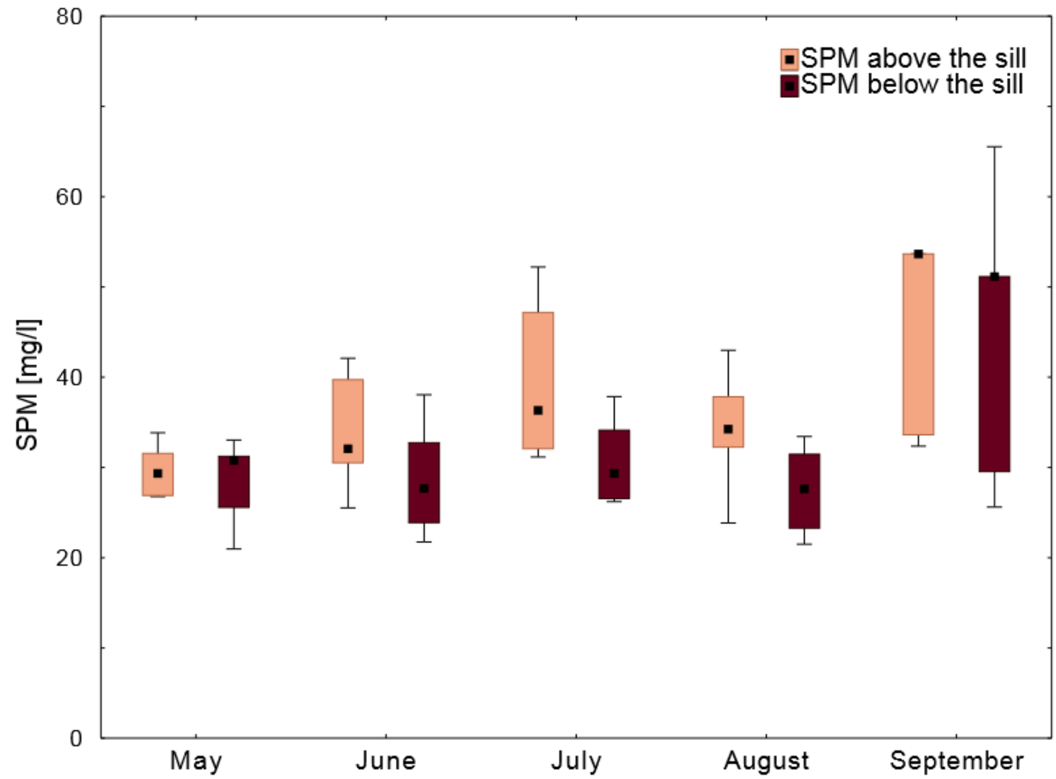

Figure 4. Variability of monthly 6-year average SPM concentration during the ablation season, divided for SPM above and below the sill. The median is indicated by the square in the bar.

from glacial melt, are estimated to have relatively fast bottom water flows of 15 cm/s, which promotes sediment resuspension (Moskalik et al., 2018; Świrad et al., 2023).

Seawater temperature ranged from −1.9°C in May 2018 to 4.7°C in August 2016 (Figure 2D). In contrast, salinity was lowest in September 2017 and highest in May and June 2018 (Figure 2E). Rapid jumps in temperature and salinity tend to the formation of a pycnocline, which reduces the mixing of water layers and again affects the distribution of SPM.

To assess the representativeness of single measurement results and to use monthly average values of the parameters from 2015–2019/20, we analysed measured data in the context of the variability of air temperature, precipitation, wave height (Figure 2ABC), seawater temperature and salinity (Figure 2DE). The analysis of the data affecting the concentration of suspension (Figure 2F) allowed us to conclude that the environmental parameters are characterised by a similar trend over the study period. Due to this closeness and in order to simplify the analysis, we decided to calculate and consider the monthly averages of SPM over and below the sill for each of the six consecutive ablation seasons from May 2015 to September 2020. Although this method carries a isk of error, we recognise that the differences between individual years have a small impact on the final results and are marginal.

The examples of the spatial distribution of SPM for different sampling months against depth and distance from the Hansbreen glacier are shown in Figure 3.

3.2 The impact of sill on suspended matter distribution within Hansbukta

The highest mean SPM concentrations averaged for 6 years of monthly data were in September, ranging from 25.6 to 65.5 mg/l, while the lowest averaged concentration was documented in May, ranging from 21.0 to 33.8 mg/l. The general trend during the analysed period is that above the sill (which coincides with the pycnocline at a similar depth), a higher concentration of suspended particulate matter is usually observed than below it, especially noticeable during the months from June to August, in line with the ablation season. May and September show the lowest differences in SPM concentration above and below the sill when better mixing in the water column results in no pycnocline (Figure 4).

The absence of a pycnocline, which is typically a good trap for suspension (Moskalik et al., 2018), leads to less stratification and therefore smaller differences in the water column. The highest concentration of SPM and the widest range of values are observed in September, which is a result of the highest rainfall in this region occurring in September and the last half of August (Łupikasza, 2013; Luckman et al.,

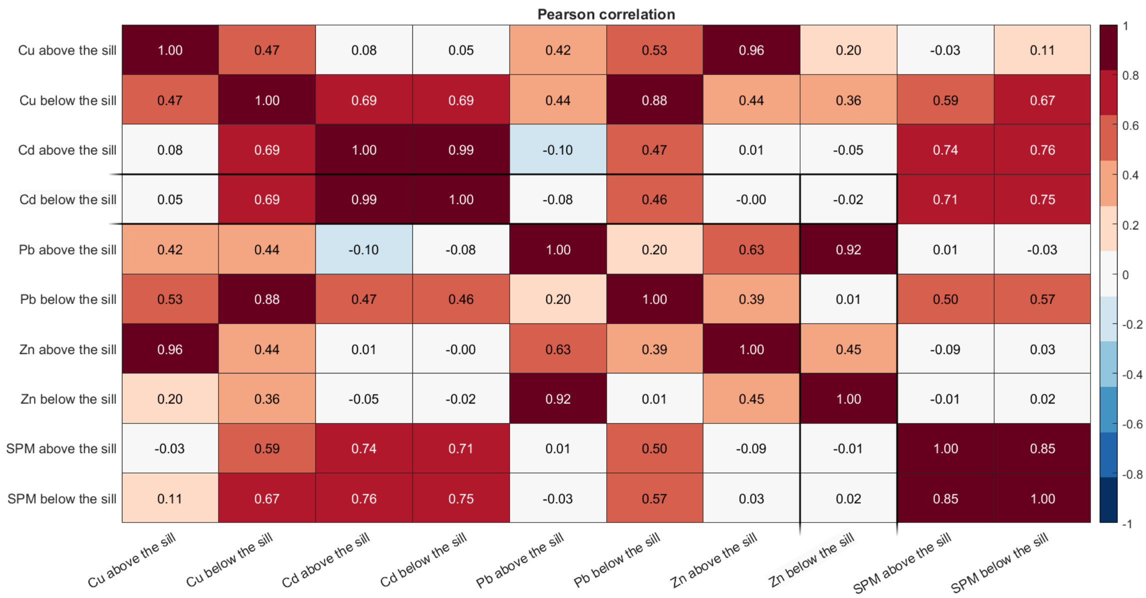

Figure 5. The correlation between heavy metal concentrations and SPM.

2015; Schellenberger et al., 2015; Osuch and Wawrzyniak, 2016).

Data presented in other glacial bays show a similar trend of higher SPM concentration in the surface water layers and near the glacier front (7.3–400.0 mg/l) compared to deeper areas and regions farther from the glacier front (0.13–10.0 mg/l) (e.g. Svendsen et al., 2002; Zajączkowski and Włodarska-Kowalczuk, 2007; Lund-Hansen et al., 2010; Politova et al., 2012, 2019; Bazzano et al., 2014; Ivanov et al., 2007; Ardini et al., 2016; Zhu et al., 2016).

3.3 Distribution and fate of heavy metals in Hansbukta

Seasonal and vertical distribution of heavy metals in the water column was measured in Hansbukta, and described in detail by Zaborska et al. (2020).

Correlation analysis of the relationship between SPM and heavy metals showed strong correlations, especially for Cd and Cu (Figure 5). For both the above and below sill layers, statistically significant positive correlations are observed with Cd and Cu concentrations, especially with suspended matter below and above the sill. The strong correlations ($r > 0.7, p < 0.001$) suggest that these metals are transported with the suspended material, indicating the role of the suspension as a metal carrier.

The presence of high correlations in the layer below the sill can be interpreted as an effect of sedimentation of the metal-rich suspension into deeper parts of the water. This supports the hypothesis that the Hansbukta may act as a heavy metal and other pollution trap, especially in the context of the inflow of material from melting glaciers. Ultimately, this suggests that increasing transport of SPM from glaciers may lead to local accumulation of pollution on the bottom layers of the fjord.

Particulate metal concentrations were recalculated according to the mass of suspended particles (SPM) present in the seawater samples and the volume of Hansbukta (up to the sill and below, respectively), resulting in the total mass of individual heavy metals in the water column. Heavy metals analysed showed fluctuations throughout the whole water column. The highest total amount of Cu adsorbed on suspended sediment in the water column was in May (976 g), while the lowest Cu mass was calculated for June (101 g). The highest values (8469 g) of Zn were found in August, while the lowest were in June (775 g). The mass of Pb (139 g) was the lowest in June, while the highest (1858 g) was in August. The highest total amount of Cd was calculated for September (403 g), while the lowest Cd was for July (2 g).

To enhance our understanding of the distribution and fate of heavy metals in Hansbukta, we analysed the data concerning their positions relative to the bottom sill. Heavy metal content exhibited variations above and below the sill. If the sill were absent, a greater proportion of heavy metals would likely be transported out of the bay, reducing local accumulation. In the layer above the sill, the highest total Cu mass was observed in May (747 g). The lowest values were observed in June (69 g). Below the sill, the highest and lowest Cu contents for the respective months were 228 g in May and 32 g in June. Above the sill, the highest total Zn mass was recorded in August (2853 g), while the lowest Zn mass (266 g) was measured in July. Below the sill, the highest and lowest Zn masses were 5616 g in August and 535 g in July. For lead (Pb), the highest total mass above the sill was found in August (1570 g), while

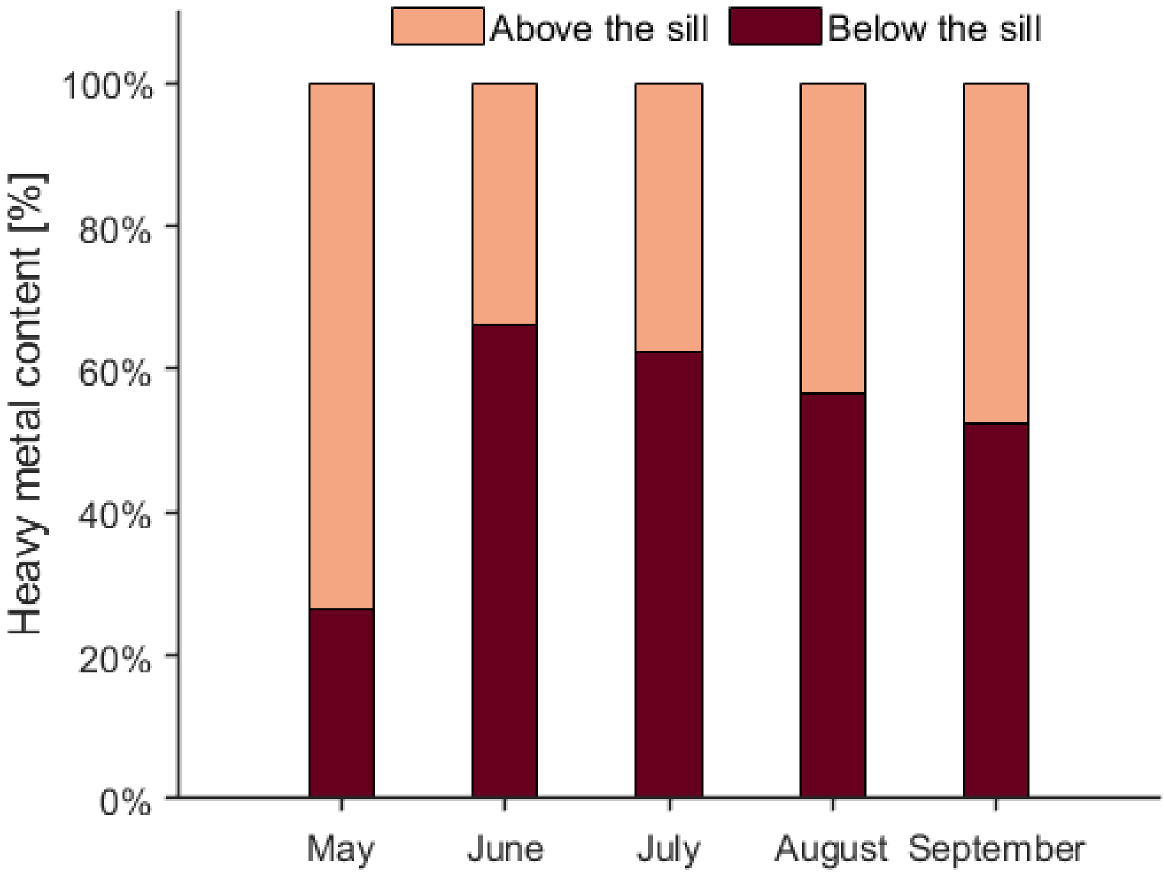

Figure 6. Variability of heavy metals content (%) during the ablation season, divided into metals above the sill (light brown) and below the sill (dark brown).

the lowest Pb masses (35 g) were measured in June. Below the sill, the highest and lowest Pb masses were equal to 424 g in September and 103 g in June. For Cd, the highest total mass above the sill was recorded in September (238 g), while the lowest Cd masses (0.4 g) were measured in July. The distribution of cadmium below the sill relative to the months was the same. The highest content was recorded in September (164 g), and the lowest in July (1.2 g). Overall, the distribution of heavy metals varied, with the highest concentrations generally observed in late summer and early fall, and the lowest in early summer.

The observed changes in metal content appear to be seasonal, with marked differences between months (Figure 6). These fluctuations have important implications for the fate of heavy metals in the Hansbukta area, especially concerning their transport (inwards and out of the bay) by hydrodynamic processes and ocean currents. In May, the layer above the sill exhibited greater content of Cu, Zn, Pb and Cd (77%, 79%, 61% and 75%, respectively). In June, elevated Cu levels were detected in the same stratum (68%), while the Zn, Pb and Cd were amassed beneath the lower sill (69%, 74% and 63%, respectively). In July, heavy metals were rapidly deposited in the deeper layers of the bay (64% for Cu, 66% for Zn, 57% for Pb, and 74% for Cd). In August, both Cu and Pb indicated similar patterns, with higher content in the water layer above the sill (53% and 84%, respectively), while Zn and Cd consistently maintained higher levels below the sill (66% and 76%, respectively). In September, only the total mass of Cd was higher in the water layer above the bottom sill (59%), while Zn was evenly distributed throughout the water column.

Considering all the heavy metals analysed and the entire ablation period, the amount of metals above and below the sill generally looks very similar, showing that approximately half of the elements from the melting glacier were deposited in the small area that is the bottom of the bay, while the other was probably transported by surface current to the central Hornsund fjord. Suspended aggregates observed in the surface water layer in summer reach an average flocculent grain size of 30 to more than 120 µm, while below the pycnocline, only aggregates with an average flocculent size of more than 125 µm are carried

(Szczuciński and Moskalik, 2017). Thus, in addition to the surface current being responsible for carrying pollutants out of the bay, the role of the pycnocline is also important. This was probably related not only to the sill, but also to the longer residence time (slower settling rate) of the smaller aggregates, which may have settled through the lower density gradient of the pycnocline (Moskalik et al., 2018). It is worth noting that, although the metals are generally present in relatively low concentrations, some metals, e.g. Cd, can seasonally and locally exceed environmental thresholds for seawater (Zaborska et al., 2020). Thus, their accumulation in Hansbukta may adversely affect local organisms. Only in May, the average of all analysed metals shows a higher concentration above the sill (Figure 6). This phenomenon can be connected to the fact that with the melting of the fast ice cover, all pollutants accumulated in the sea ice over the winter and early spring season are released to the water column (Zaborska et al., 2020). In contrast, the largest discharges of melted glacier from underwater subglacial tunnels that start to increase in July are not located at the seawater surface but closer to the bottom of the glacier in the eastern and central glacier terminus at a depth of about 40 m (Pälli et al., 2003).

In order to further examine the spatial differences in metal concentrations near the meltwater plume, an additional set of surface SPM samples was collected in July 2022 directly at the discharge of Hansbreen using a remotely operated vehicle (ROV) (Zaborska et al., in prep). The average SPM concentration in these samples was 274.7 mg/l, which was several times higher than in a surface sample collected further away from the glacier during the same month (57.4 mg/l). Concentrations of dissolved metals were also notably higher near the discharge: Pb reached 5574.1 ng/l (compared to 529.0 ng/l at the more distant station), Zn 38,975.0 ng/l (vs. 13,792.2 ng/l), and Cu 7781.3 ng/l (vs. 941.8 ng/l). Cd concentrations were more similar between the two locations (37.2 vs. 34.3 ng/l). The content of metals associated with SPM showed higher variability – Zn, Cu, and Cd were present at higher levels near the glacier (148.9, 29.5, and 0.1 µg/kg, respectively), while higher Pb content was recorded in the samples collected farther from the glacier front (38.8 µg/kg vs. 21.9 µg/kg). The SPM content in surface seawater samples collected farther from the glacier front in other months was even eleven times lower (23.0 mg/l) than that collected near the front in 2022. Similarly, the dissolved metal concentrations were also much lower at the more distant station. For the particulate fraction, the opposite trend was observed: Pb and Cd contents were higher in the distant samples (61.9 and 7.0 µg/kg, respectively) compared to those near the glacier (21.9 and 0.1 µg/kg). In contrast, Zn and Cu in SPM were slightly more concentrated near the glacier (148.9 and 29.5 µg/kg) than farther away (208.5 and 39.5 µg/kg). These results support the general pattern observed in previous studies: the highest loads of dissolved metals and suspended matter tend to occur locally at the point of discharge. The additional results confirm a very important role of glaciers in discharging metals to the glacial bays. The greater share of metals associated with particles at distant parts of the fjord can be linked to post-depositional processes such as sorption, sedimentation, or differences in the composition of the suspended material (Lu et al., 2013; Grotti et al., 2017; Moskalik et al., 2018; Zaborska et al., 2020).

The phenomenon of retention and high accumulation of pollutants in Hansbukta can be relevant for other glacial bays characterised by the presence of an underwater sill. Thus, further studies are necessary to understand the fate of pollutants discharged to the glacial bays with glacier meltwater.

3.4 Long-term SPM sedimentation patterns and implications for further heavy metal accumulation in bottom sediments

In order to investigate the long-term variability of SPM sedimentation and accumulation in bottom sediments in Hansbukta, the results achieved in this study at station H3 were compared to sediment core analyses from the same station presented by Rudnicka-Kępa et al. (2024). Sediment accumulation rate was modelled using the 210Pb dating method (CRS model). In the upper part of the core (0–5 cm), corresponding to the period of 2010–2016 (including two years considered in this article), the particle mass accumulation rate varied from 302 to 383 mg/cm^2 yr (Rudnicka-Kępa et al., 2024). The accumulation rate in surface sediments was quite stable as compared to older sediment layers, which were from 160 to 512 mg of particles per square centimetre deposited annually. This can suggest that the SPM flux to Hansbukta bottom sediments does not exhibit recently large inter-annual variability.

The concentrations of heavy metals such as Cu, Zn, Pb, and Cd in surface sediments also showed relatively stable values (22.6–24.5 mg/kg, 81.2–87.8 mg/kg, 15.0–17.8 mg/kg, and 0.17–0.22 mg/kg, respectively) (Rudnicka-Kępa et al., 2024). Meanwhile, the average contents of the same metals in SPM were significantly higher: 39.5 mg/kg, 208.5 mg/kg, 61.9 mg/kg and 7.0 mg/kg, respectively. This may indicate that monthly changes in metal concentrations in the suspension were not strongly reflected in the bottom sediments. If particulate discharges from the glaciers are temporarily higher, metals dilute in high suspension, thus those changes are not reflected in the bottom sediments. A similar process was previously described by Zaborska et al. (2017) for the Kongsfjorden, where, despite high SPM concentrations, metal concentration in sediments was lower than elsewhere. Additionally, similar observations were reported in other studies of Arctic fjords, where despite variable inflow of suspended material, metal concentrations in bottom sediments showed relative stability, and their variability was strongly dependent on the rate of sediment accumulation and the characteristics of the sediment material, and not only on the amount of metal inflow (Choudhary et al., 2020; MK et al., 2021; Choudhary et al., 2024).

On average, half of the metals adsorbed on suspended sediment in the whole glacial bay during the sampling day (Cu: 101–976 g, Zn: 775–8469 g, Pb: 139–1858 g and Cd: 2–403 g) is deposited within glacial bay sediments. The mean annual accumulation of metals at the bay bottom was 22 mg/m^2 yr for Cu, 170 mg/m^2 yr for Zn, 34 mg/m^2 yr for Pb and 1 mg/m^2 yr for Cd (Rudnicka-Kępa et al., 2024), while the annual particle (SPM) accumulation rates were of 3.0 to 3.8 kg/m^2 from 2010 to 2016.

4. Conclusions and significance for further research

This study represents the first detailed analysis of the impact of underwater sills on the distribution and fate of SPM and heavy metal content in the Arctic glacier bay. Our results show that Hansbukta, separated from the main Hornsund fjord by a shallow sill, retains a significant portion of glacier-derived SPM and associated pollutants. During the ablation season, about half of the metal load (Cd, Cu, Pb, Zn) transported by glacial meltwater is deposited below the sill, suggesting that specific bathymetry plays a key role in local contaminant retention. This can lead to the formation of pollution hotspots, which are particularly dangerous for less mobile benthic organisms. These phenomena can be relevant for all glacial bays characterised by the presence of a sill limiting the seawater exchange. Similar fjords with underwater sills appear not only in Spitsbergen but also in Greenland (e.g., Ilulissat Icefjord; Gladish et al., 2014; Petermann Fjord; Hogan et al., 2020), Antarctica (e.g., Andvord Bay; Lundesgaard et al., 2020), New Zealand (e.g., Bligh Sound, George Sound; Stanton and Pickard, 1981), Alaska (e.g., Glacier Bay; Matthews, 1981; Hooge and Hooge, 2002) and Patagonia (e.g., Reloncaví Fjord; Castillo et al., 2016; Puyuhuapi Fjord; Pinilla et al., 2020).

As a warming climate accelerates the melting of glaciers (Rantanen et al., 2022; Biskaborn et al., 2019), such semi-enclosed bays may increasingly act as sinks for both older and modern pollutants (Rudnicka-Kępa and Zaborska, 2021; AMAP, 1998). Given the persistence and toxicity of trace metals and their ability to bioaccumulate (Zaborska et al., 2020; Chételat et al., 2022), this phenomenon represents a growing ecological risk. Further research and monitoring of these processes, particularly in enclosed glacial bays, is needed to better understand the impact of climate change on the Arctic environment.

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Conflict of interest

None declared.

Supplementary material

Supplementary material associated with this article can be found here.

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