The new kids on the block of Arctic coasts – Formation and Morphodynamics of Paraglacial Moraine Lagoons in Svalbard

Zofia Owczarek[1], Oskar Kostrzewa[1], Wojciech Piskorski[1], Mateusz C. Strzelecki[1]

[1]Alfred Jahn Cold Regions Research Centre, University of Wrocław, Wrocław, 50-137, Poland

Correspondence to: Zofia Owczarek (zofia.owczarek@uwr.edu.pl) & Mateusz C. Strzelecki (mateusz.strzelecki@uwr.edu.pl)

Abstract. As Arctic amplification accelerates glacier retreat, new dynamic landscapes are emerging at the interface of terrestrial and marine systems. This study identifies and analyses a distinct coastal landform: the Paraglacial Moraine Lagoon (PML). Formed by coastal barriers composed of terminal or lateral moraines deposited during the Little Ice Age, PMLs represent a critical yet understudied component of the glacier–climate change feedback system. Using a multi-decadal record (1936–2024) comprising aerial photography, satellite imagery, and the Digital Shoreline Analysis System (DSAS), we quantified the evolution of fourteen PML systems across the Svalbard Archipelago. Our results show that PMLs now occupy over 56% of Svalbard's total lagoon area (ca. 83 km^2), nearly triple the area they occupied in the 1930s. We identify two divergent evolutionary trajectories: (1) an erosional – fragmenting pathway (e.g., Tjuvfjordlaguna), where marine forcing leads to barrier narrowing and inlet expansion, and (2) a stabilizing – isolating pathway (e.g., Femtelaguna), where land-terminating glaciers drive rapid terrestrial sediment infilling and barrier progradation. We argue that PMLs function as essential "paraglacial sinks" trapping glaciogenic sediments and organic matter, thereby creating sheltered biodiversity hubs in otherwise harsh coastal environments. As transient features, the formation and eventual destruction of PMLs serve as a high-resolution proxy for the rapid paraglacial adjustment of polar coastlines.

Paper highlights:

- **New Landform Classification:** Formalizes the "Paraglacial Moraine Lagoon" (PML) as a distinct, moraine-controlled coastal system in the Arctic.
- **Rapid Spatial Expansion:** PML surface area in Svalbard has tripled since 1936, now covering ca. 83 km^2.
- **Divergent Trajectories:** Identification of two evolutionary pathways – marine-driven fragmentation versus terrestrial-driven isolation – based on glacier connectivity.
- **Sediment Budget Buffers:** PMLs act as critical "sediment traps", preventing the immediate loss of glaciogenic material to the deep shelf.
- **Geoecological Refugia:** Moraine barriers create low-energy habitats that support benthic biodiversity and migratory bird stopovers in high-energy polar zones.

1 Introduction

Climate change is particularly pronounced in the Arctic, where, due to the phenomenon of Arctic amplification, warming occurs at nearly four times the global average rate (Rantanen et al., 2022). Such intense warming triggers a cascade of environmental changes, leading to rapid transformations of the polar landscape and the functioning of glacial and paraglacial systems (Ballantyne, 2002; Bendixen and Kroon, 2017; Kavan et al., 2024; Overeem et al., 2022; Strzelecki et al., 2017, 2020; Zagórski et al., 2012). One of the most visible consequences of contemporary warming is the accelerated melting and retreat of glaciers (Błaszczyk et al., 2013; Geyman et al., 2022; Kavan and Strzelecki, 2023), which significantly impacts the geometry and dynamics of Arctic coastlines (Kavan et al., 2025). Glacier retreat exposes new land surfaces, creating young, dynamic coastlines shaped by a combination of geomorphological processes, including erosion, sediment transport, and redeposition (Strzelecki et al., 2018, 2020; Zagórski et al., 2020). In some instances, newly exposed areas emerge as rocky islands (Ziaja and Haska, 2023; Ziaja and Ostafin, 2019). The functioning of paraglacial coasts largely depends on sediment availability and glacier-front dynamics. Marine-terminating glaciers can generate high-energy waves through calving (Wolper et al., 2021), which intensely reshape young coastlines (Kostrzewa et al., 2024). Additionally, episodic sediment inputs from eroding moraines and rock landslides influence both the rate and irregularity of coastal evolution (Frydrych and Zagórski, 2024; Svennevig et al., 2024).

Arctic lagoons are among the most dynamic coastal environments, highly sensitive to sea-level changes, wave regimes, and sediment supply. In regions experiencing intensive deglaciation, they act as transitional, sedimentary reservoirs, responding rapidly to changes in climate and hydrology (Angelopoulos et al., 2020; Primo et al., 2018; Ziaja et al., 2009). In Svalbard, the formation of many new lagoons since the end of the Little Ice Age (in Svalbard, this corresponds to the early 20th century) is closely linked to glacier retreat and paraglacial processes (Owczarek, 2025). The development of the paraglacial lagoon – Recherchelaguna – was documented by Zagórski et al. (2012) and was associated with a surge of Recherebreen that created a natural dam from emerging deltas, enabling the rapid establishment of a water body at the glacier front. After another surge between 2019 and 2020, the formation of a delta was observed once again in front of the glacier's subglacial meltwater outlet, this time reducing the lagoon’s area (Kavan et al., 2024). The rapidly changing environment of paraglacial lagoons is not only associated with the marine-terminating glaciers. Detailed studies of the Eidemlaguna (associated with a land-based Eidembreen) also reveal the complex and dynamic nature of the paraglacial lagoon (Šiaulys et al., 2026). It remains in a state of continuous transformation and responds dynamically to ongoing deglaciation, changes in sediment supply, and episodic geomorphological events.

Glacier retreat exposes new land surfaces and creates dynamic coastlines shaped by erosion, sediment transport, and redeposition. In some instances, these processes lead to the formation of unique coastal landforms. Of particular interest is a newly identified type of moraine-controlled system forming in glacier frontal zones: the Paraglacial Moraine Lagoon (PML). We define PMLs as lagoon systems separated from the open sea by barriers primarily composed of former push or terminal moraines, often partially ice-cored, deposited during recent glacier retreat. This moraine-based structural foundation distinguishes PMLs from lagoons built by proglacial deltas or sandy barriers and fundamentally controls their stability and evolution. We hypothesize that these lagoons act as transitional, sedimentary reservoirs, responding rapidly to changes in climate and hydrology. Their evolution is likely controlled by the interplay between glacier retreat, relative sea-level changes, and the inherent stability of the moraine barriers. In this framework, PMLs represent a key component of the feedback system linking glacier activity and the Arctic coastal environment. Although the preliminary concept of these landforms was introduced previously under different terminology (Owczarek, 2025 – MCPALS from moraine-controlled paraglacial lagoon systems), we now advocate adopting PML as the standard geomorphological nomenclature. This article aims to analyse the mechanisms driving the evolution of a complete set of 14 PMLs in Svalbard and to assess their role as a new paraglacial storage and landform system in the evolving Arctic environment during deglaciation.

2 Study area

The research area covers five islands that are part of the Svalbard Archipelago: Spitsbergen, Nordaustlandet, Edgeøya, Barentsøya, and Prins Karls Forland (Fig. 1) located in the European Arctic and bordered by the Barents Sea to the east, the Greenland Sea to the west, and the Arctic Ocean to the north. The regional climate of Svalbard is strongly influenced by oceanic circulation, with the warm West Spitsbergen Current (WSC) affecting the western part of the archipelago and the cold East Spitsbergen Current influencing the eastern sector. The inflow of warm Atlantic water via the WSC results in milder climatic conditions compared to other regions at similar latitudes, enhancing glacier sensitivity to atmospheric and oceanic warming (Noël et al., 2020).

The Svalbard Archipelago is still largely covered by glaciers and ice caps (about 60% of its surface area), with Svalbard's glaciers having a relatively flat surface and located mainly at an altitude of less than 450 metres above sea level (compared to Greenland or Canada at 800–1400 metres above sea level) (Noël et al., 2020). This hypsometric setting makes Svalbard’s glaciers particularly vulnerable to atmospheric warming, resulting in one of the fastest rates of surface mass loss observed globally (Noël et al., 2020).

Glacier retreat and thinning have led to profound transformations of Svalbard’s coastal zones, including the rapid exposure of previously ice-covered shorelines and the release of large volumes of glacial and paraglacial sediments. These processes create favourable conditions for the formation and rapid evolution of new coastal landforms, including paraglacial lagoon systems developing in the glacier foreland (Kavan and Strzelecki, 2023). To analyse their temporal evolution and geomorphological diversity, we identified and examined the complete set of 14 PMLs currently existing across the archipelago. These 14 sites encompass the full range of observed glacier–coast interactions and deglaciation stages in the region.

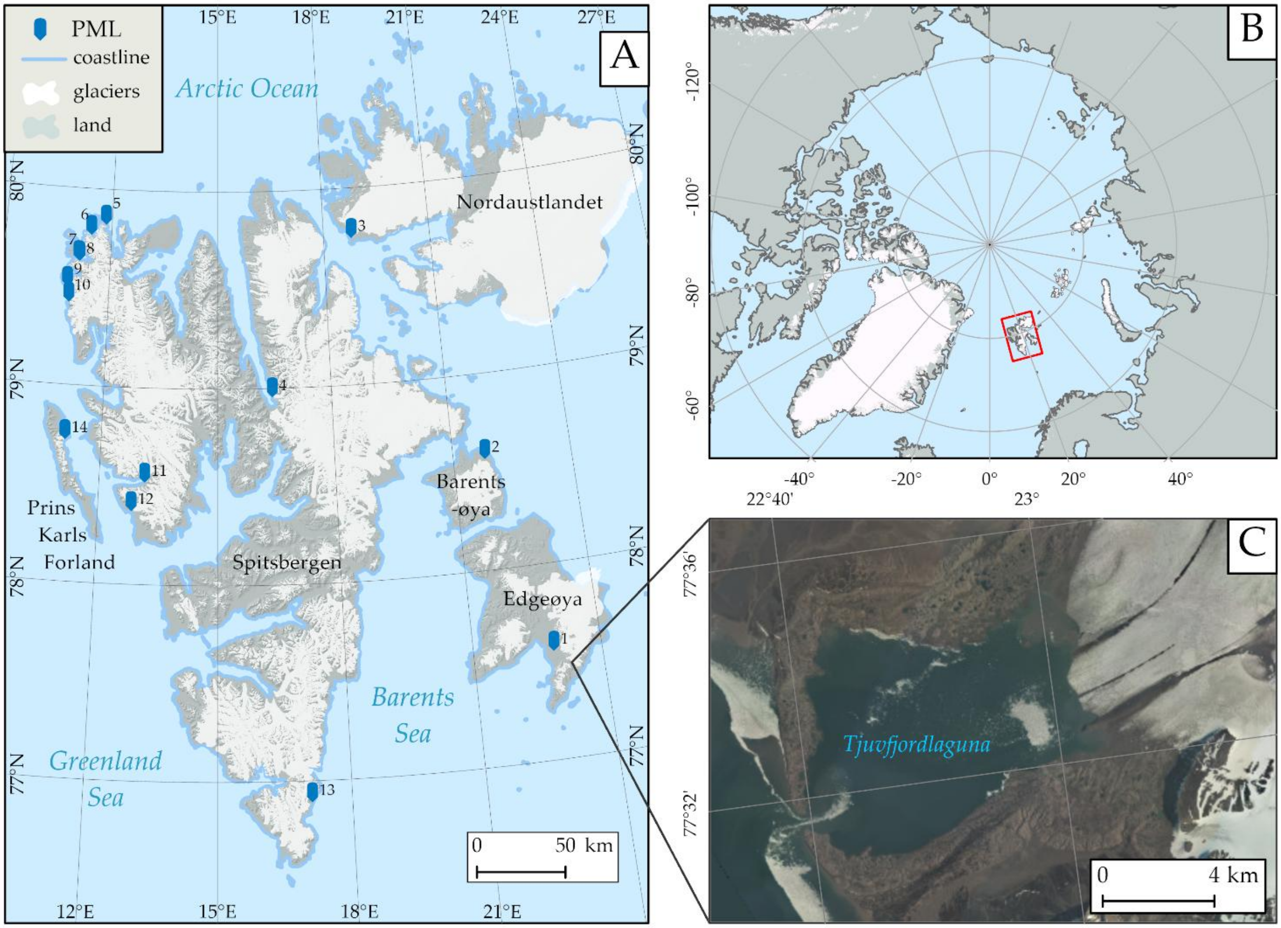

Figure 1: (A) PMLs' location on Svalbard. 1 – Tjuvfjordlaguna, 2 – Kapplaguna, 3 – Gimlelaguna, 4 – Snaddlaguna, 5 – Makarovlaguna, 6 – Rissalaguna, 7 – Schielaguna, 8 – Skodelaguna, 9 – Sjulaguna, 10 – Femtelaguna, 11 – Charleslaguna, 12 – Eidemlaguna, 13 – Tromsølaguna, 14 – Murraylaguna. (B) Svalbard (marked with a red rectangle) on an Arctic map. (C) The most representative paraglacial moraine lagoon in Svalbard – Tjuvfjordlaguna. Base map: 2010 orthophotomap comes from the (Norwegian Polar Institute, n.d.).

3 Data and methods

Spatial data for the analysis were derived from aerial photographs, satellite imagery, and orthophotomaps. This multi-source approach enabled the acquisition of information spanning almost 90 years of environmental changes. Aerial photographs, originating from Norwegian Aerial Campaigns conducted in the 1930s, 1960s, and 1990s, were obtained from the Norwegian Polar Institute (NPI). An orthophotomap, generated for the 1930s from oblique aerial photographs (Geyman et al., 2022), covers nearly the entirety of the Svalbard Archipelago (excluding the northeastern part of Nordaustlandet). Contemporary changes in the lagoon systems were assessed using satellite imagery from the Sentinel, Planet, and Landsat missions. These images were specifically acquired during the July–September period of 2024, coinciding with the polar day and minimizing the influence of snow cover for data interpretation.

Data resolution varied depending on the source. Satellite imagery from the last decade offered resolutions of up to 3 meters, while aerial photographs provided resolutions of approximately 1 meter. It should be noted that, due to limitations associated with this method of data collection, aerial photographs did not always cover all of the studied lagoons. This was either because flights did not cover the study area or because only a fragment of the lagoon was captured. In some cases, photographs could not be georeferenced due to an insufficient number of reference points. These photographs were not used for measurements but served only as qualitative data to visualise the environment at a given time.

The 5 meters resolution orthophotomap was generated from the 1930s oblique aerial photographs by Geyman et al. (2022). Despite the high quality of the original images, their conversion required complex orthorectification to correct for terrain and perspective distortions. Although essential for creating a map-accurate representation, this correction process ultimately degraded the final data quality by introducing minor geometric errors and lowering the representational accuracy.

The above-mentioned data sources were used for manual digitalisation, performed with QGIS 3.34 and ArcMap 10.8. This process enabled the analysis of morphological changes in the lagoons, moraines, and barriers over the specified period (1936–2024). However, it is acknowledged that manual vectorization introduces a degree of subjectivity in lagoon identification. Nonetheless, automated data extraction methods previously applied in Svalbard (Urbański, 2022) have proven to be inappropriate for lagoons in this region. This is primarily due to the water's characteristic coloration, often exhibiting brown or rust hues from sediment input from glacial meltwater.

Supplementary data regarding the lagoon systems were obtained from the Norwegian Polar Institute's TopoSvalbard map service. TopoSvalbard provided information on lagoon and glacier identification, which was used to determine the elevations of the barriers separating the lagoons from the sea during the 2010s.

The analysis of coastal dynamics was supported by the Digital Shoreline Analysis System (DSAS) version 6.0, widely used to quantify shoreline changes in Svalbard (e.g., Czarnecki and Sobota, 2025; Himmelstoss et al., 2021; Zagórski et al., 2015, 2020). DSAS was applied to determine rates of progradation or retreat of lagoon barriers and adjacent shoreline segments based on digitised shoreline positions, primarily from 1936 and 2024, to capture the largest changes. In the case of Femtelaguna, the DSAS analysis was performed for the 2010 and 2024 coastlines (in 1936, the lagoon did not exist, and during digitalisation, interesting changes in the barrier were noticed, which we wanted to present quantitatively). Baselines were manually defined parallel to the general orientation of the coast, and transects were automatically generated at fixed 1 m intervals, ensuring high measurement resolution. Changes were quantified using the End Point Rate (EPR) and Net Shoreline Movement (NSM) methods, with estimated positional uncertainty ranging up to 5 m depending on the quality of the source data and georeferencing accuracy. DSAS outputs provided quantitative estimates of linear change rates, complementing qualitative and morphological analyses of lagoon evolution and enabling standardized comparisons of coastal dynamics across the studied PML systems.

Given the association of each PML with the glacier forming its terminal moraine, glacier retreat rates were calculated as the mean of three measurement points for each glacier over defined time periods. The data included mean distances from previous glacier extents, overall average retreat distances, and average retreat rates, allowing a comprehensive assessment of glacial dynamics and their influence on lagoon system development. Integrating glacier retreat data with DSAS results enabled a coherent connection between morphological changes of lagoons, coasts, and glacier dynamics, providing a more complete understanding of the processes shaping PML systems in Svalbard (Barnes, 1980; Kjerfve and Magill, 1989; Owczarek, 2025).

4 Results

4.1 Spatiotemporal evolution of PMLs

In Svalbard, more than half of the lagoon area (56.3%) is occupied by PMLs, covering over 82.9 km^2 (Table 1). In the 1930s, six of the 14 selected lagoons did not yet exist, and two were glacial lakes. The area of the six PMLs existing in the 1930s was approximately 27.7 km². Over the course of 88 years, the PML's area has nearly tripled. The largest Svalbard lagoon, Tjuvfjordlaguna (Fig. 2), is the best example of PML and in 2024 covers an area of more than 61 km^2 (73.7 % of the PML's total area). It is more than twice the total area of all 13 other lagoons combined (21.8 km^2). In 1936, the lagoon measured approximately 3500 m east–west and 7000 m north–south; by 2024, these dimensions shifted to 11,000 m and 4500 m, respectively. This eastward expansion aligns with a calculated glacier recession rate of 75.5 m·yr^{-1} (Table 2). Between 2010 and 2024 (during which time all lagoons already existed), the area of PMLs increased by more than 14 km². The Tjuvfjordlaguna area alone increased by as much as 10 km².

Table 1: The area of PMLs (existed means that the lagoon existed at that time, but its area could not be measured due to the mismatch of the aerial photograph; x means no data). *The Murraylaguna is included in the total area of PML, but we believe that after 2010, the barriers separating the lagoon from the sea are too small to refer to it as a leaky lagoon. In our opinion, it is a bay in its current state.

Name	Lagoon area [km^2]				
	1936	1960	1990	2010	2024
Charleslaguna	0.940	existed	x	0.991	0.867
Eidemlaguna	0.097	1.606	2.769	5.239	6.076
Femtelaguna	not existed	existed	x	0.408	0.384
Gimlelaguna	glacial lake	x	x	0.381	0.386
Kapplaguna	glacial lake	x	x	0.292	0.285
Makarovlaguna	0.196	0.531	0.756	0.881	0.916
Murraylaguna	not existed	1.467	1.974	2.847	3.617
Rissalaguna	not existed	x	x	0.022	0.021
Scheilaguna	not existed	existed	x	0.677	0.685

Sjulaguna	0.632	existed	x	1.780	2.075
Skoddelaguna	not existed	existed	x	0.541	0.766
Snaddlaguna	not existed	x	x	3.291	5.042
Tjuvfjordlaguna	25.759	x	41.028	50.885	61.170
Tromsølaguna	0.074	x	x	0.643	0.640
Sum	27.698	3.604	46.527	68.877	82.928

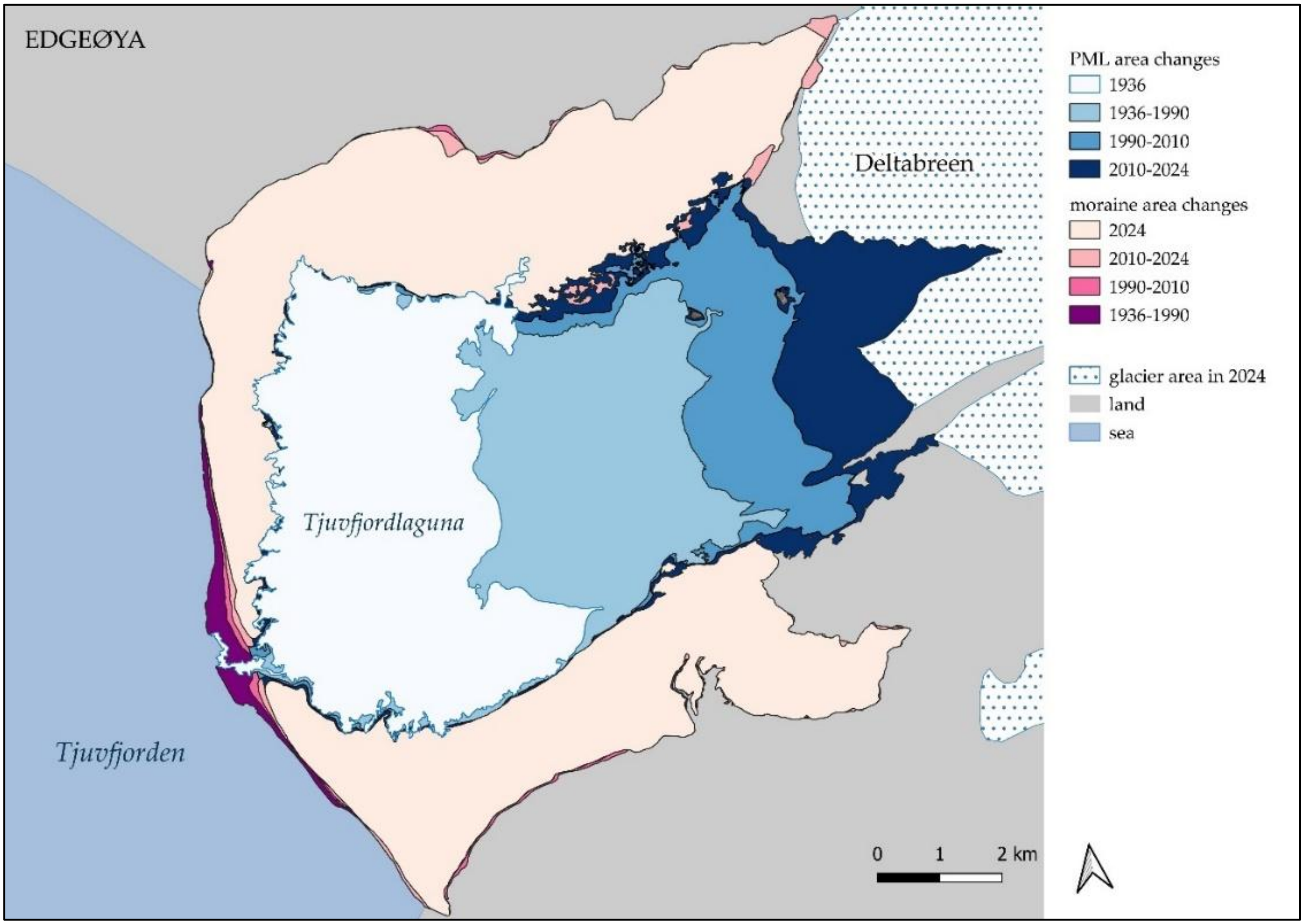

Figure 2: The map shows changes in the surface area of the Tjuvfjordlaguna and moraines over the years.

Further notable changes occurred in Snaddlaguna (Table 1 and Fig. 3) and Eidemlaguna (Table 1 and Fig. 4). Their areas increased by 1.751 km² and 0.837 km², respectively. It is worth noting that Eidemlaguna recorded the most spectacular relative increase. From a small lagoon with an area of 0.09 km² in the 1930s (the second smallest lagoon measured at that time), it has become a huge reservoir with an area of 6.1 km². This is an increase of over 6700%, making it the most rapidly growing system in terms of growth rate. The dynamically changing Eidemlaguna environment is also highlighted by Šiaulys et al. (2026). It is also worth mentioning that the surface area of Eidemlaguna was as large as 6.6 km² in 2023 (Šiaulys et al., 2026) and 6.1 km² in 2024 (Table 1). This change may be due to the sediment flux from the Eidembreen, which built up the islands that were previously located there, thus reducing the lagoon surface area.

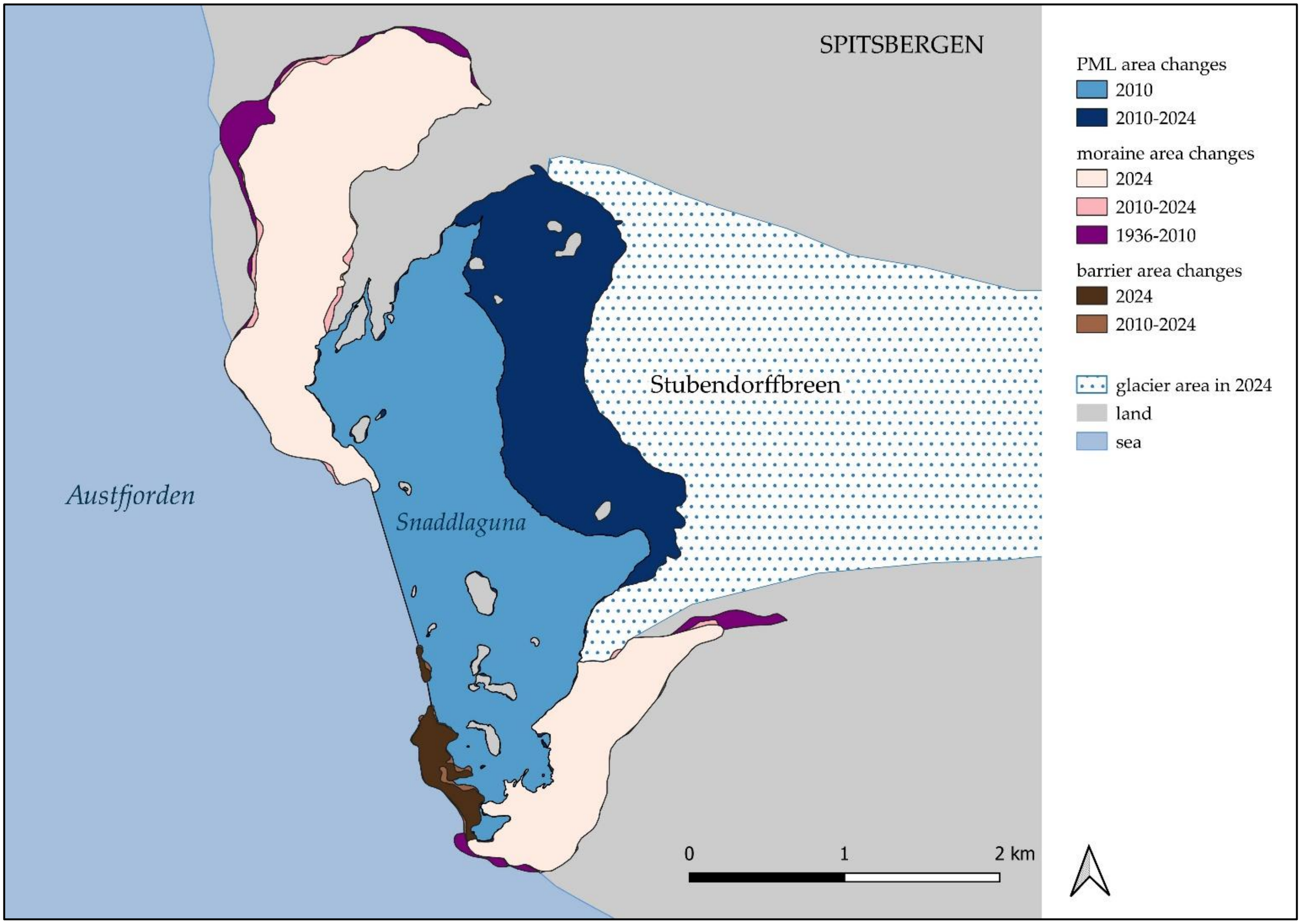

Figure 3: The map shows changes in the surface area of the Snaddlaguna, barriers, and moraines over the years.

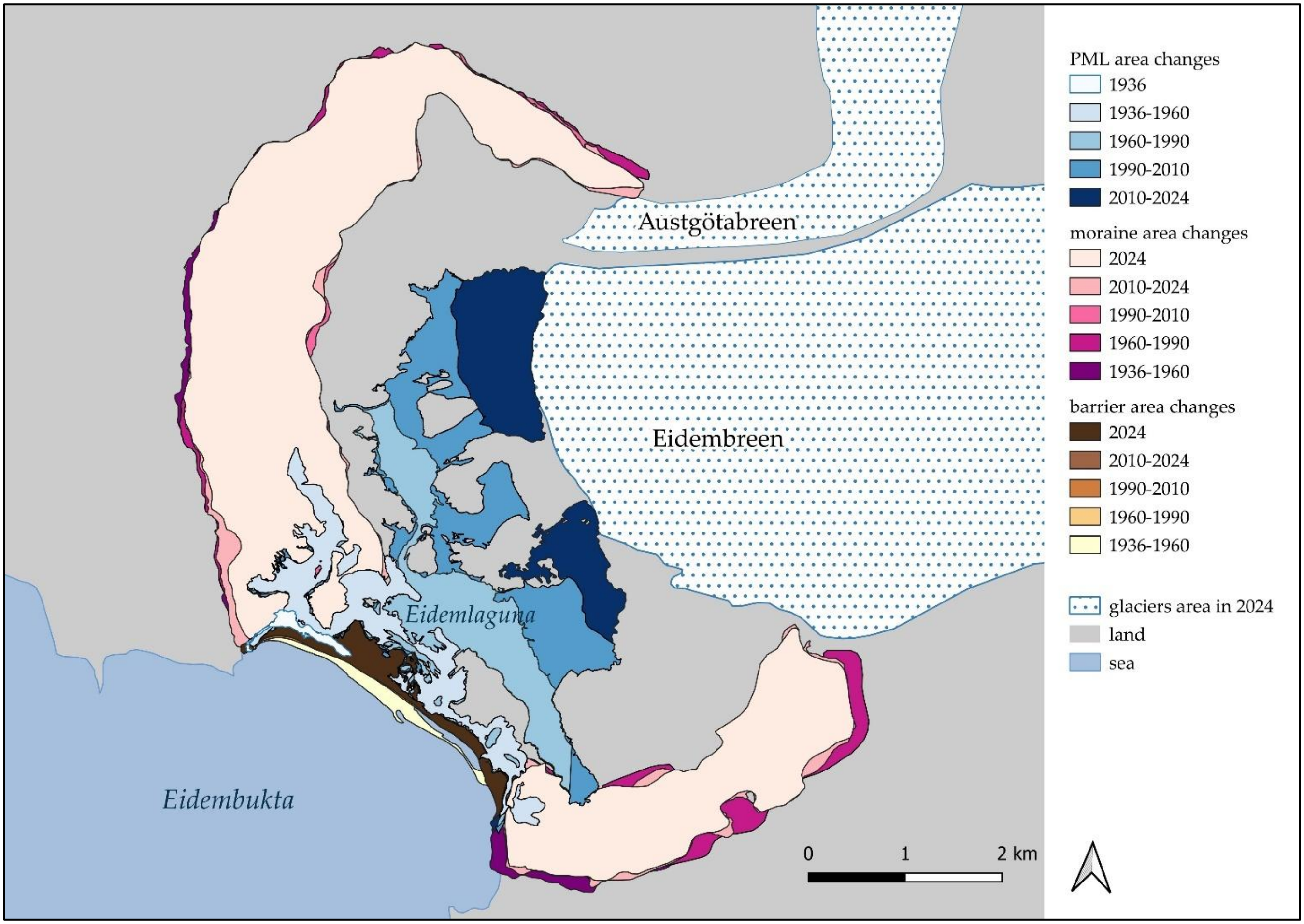

Figure 4: The map shows changes in the surface area of the Eidemlaguna, barriers, and moraines over the years.

In most cases, PMLs are expanding, but in four cases, their area is decreasing. The largest area decrease was recorded in Charleslaguna (Fig. 5), from 0.991 km² to 0.867 km² (a 12.5 % area decrease over 14 years). Femtelaguna (Fig. 6) was second, with a 6 % change in area, losing 0.025 km². Overall, over the past almost 90 years, the area of PMLs in Svalbard has increased notably, with only a few lagoons showing a slight decrease.

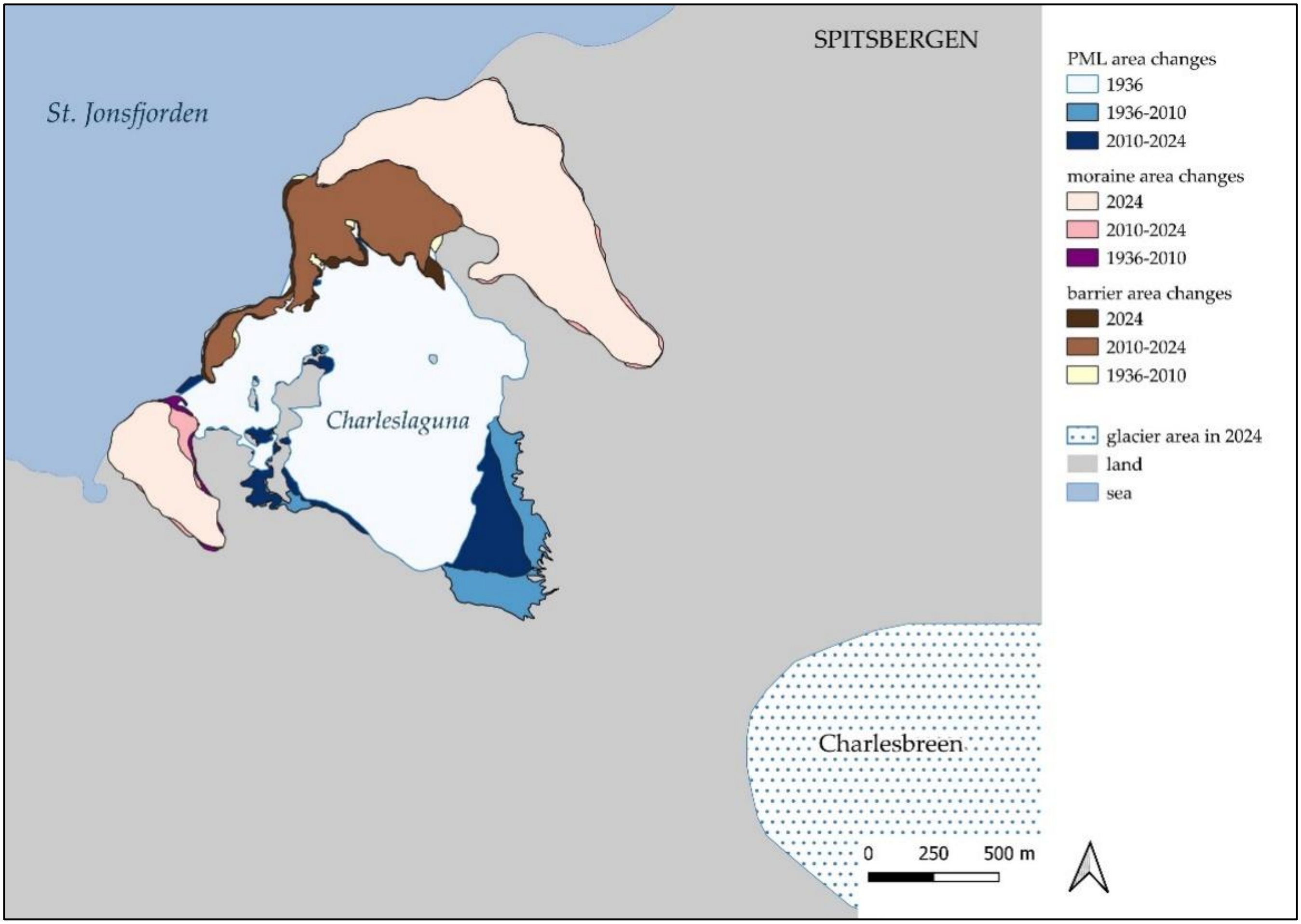

Figure 5: The map shows changes in the surface area of the Charleslaguna, barriers, and moraines over the years.

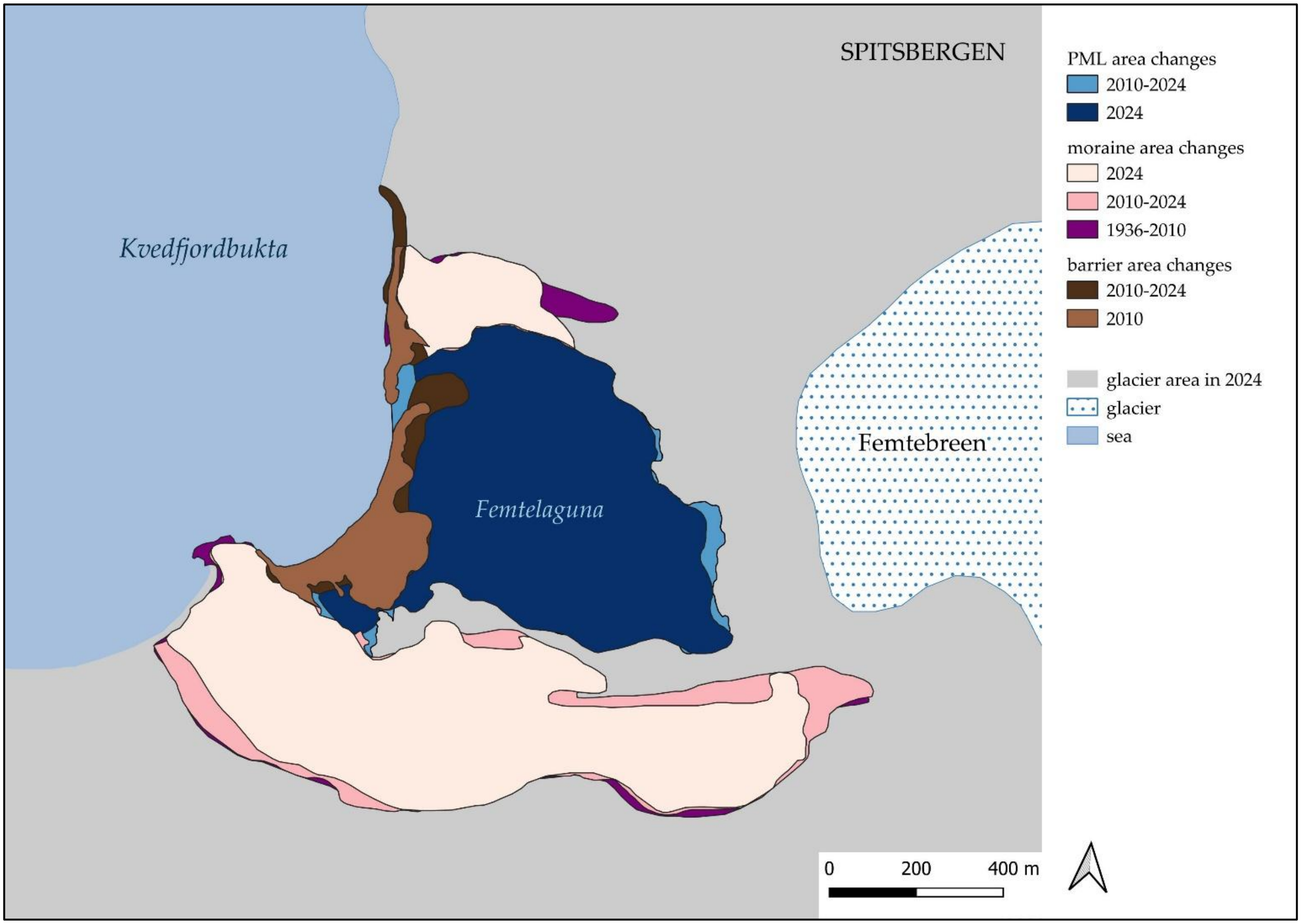

Figure 6: The map shows changes in the surface area of the Femtelaguna, barriers, and moraines over the years.

4.2 Glaciers retreat and marine connectivity

The glaciers' retreat associated with PMLs exhibits notable spatial and temporal variability across Svalbard (Tables 2 and 3). Overall, every studied system is linked to a retreating glacier, with average recession rates ranging from 7.6 m·yr^{-1} to over 75 m·yr^{-1} (Table 2). Changes in PMLs are primarily a consequence of melting glaciers. In this case, the greatest change was observed in Deltabreen – the glacier connected to Tjuvfjordlaguna. Over the course of 88 years, the glacier retreated inland by more than 6.6 km (at a rate of approx. 75 m·yr^{-1}). During the most recent interval (2010–2024), Deltabreen also exhibited the greatest recession, retreating by approximately 1.7 km, followed by Eidembreen at 0.85 km. Both glaciers demonstrated relatively consistent retreat rates throughout the entire study period. In contrast, Makarovbreen, Makarovlaguna's (Fig. 7) "parent" glacier, showed a notable deceleration. Despite previous retreat magnitudes ranging from 0.282 km to 0.589 km per period (0.484 km between 1936 and 1960, 0.589 km between 1960 and 1990, and 0.282 km between 1990 and 2010), its margin remained nearly stationary between 2010 and 2024, with a negligible shift of only 0.002 km.

These rates are broadly consistent with previously published values for comparable glaciers, although glacier-specific retreat estimates for the individual systems studied here are largely absent from the literature, so comparisons are necessarily drawn at the scale of regionally and morphologically analogous glaciers. The closest analogue is the work of (Kavan et al., 2022), who examined 11 tidewater glaciers along the south-east coast of Spitsbergen using a 1970 DEM combined with recent ArcticDEM and Landsat/Sentinel-2 imagery, and reported an average frontal retreat rate of 48 $\mathrm{m \cdot yr^{-1}}$ (range 10–150 $\mathrm{m \cdot yr^{-1}}$), with four of the eleven glaciers becoming land-based as their termini retreated. Our values fall squarely within this published range: the lower end of our dataset (7.6 $\mathrm{m \cdot yr^{-1}}$) corresponds to typical land-terminating behaviour, while Deltabreen's ~75 $\mathrm{m \cdot yr^{-1}}$ lies within the upper-middle of the tidewater range. This is also in line with the glacier-type typology of Rachlewicz et al. (2007), who distinguished land-terminating glaciers receding at roughly 5–15 $\mathrm{m \cdot yr^{-1}}$, non-surging tidewater glaciers at about 15–70 $\mathrm{m \cdot yr^{-1}}$, and surging tidewater glaciers reaching 100–220 $\mathrm{m \cdot yr^{-1}}$. More broadly, our findings support the regional picture in which eastern Svalbard has experienced some of the most pronounced ice loss in the archipelago: the Edgeøya ice field has shown the largest retreat rates of all Svalbard glaciers over recent decades (Nuth et al., 2013), and since the Little Ice Age, glaciers on Barentsøya and Edgeøya have lost 16.7% of their area – the highest proportional loss among the main islands of the archipelago (Martín-Moreno et al., 2017).

Differences between our rates and previously published values can be attributed to several factors. First, methodological and temporal differences are important: our long-term rates are centreline recession distances averaged over an 88-year, multi-epoch baseline (1936–2024), whereas satellite-era studies such as Li et al. (2025), who resolved calving-front change across the Barentsøya – Edgeøya sector, derive shorter-interval, calving-front rates that are more sensitive to seasonal and interannual variability; averaging over different epochs and reference baselines inevitably yields divergent values. Second, glacier dynamics play a role, as eastern Svalbard is one of the principal clusters of surge-type glaciers, and terminus advances during surges have historically punctuated the general post-LIA retreat in this region; the near-stationary margin of Makarovbreen between 2010 and 2024 is consistent with a post-surge quiescent phase rather than a simple climatic deceleration. Third, and most likely for the decelerating systems, the transition from a marine- to a land-terminating configuration removes the calving and submarine-melt component that drives rapid tidewater retreat; once a terminus grounds in shallower water or on land, retreat tends to slow, a mechanism invoked to explain the eventual stabilisation of retreating Svalbard tidewater glaciers (Li et al., 2025), and this paraglacial transition is itself the process generating the new coastal lagoons examined here (Kavan and Strzelecki, 2023). Finally, local controls – bed slope and overdeepening, water depth at the grounding line, aspect, and hypsometry – produce substantial inter-glacier variability superimposed on the regional climatic signal (Małecki, 2013; Rachlewicz et al., 2007).

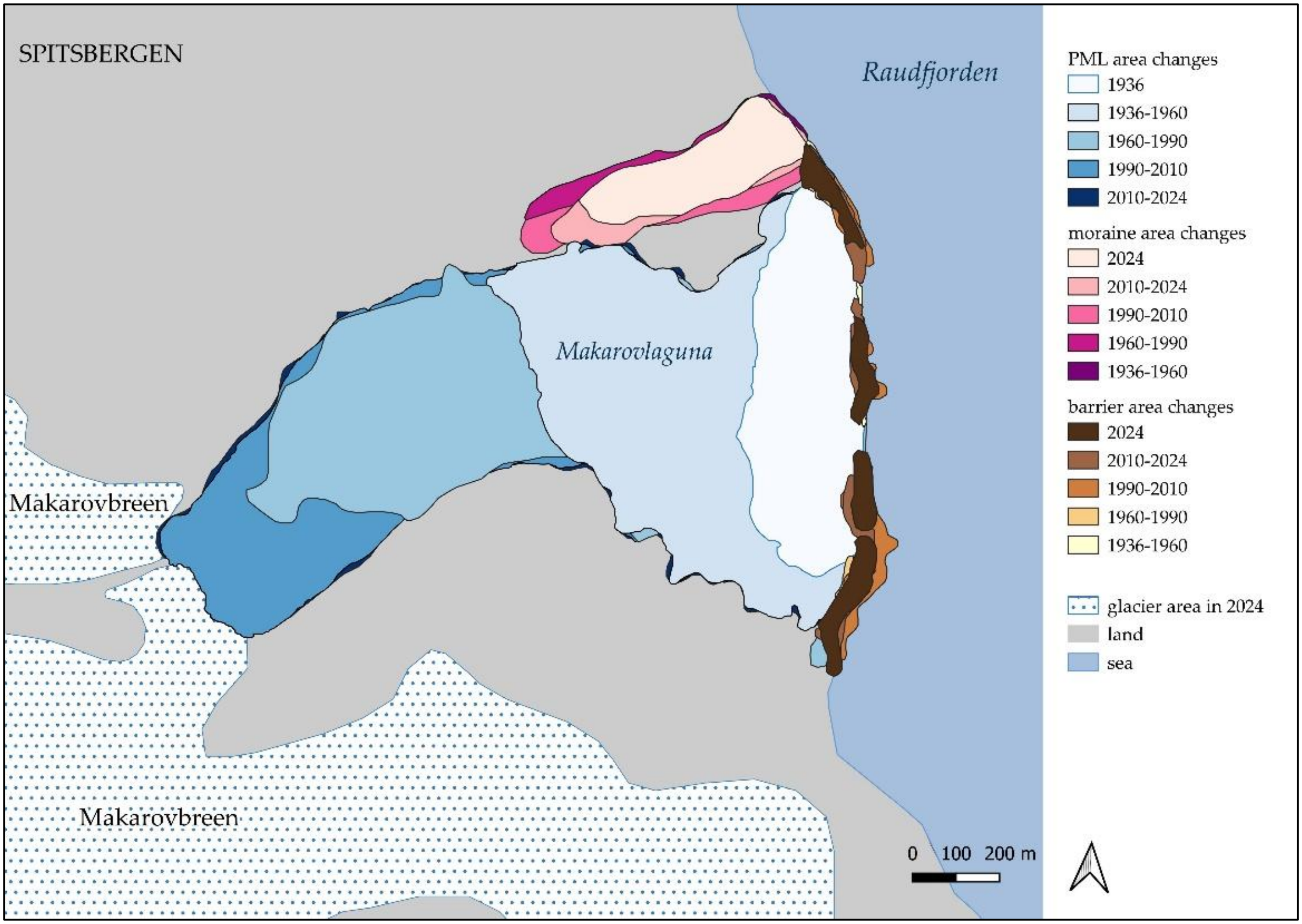

Figure 7: The map shows changes in the surface area of the Makarovlaguna, barriers, and moraines over the years.

Glacial dynamics analysis (Table 3) reveals a progressive loss of direct connectivity between glaciers and their respective lagoons. Currently, in five out of the fourteen studied cases, the glaciers have completely retreated onto land, losing their marine margins. This terrestrial transition is particularly evident in Charleslaguna, where the "parent" glacier no longer terminates in the lagoon waters but contributes via fluvial systems. In general, when a lagoon loses contact with a glacier, its dynamics change, most often stabilising the lagoon's development.

Table 2: Glacier retreat rates since 1936.

Glacier	Lagoon connected with the glacier	Mean Difference with Previous Glacier Extent [m]					Average Glacier Retreat Length [m]	Average Rate of Glacier Retreat [$m\cdot yr^{-1}$]
		1936	1960	1990	2010	2024		

Charlesbreen	**Charleslaguna**	x			1 145.33	391.67	1 537.00	17.47
Eidembreen	**Eidemlaguna**	x	843.00	807.33	677.00	853.00	3 180.33	36.14
Femtebreen	**Femtelaguna**	x			815.00	529.33	1 344.33	15.28
Gimlebreen	**Gimlelaguna**	x			1 144.00	632.00	1 776.00	20.18
Augnebreen	**Kapplaguna**	x			5 993.00	429.00	6 422.00	72.98
Makarovbreen	**Makarovlaguna**	x	484.00	588.67	282.33	1.67	1 356.67	15.42
Murraybreen	**Murraylaguna**	x	485.00	260.00	270.67	577.67	1593.33	18.11
Rissabreen	**Rissalaguna**	x			201.67	4.00	205.67	2.34
Kvasspiggbreen	**Scheilaguna**	x			849.33	63.00	912.33	10.37
Sjubreen	**Sjulaguna**	x			1 220.00	539.33	1 759.33	19.99
Scheibreen	**Skoddelaguna**	x			609.67	190.33	800.00	9.09
Stubendorffbreen	**Snaddlaguna**	x			757.00	829.67	1 586.67	18.03
Deltabreen	**Tjuvfjordlaguna**	x		3 407.00	1 513.67	1 726.33	6 647.00	75.53
Tromsøbreen	**Tromsølaguna**	x			1 581.33	293.00	1 874.33	21.30

Table 3: Temporary changes in the connection between the lagoon and the glacier that formed the moraine (x means no data).

Name	**Connection with the glacier**				
	1936	**1960**	**1990**	**2010**	**2024**
Charleslaguna	yes	yes	x	no	no
Eidemlaguna	yes	yes	yes	yes	yes
Femtelaguna	not existed	yes	x	yes	no
Gimlelaguna	glacial lake	x	x	no	no
Kapplaguna	glacial lake	x	x	no	no
Makarovlaguna	yes	yes	yes	yes	yes
Murraylaguna	not existed	yes	yes	yes	yes
Rissalaguna	not existed	x	x	yes	yes
Scheilaguna	not existed	yes	x	no	no
Sjulaguna	yes	yes	x	yes	yes
Skoddelaguna	not existed	yes	x	yes	yes
Snaddlaguna	not existed	x	x	yes	yes
Tjuvfjordlaguna	yes	x	yes	yes	yes
Tromsølaguna	yes	x	x	no	no

4.3 Moraine-barrier changes

Quantitative shoreline-change metrics derived from DSAS (Table 4) confirm that moraine barriers associated with PMLs on Svalbard are highly dynamic and exhibit both rapid erosion and localised accretion, depending on sediment supply, glacier position, and hydrodynamic exposure.

Table 4: The rate (EPR – End Point Rate) and direction (NSM – Net Shoreline Movement) of shoreline changes between 1936 and 2024 (for Femtelaguna between 2010 and 2024) for individual coastal segments, determined using DSAS.

Lagoon	EPR min [m·yr⁻¹]	EPR max [m·yr⁻¹]	EPR mean [m·yr⁻¹]	NSM min [m]	NSM max [m]	NSM mean [m]
Eidemlaguna	-2.69	0.35	-1.18	-236.58	30.41	-103.58
Femtelaguna	-2.21	2.45	-1.39	-30.89	34.27	-19.45
Makarovlaguna	-0.18	0.32	0.05	-16.17	27.77	4.81
Scheilaguna	0.32	0.62	0.39	27.81	54.15	34.73
Sjulaguna	-0.47	0.18	-0.12	-41.7	16.04	-10.41
Tjuvfjordlaguna	-7.91	0.46	-1.50	-695.95	40.65	-132.19
Tromsølaguna	-0.48	0.29	-0.13	-42.57	25.48	-11.05
Snaddlaguna	-1.79	1.47	-0.52	-157.91	128.96	-46.06

The Tjuvfjordlaguna barrier-moraine system, totalling 9.5 km in length, shows substantial narrowing, with the northern arc decreasing in some points from 950 m to 375 m and the southern arc from 741 m to 260 m in width (Fig. 2 and Fig. 8A). This extreme retreat is reflected in the DSAS results, which show a minimum EPR of −7.91 $m \cdot yr^{-1}$ and a mean EPR of −1.50 $m \cdot yr^{-1}$, accompanied by a minimum NSM of −695.95 m and a mean NSM of −132.19 m. These values are an order of magnitude higher than those observed for other PMLs, indicating sustained, long-term erosion rather than short-lived fluctuations. Analysis of the inlet reveals a more than tenfold expansion: the narrowest point widened from 26.84 m in 1936 to 723.38 m in 2024, with the average width increasing from 72.8 m to 805.6 m. The moraine has retreated more noticeably on the sea-facing side (west) than the lagoon-facing side (east). This asymmetric retreat reflects stronger erosion on the sea-facing side compared to the lagoon-facing side, with observed narrowing of the barrier and expansion of the inlet indicating ongoing morphological adjustment under marine forcing.

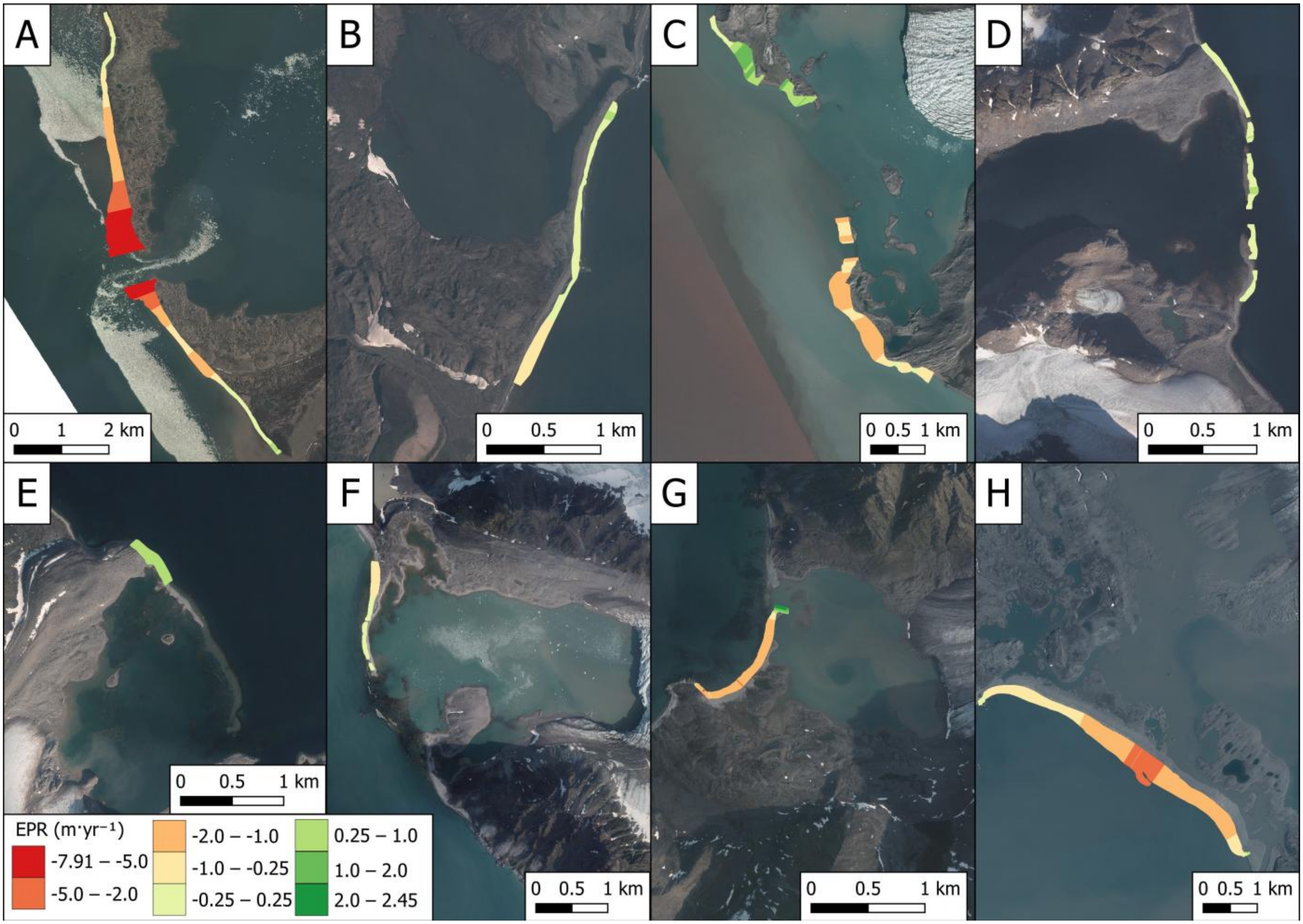

Figure 8: Shoreline changes determined by End Point Rate (EPR) for the period 1936–2024, except for Femtelaguna, where EPR was calculated for 2010–2024. (A) Tjuvfjordlaguna, (B) Tromsølaguna, (C) Snaddlaguna, (D) Makarovlaguna, (E) Scheilaguna, (F) Sjulaguna, (G) Femtelaguna, (H) Eidemlaguna. Base maps: all orthophotomaps come from the (Norwegian Polar Institute, n.d.) A, B, E – from 2010; C, D – from 2011; F, G, H – from 2009.

In contrast, Scheilaguna (Fig. 8E and Fig. 9) represents the opposite end-member of PML evolution, characterised by barrier growth and increasing isolation from the open sea. DSAS results show consistently positive shoreline-change rates (EPR mean 0.39 m·yr^{-1}; NSM mean 34.73 m), indicating net accretion. The Kvasspiggbreen terminal moraine is largely submerged, emerging only during low tide. By 2024, this barrier had extended by 530 meters compared to observations from the 2010s. Currently, the inlet at Scheilaguna narrows to 106 meters at low tide. A similar case can be seen at Femtelaguna (Fig. 6 and Fig. 8G), where between 2010 and 2024 the barrier lengthened by 88 metres, visibly narrowing the PML inlet. Despite locally positive EPR values (EPR max 2.45 m·yr^{-1}), the mean EPR (−1.39 m·yr^{-1}) and NSM (−19.45 m) indicate that accretion at the inlet coexists with erosion elsewhere along the barrier. In both cases, the "parent" glacier is located on land and no longer has a direct connection with the lagoon.

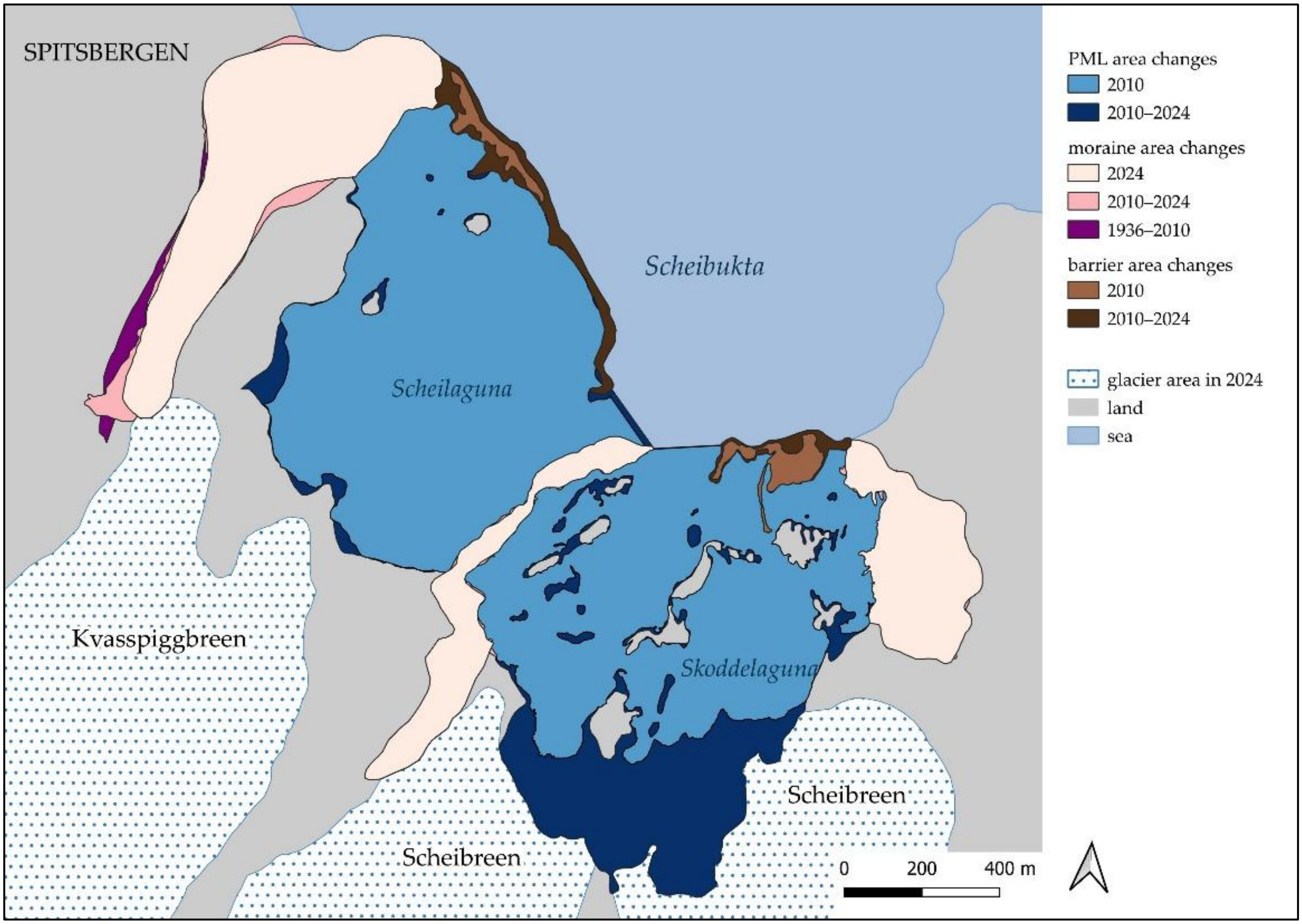

Figure 9: The map shows changes in the surface area of the two PLMs – Scheilaguna and Skoddelaguna – barriers and moraines over the years.

Eidemlaguna (Fig. 4) deserves particular attention due to its complex and non-linear evolutionary trajectory. Although DSAS indicates a predominantly erosional trend (EPR mean −1.18 m·yr^{-1}; NSM mean −103.58 m) (Table 4 and Fig. 8H), this lagoon is the only one in the study area to have changed its openness type twice (Table 5). In 1936, Eidemlaguna had one inlet from the northern part of the barrier, and until 2010 it had another inlet from the southern part of the barrier. In 2010, the northern inlet was closed and remains so to this day. This demonstrates that shoreline retreat does not necessarily translate directly into increased openness and that local sediment redistribution and barrier reconfiguration can temporarily offset erosion-driven widening.

Table 5: Temporal changes in lagoon openness. Closed – a closed lagoon, with only a temporary connection to the sea; choked – single-inlet lagoons; restricted – two-inlet lagoons; leaky – a lagoon with three or more inlets (Kjervfe, 1994).

Name	Openness type				
	1936	1960	1990	2010	2024

Charleslaguna	restricted	restricted	x	choked	choked
Eidemlaguna	choked	restricted	restricted	choked	choked
Femtelaguna	non existing	leaky	x	choked	choked
Gimlelaguna	glacial lake	x	x	choked	choked
Kapplaguna	glacial lake	x	x	choked	restricted
Makarovlaguna	leaky	leaky	leaky	leaky	restricted
Murraylaguna	non existing	leaky	leaky	leaky	leaky
Rissalaguna	non existing	x	x	choked	choked
Scheilaguna	non existing	restricted	x	choked	choked
Sjulaguna	leaky	leaky	x	restricted	restricted
Skoddelaguna	non existing	leaky	x	leaky	leaky
Snaddlaguna	non existing	x	x	leaky	leaky
Tjuvfjordlaguna	choked	x	choked	choked	choked
Tromsølaguna	choked	x	x	choked	choked

The remaining PMLs (Makarovlaguna, Sjulaguna, and Tromsølaguna) show comparatively low rates of change, with EPR mean values close to zero (from −0.13 to 0.05 m·yr^{-1}) and modest NSM values, indicating limited net shoreline displacement (Supplement material). These systems appear to occupy an intermediate state in which erosional and depositional processes are broadly balanced. Taken together, the DSAS metrics and morphological observations demonstrate that PML barriers do not evolve uniformly but instead follow divergent pathways of either rapid erosion and fragmentation or short-term stabilisation and inlet closure. Snaddlaguna (Fig. 3 and Fig. 8C) exhibits a predominantly erosional trend, with DSAS results showing a mean EPR of −0.52 m·yr^{-1} (minimum −1.79 m·yr^{-1}; maximum 1.47 m·yr^{-1}) and a mean NSM of −46.06 m (minimum −157.91 m; maximum 128.96 m). This indicates that while some sections of the barrier experience accretion, overall retreat dominates, reflecting dynamic sediment redistribution and partial narrowing under variable hydrodynamic conditions. Overall, these metrics demonstrate that PML barriers exhibit divergent pathways, ranging from rapid erosion and fragmentation to short-term stabilization and inlet closure, reflecting the range of observed morphodynamic behaviours in the study area.

5 Discussion

5.1 Coastal Change Studies

The retreat of marine-terminating glaciers in Svalbard has exposed extensive new coastal sectors that undergo rapid geomorphological reorganization (Kavan et al., 2025; Kavan and Strzelecki, 2023). In this study, we define Paraglacial Moraine Lagoons (PMLs) as systems separated from the open sea by barriers composed of former terminal or lateral moraines.

Often partially ice-cored, these landforms are a direct consequence of recent glacial recession (Owczarek, 2025). This moraine-based foundation distinguishes PMLs from deltaic or sandy barrier lagoons and fundamentally dictates their stability.

Over the past century, Svalbard's coastline has undergone substantial transformation, with 98 new lagoons forming and 29 losing marine connectivity (Owczarek, 2025). While open and leaky lagoons often transition into closed systems via spit progradation and barrier migration (Kavan and Strzelecki, 2023), glacio-isostatic uplift provides an additional control. Reaching up to 10 $\mathrm{mm \cdot yr^{-1}}$ in certain regions, this uplift offers partial protection from wave energy but may also accelerate the eventual isolation of lagoons from the sea (Kierulf et al., 2022).

Shoreline migration quantified using DSAS indicates that most of the analysed PMLs are currently dominated by erosion. Six out of seven lagoons exhibit negative mean EPR values, reflecting net retreat. Erosion is particularly pronounced at Tjuvfjordlaguna, where the mean EPR reaches –1.50 $\mathrm{m \cdot yr^{-1}}$ (minimum –7.91 $\mathrm{m \cdot yr^{-1}}$) and the mean NSM is –132.19 m. Eidemlaguna and Femtelaguna also experience sustained retreat, with mean EPR values below –1 $\mathrm{m \cdot yr^{-1}}$. These rates are generally higher than those reported for more sheltered Svalbard coasts, such as Isbjørnhamna (Zagórski et al., 2015), Calypsostranda (Zagórski et al., 2020), Adventfjorden (Nicu et al., 2021), or Kaffiøyra (Czarnecki and Sobota, 2025), where mean erosion rarely exceeds –0.4 $\mathrm{m \cdot yr^{-1}}$. The variability in lagoon openness over time is also consistent with observations across Svalbard, where some lagoons have disappeared due to barrier erosion, glacial sediment infilling, or isolation from the sea (Owczarek, 2025; Wołoszyn et al., 2022; Ziaja et al., 2009, 2023), illustrating the sensitivity of these coastal systems to both marine and terrestrial processes.

Despite this, the retreat rates of the most dynamic PMLs remain notably lower than extreme Arctic erosion hotspots, such as ice-rich permafrost cliffs at Drew Point (-38.3 $\mathrm{m \cdot yr^{-1}}$, Alaska, Wang et al., 2022) or Pelly Island (-5.5 $\mathrm{m \cdot yr^{-1}}$, Canada, Malenfant et al., 2022). These comparisons are intended for contextual purposes rather than implying equivalent processes, as PML barriers differ substantially from permafrost-dominated thermoabrasional coasts. Nonetheless, the intermediate erosion magnitude highlights the high sensitivity of moraine-based lagoon barriers compared to typical Svalbard fjord shorelines. The wide range of NSM values within individual lagoons further indicates pronounced spatial heterogeneity, suggesting that erosion and progradation may occur simultaneously along different sectors of the same moraine barrier, reflecting the inherent instability of recently deglaciated paraglacial coasts. Rapid terrestrial events, such as glacial lake outburst floods (GLOFs), have also been documented (Wołoszyn et al., 2022) to dramatically reshape lagoon morphology within days to weeks, emphasizing the dynamic interplay between coastal and glacial processes in Svalbard.

A contrasting example is Recherchelaguna, one of the best-described lagoon systems in Svalbard. Although genetically paraglacial, its barriers were constructed from proglacial deltas in front of Recherchebreen in the early 20th century and lack a moraine core (Kavan et al., 2024; Zagórski et al., 2012). For this reason, Recherchelaguna does not meet the structural PML criteria. This distinction is important: while delta-built barriers are governed primarily by fluvial sediment supply, PML evolution is strongly controlled by the mechanical properties, ice content, and geometry of former moraines. Consequently, Recherchelaguna represents a unique delta-based paraglacial lagoon, whereas PMLs constitute a separate moraine-controlled category occurring in multiple Svalbard fjords. Furthermore, the formation and evolution of PMLs are influenced by ongoing post-glacial processes, including glacio-isostatic uplift (Kierulf et al., 2022) and sediment transport (Kavan and Strzelecki, 2023), which together determine whether lagoons remain connected to the sea, become isolated, or experience barrier fragmentation.

An important trend observed in this study is the relationship between lagoon surface reduction and glacier configuration. In 75% of cases where the lagoon area decreased, the "parent" glacier had already retreated entirely onto land. Although this temporal correspondence does not establish direct causation, it strongly suggests a shift in sedimentary regime following glacier detachment from the marine margin. Once glaciers become land-terminating, calving and subaqueous scouring cease, and proglacial rivers deliver glaciogenic sediments directly into the lagoon basin. This enhanced terrestrial sediment flux likely accelerates infilling and barrier aggradation, progressively restricting marine connectivity. This stabilising–isolating trajectory is exemplified by Scheilaguna, where exclusively positive EPR values (mean 0.39 $m \cdot yr^{-1}$) and a calculated barrier extension rate of 2.86 $m \cdot yr^{-1}$ indicate systematic progradation (Table 4). If current trends continue, complete isolation from the sea may occur within several decades, leading to gradual terrestrialisation of the lagoon. These trends mirror broader coastal changes observed in Svalbard, where both natural sediment dynamics and the interaction of morainic barriers with post-glacial uplift govern lagoon evolution (Ziaja et al., 2009, 2023).

In contrast, Tjuvfjordlaguna illustrates an erosional–fragmenting trajectory. Over 88 years, the moraine width decreased by approximately 650 m (Fig. 8A, Table 4). Continued retreat at similar rates could result in breaching of the narrowest barrier sections within a few decades, potentially fragmenting the moraine and re-establishing an open marine embayment. This example demonstrates that moraine barriers may not stabilise post-deglaciation but can instead undergo substantial marine reworking and structural degradation.

Finally, Murraylaguna (Fig. 10) represents a configuration in which PML development appears possible but was not fully realised. While the former Murraybreen moraine is partly submerged and visible only in archival imagery, current sediment routing favours island formation near the glacier front rather than nourishment of the former moraine ridge. This evidence suggests a potential, though unrealised, pathway of PML development, likely constrained by local bathymetry and sediment distribution.

Overall, these results indicate that PMLs are short-lived geomorphological features confined to a limited paraglacial time window following glacier retreat. After detachment from the marine margin, lagoon systems diverge toward one of two dominant trajectories: (1) stabilisation, isolation, and infilling driven by enhanced terrestrial sediment flux, or (2) barrier erosion and fragmentation under dominant marine forcing. DSAS-derived shoreline metrics provide quantitative support for this dual behaviour, reinforcing the interpretation of PMLs as highly transitional elements within the evolving coastal landscapes of Svalbard. The broader historical record of Svalbard lagoons confirms these patterns (Owczarek, 2025; Ziaja et al., 2009, 2023), showing that coastal change operates over multiple scales and through a combination of gradual processes, episodic events, and post-glacial uplift, all of which critically shape the formation, evolution, and eventual fate of PMLs.

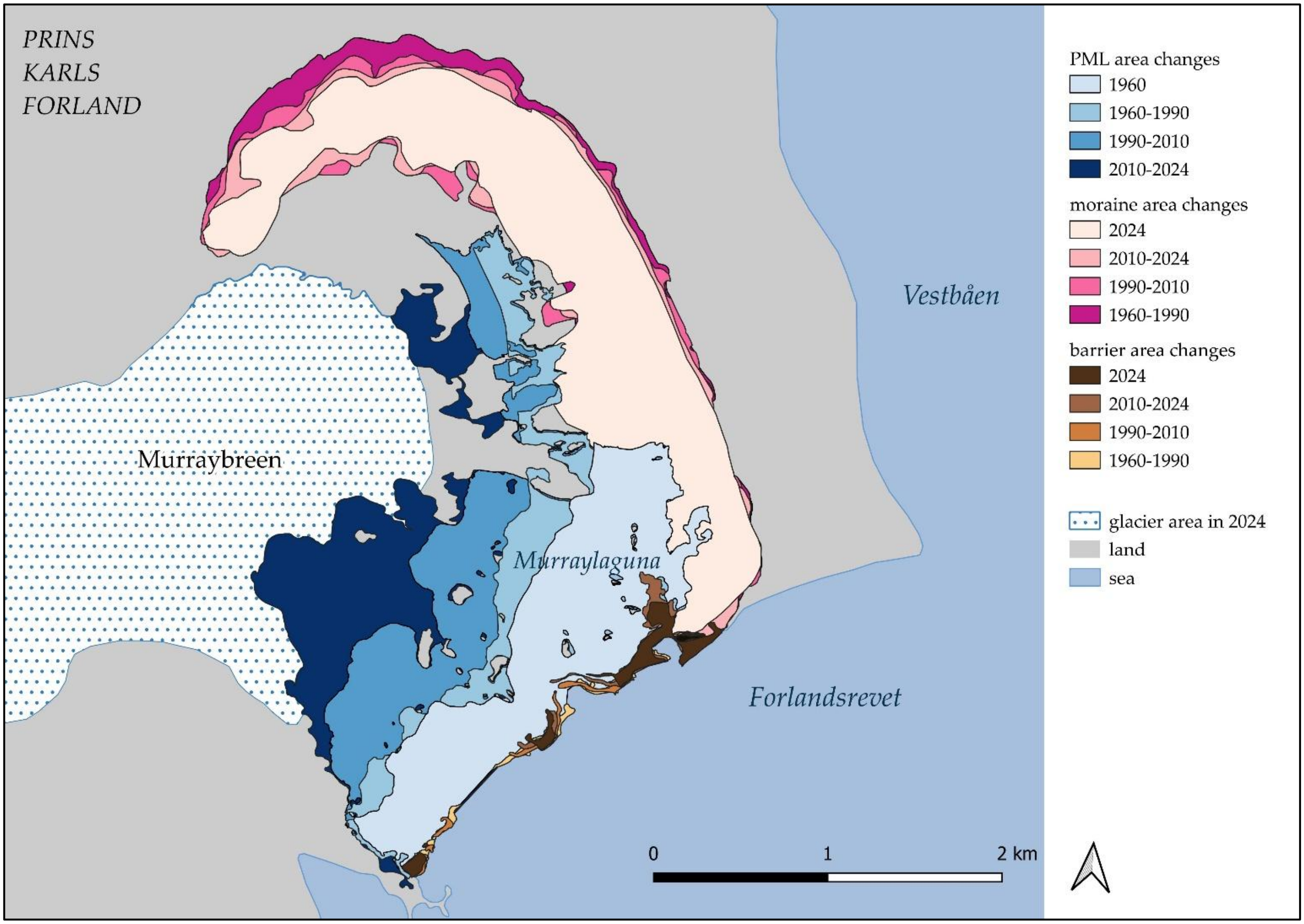

Figure 10: The map shows changes in the surface area of the Murraylaguna, barriers, and moraines over the years.

5.2 Paraglacial cascades

The evolution of PMLs is fundamentally dictated by terrestrial paraglacial processes, which redefine the traditional sediment flux of Arctic coastlines. While paraglacial coasts typically exhibit rapid sediment flushing, PMLs introduce a critical "sedimentary sink"–a temporal pause where coarse glaciogenic material is sequestered in the nearshore zone rather than being lost to the continental shelf or deep-sea basins. This mechanism disrupts the standard delivery of meltwater and sediment directly into the marine environment. The vulnerability of these systems to terrestrial events is exemplified by GLOFs, which can cause the instantaneous "extinction" of a lagoon via catastrophic infilling (Wołoszyn et al., 2022). Such events underscore the role of PMLs as geomorphological buffers. Furthermore, contemporary observations at Recherchelaguna (Kavan et al., 2024) and Charleslaguna demonstrate a shift toward terrestrialization; in the latter, the development of a proglacial delta (0.042 km^2) between 2010 and 2024 (Fig. 11) has significantly reduced the lagoon's accommodation space. Neglecting PMLs in coastal models leads to a fundamental miscalculation of the sediment budgets defining glaciated Arctic margins.

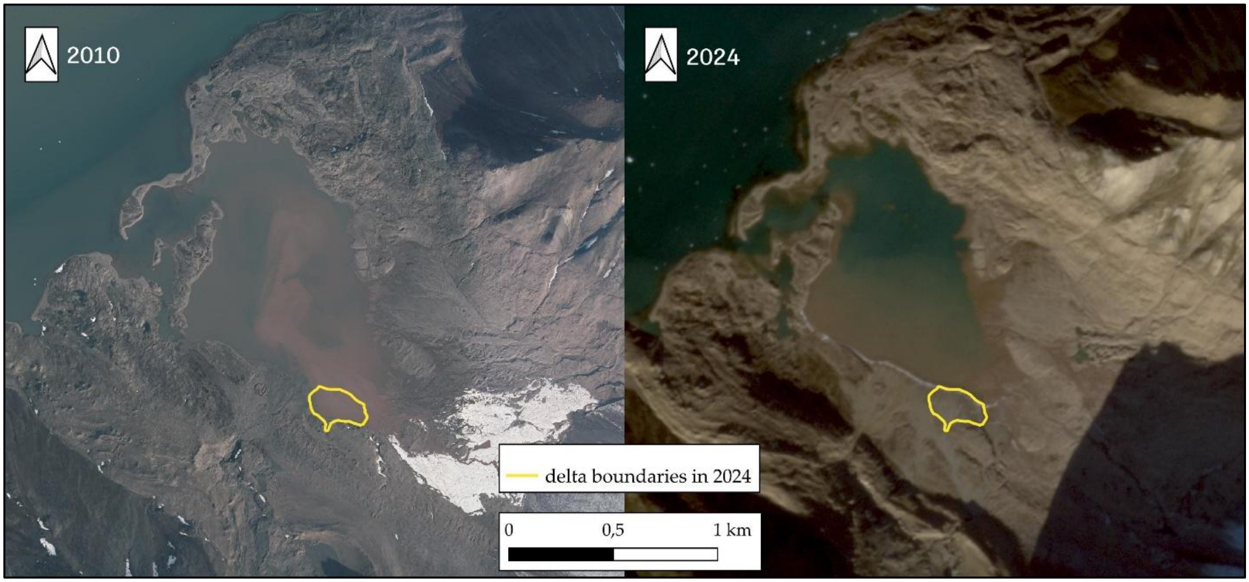

Figure 11: Development of a new delta (approximately 0.04 km^2) on the southern Charleslaguna shore. Base maps: the 2010 orthophotomap comes from (Norwegian Polar Institute, n.d.), and the 2024 satellite imagery comes from (Planet Labs: Satellite Imagery & Earth Data Analytics, n.d).

5.3 Potential for Geoecological Shifts

The formation of PMLs introduces a fundamental shift in the physical energy of the nearshore environment. By establishing a moraine barrier, these systems transform high-energy, wave-dominated open coasts into sheltered, low-energy basins. This transition significantly alters the physical template available for colonization. In Svalbard, such sheltered conditions are typically associated with increased retention of fine-grained sediments and organic matter, which are otherwise flushed into the deeper fjord (Kavan and Strzelecki, 2023). While the temporal window of PMLs is transient, the immediate transition from a glacial terminus to a sheltered lagoon creates a unique brackish-water habitat. These geomorphological changes suggest that PMLs may function as temporary biodiversity centers, though empirical evidence regarding the specific rate of benthic species establishment or the role of these lagoons as stopover sites for migrating fauna remains to be gathered.

5.4 Paraglacial Moraine Lagoons: Evolution and Stages – Conceptual model

We propose that PMLs represent a distinct, previously unclassified genetic category of Arctic lagoons. In our conceptual model, PMLs are defined by a "glacial legacy" barrier–a terminal or lateral moraine system that decouples the glacier–coast interface from open-sea energy, a feature notably absent in typical paraglacial environments. We define the evolution of these systems through the following four key stages (Fig. 12).

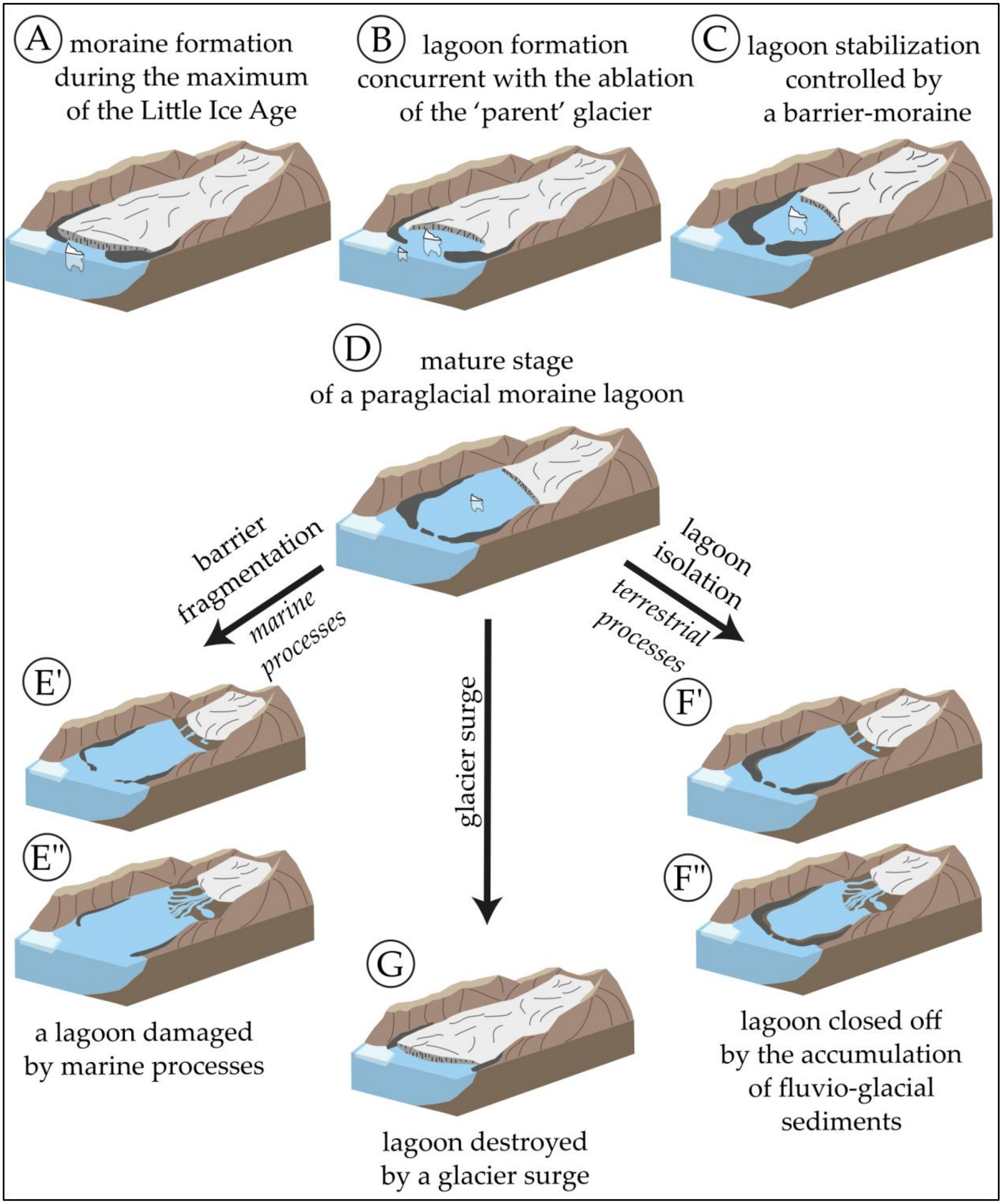

Figure 12: The Paraglacial Moraine Lagoon (PML) evolution model. (A) Stage 1: Moraine Foundation; (B–C) Stage 2: Lagoon Genesis; (D) Mature Lagoon Stage, (E–F) Stage 3: Terrestrial Transition; (E''–F'') Stage 4: Marine-driven fragmentation versus terrestrial-driven isolation; (G) Lagoon destruction by glacier surge.

Stage 1: Moraine Foundation (Little Ice Age Framework)

During the glacial phase (Fig. 12A), terminal and lateral moraines deposited at the LIA maximum provide the structural foundation for the PML system. Here, the moraine is not a passive depositional feature but an active element in the feedback between glacial sediment supply and marine abrasion. It functions as a hydrodynamic buffer, reducing wave energy at the glacier front and potentially limiting calving intensity. The stability of this moraine barrier determines whether a lagoon can later form; without it, the system would not follow the PML trajectory.

Stage 2: Lagoon Genesis (Post-LIA Retreat)

As climate-driven warming triggers the retreat of the glacier margin from its LIA maximum, the depression becomes flooded with seawater, forming a low-energy lagoon basin (Fig. 12B–C). This intermediate environment bridges the gap between classic glacial fjords and open paraglacial coasts.

The key transition is from a system directly exposed to the open sea (Fig. 12B) to a partially isolated lagoon controlled by the moraine (Fig. 12C). Even marine-terminating glaciers exhibit reduced calving efficiency in this environment. The moraine barrier not only facilitates lagoon formation but also modifies glacier retreat dynamics.

Stabilization of the lagoon basin promotes redeposition of glacial sediments, reshaping barrier morphology through sediment supply from the active glacier, lagoon water-level fluctuations, internal currents, and calving-generated waves. This process gradually transforms the moraine into a structure with increasingly coastal characteristics.

At this mature lagoon stage (Fig. 12D), the moraine still regulates energy exchange with the sea, but its morphology reflects both glacial deposition and paraglacial processes. Tjuvfjordlaguna, Makarovlaguna, Sjulaguna, and Snaddlaguna currently exemplify this stage.

Stage 3: Terrestrial Transition and Sediment Trap

As the glacier retreats onto land (Fig. 12E–F), the lagoon undergoes major sedimentary reorganization. Calving cessation and exposure of ground moraines promote proglacial drainage, increasing fluvio-glacial sediment supply and initiating delta formation. At this stage, PMLs serve as primary sediment traps within the paraglacial transport cascade, retaining coarse material that would otherwise reach the deep shelf. Their buffering role aligns with paraglacial slope readjustment and sediment redistribution after glacier retreat (Ballantyne, 2002; Forbes and Syvitski, 1994; Kavan et al., 2024; Strzelecki et al., 2020; Zagórski et al., 2012). Moraine stability becomes controlled by the balance between terrestrial sediment supply and marine erosive pressure. Two scenarios are possible now: the first, where erosion exceeds sediment supply (Fig. 12E'), and the second, the opposite scenario, in which sediment supply exceeds the erosion rate (Fig. 12F'). However, glacier re-advances (also glacier surges) can destroy lagoons, as likely occurred during LIA glacier expansions (Fig. 12G).

Stage 4: Marine-driven fragmentation versus terrestrial-driven isolation

The final stage is nonlinear, governed by the balance between sediment delivery and marine erosion. Proglacial delta growth can lead to increased sediment accumulation in the glacier's foreland. Limiting the sediment supply to the barrier-moraine while maintaining the same level of marine erosion may lead to the barrier's destruction. Murraylaguna can be considered an example of such a situation, even though Murraybreen is not yet completely on land (Fig. 12E").

Despite the formation of a proglacial delta, the sediment supply is sufficient to maintain the current state of the barrier moraine or even to build it up (Fig. 12F"). As deltas expand, they reduce the lagoon’s accommodation space, potentially bifurcating the basin or severing its connection to the sea; further driving the lagoon toward terrestrialization. Examples of such PMLs are Femtelaguna and Charleslaguna.

This stage highlights that PML evolution is controlled by glacial legacy but unfolds through paraglacial processes – slope, fluvio-glacial, and coastal – which collectively dictate the pace and direction of system transformation (Ballantyne, 2002).

5.5 Perspectives and Future Research

The identification of Paraglacial Moraine Lagoons (PMLs) as a distinct landform category opens several new avenues for Arctic coastal research. Because these features represent a transient state in the paraglacial landscape cycle, their future evolution will likely serve as a high-resolution indicator of the pace of Arctic coastal reorganization. However, fully decoding the role of PMLs in the changing Arctic requires a shift toward integrated, interdisciplinary studies that bridge the gap between geomorphology, cryospheric science, and marine ecology:

- A critical uncertainty remains regarding the internal structure of PML barriers, necessitating collaboration between geomorphologists and geophysicists. Since many terminal moraines in Svalbard are known to be ice-cored, rising Arctic temperatures and the impact of waves may trigger accelerated degradation through thermo-abrasion. This could lead to catastrophic barrier failure and breaching. Future research utilizing geophysical surveys with ground penetrating radars or electrical resistivity tomography is needed to quantify the presence and volume of ground ice within these barriers and predict their vulnerability to sudden structural collapse.
- The function of these basins as low-energy traps suggests a major opportunity for environmental change reconstruction. PMLs likely contain undisturbed, high-resolution sedimentary records of post-Little Ice Age environmental change that are often erased on high-energy open coasts. Extracting these site-specific insights into past glacier retreat and meltwater fluctuations requires an interdisciplinary approach combining sedimentology with biogeochemical investigations to quantify the potential for these lagoons to sequester terrestrial organic carbon before it reaches the deep ocean.
- The physical transition from high-energy open coasts to sheltered, brackish-water basins creates a unique template for colonization, raising a fundamental question for marine biologists and ecologists regarding the ecological window of these systems. It remains unknown if the transient lifespan of a PML–often only decades to a few centuries–is sufficient for the establishment of stable benthic communities. Interdisciplinary efforts are required to investigate

whether these lagoons provide critical refugia for species moving northward due to "atlantification," or if their rapid geomorphological evolution makes them too ephemeral for complex food-web maturation.

- Finally, large-scale climate and oceanographic models must account for the geomorphological "pause" created by PML formation. By trapping coarse glaciogenic material that would otherwise be lost to the shelf or deep sea, PMLs fundamentally alter the sediment budget of glaciated coasts. Integrating these landforms into regional sediment transport models is essential for coastal managers and oceanographers to avoid miscalculating the volume of material delivered from land to sea in a warming Svalbard region.

6 Conclusion

The rapid retreat of Svalbard's glaciers has transitioned the archipelago into a new paraglacial stage, characterised by the widespread emergence of Paraglacial Moraine Lagoons (PMLs). This study provides the first archipelago-wide identification and quantitative analysis of this landform, formalising the PML as a distinct, moraine-controlled category of Arctic lagoon – one whose stability and evolution are governed by the mechanical properties, ice content, and geometry of former Little Ice Age moraines rather than by the fluvial or sandy-barrier dynamics that define previously described paraglacial lagoons.

Drawing on a near-90-year, multi-source record (1936–2024) and standardised DSAS shoreline analysis across the complete set of 14 systems, we demonstrate that PMLs are not merely passive features of deglaciation but active, transient "sinks" in the Arctic coastal system. Their surface area has nearly tripled since the 1930s, now covering approximately 83 km² and accounting for more than half (56%) of Svalbard's total lagoon area – a clear signal of how quickly moraine-controlled coasts are expanding under Arctic amplification. Crucially, we show that the fate of each PML is inextricably linked to the status of its "parent" glacier. While glaciers remain marine-terminating, lagoons undergo massive expansion and intense marine reworking; once a glacier retreats onto land, the sedimentary regime shifts and the lagoon begins to act as a terminal sink for glacio-fluvial material, leading to rapid infilling and eventual terrestrialisation. From this glacier–coast coupling, we derive two divergent evolutionary trajectories – an erosional–fragmenting pathway dominated by marine forcing (e.g., Tjuvfjordlaguna) and a stabilising-isolating pathway driven by terrestrial sediment supply (e.g., Scheilaguna, Femtelaguna) – which we synthesise into a four-stage conceptual model of PML genesis, maturation, terrestrial transition, and destruction.

The significance of these findings extends well beyond landform taxonomy. First, by sequestering coarse glaciogenic material in the nearshore zone rather than delivering it directly to the shelf or deep sea, PMLs introduce a previously unrecognised "pause" in the paraglacial sediment cascade; neglecting them risks a systematic miscalculation of the land-to-sea sediment budgets of glaciated Arctic margins. Second, by converting high-energy, wave-dominated open coasts into sheltered, low-energy brackish basins, PMLs create distinctive habitat templates that may serve as transient biodiversity refugia – potentially important for species advancing northward under ongoing atlantification. Third, because PMLs are short-lived features confined to a narrow paraglacial time window, their formation and eventual destruction constitute a high-resolution proxy for the pace of polar coastal reorganisation, and their low-energy basins are likely to preserve undisturbed sedimentary archives of post-Little Ice Age environmental change that are typically erased on exposed coasts.

Taken together, our results establish PMLs as a key, climate-sensitive component of the feedback system linking glacier activity to the evolving Arctic coast. As warming continues and more glaciers detach from their marine margins, both the proliferation of new PMLs and the terrestrialisation or fragmentation of existing ones are expected to accelerate. Quantifying the internal (ice-cored) structure of moraine barriers, the carbon-sequestration potential of these sediment traps, and the ecological viability of their transient habitats now emerges as a priority for integrated geomorphological, cryospheric, and marine-ecological research in a rapidly changing Svalbard.

Author contributions

M.C.S. obtained funding for this study. The study design was developed by Z.O. supervised by M.C.S. Z.O. led the work on geomorphological mapping, O.K. carried out DSAS analyses, and designed graphics for the conceptual model. W.P., O.K., and Z.O. were responsible for describing the stages of the conceptual model. Z.O. wrote the original draft, and all authors contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

Data availability

Sentinel-2 and Landsat images were available from the Sentinel Hub EO Browser (available apps.sentinel-hub.com, last access: 29.11.2024). The topographic data of Svalbard are available from the NPI (https://toposvalbard.npolar.no/, last access: 22.02.2026, and https://geodata.npolar.no/, last access: 22.02.2025). The Planet satellite images were downloaded from the Planet website (available at https://www.planet.com/, last access: 22.02.2025) thanks to access to the Educational and Research Programme. We have uploaded shapefiles presenting PML's changes over 1936–2024 to the Polish Polar Data Base repository, where the files can be accessed using the following link https://polar.cenagis.edu.pl/dataset/post-lia-evolution-of-svalbard-paraglacial-moraine-lagoon-systems.

Appendices

Appendix A1: The map shows changes in the surface area of the Kapplaguna, barriers, and moraines over the years.
Appendix A2: The map shows changes in the surface area of the Gimlelaguna, barriers, and moraines over the years.
Appendix A3: The map shows changes in the surface area of the Rissalaguna, barriers, and moraines over the years.

Appendix A4: The map shows changes in the surface area of the Sjulaguna, barriers, and moraines over the years.

Appendix A5: The map shows changes in the surface area of the Tromsølaguna, barriers, and moraines over the years.

Disclaimer

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Review statement

References

Angelopoulos, M., Overduin, P. P., Westermann, S., Tronicke, J., Strauss, J., Schirrmeister, L., Biskaborn, B. K., Liebner, S., Maksimov, G., Grigoriev, M. N., and Grosse, G.: Thermokarst Lake to Lagoon Transitions in Eastern Siberia: Do Submerged Taliks Refreeze?, J. Geophys. Res. Earth Surf., 125, https://doi.org/10.1029/2019JF005424, 2020.

Ballantyne, C. K.: Paraglacial geomorphology, Quat. Sci. Rev., 21, 1935–2017, https://doi.org/https://doi.org/10.1016/S0277-3791(02)00005-7, 2002.

Barnes, R.: Coastal lagoons, Cambridge Uni Press, 1980.

Bendixen, M. and Kroon, A.: Conceptualizing delta forms and processes in Arctic coastal environments, Earth Surf. Process. Landf., 42, 1227–1237, https://doi.org/10.1002/esp.4097, 2017.

Błaszczyk, M., Jania, J. A., and Kolondra, L.: Fluctuations of tidewater glaciers in Hornsund Fjord (Southern Svalbard) since the beginning of the 20 th century, Polar Res, 34, 327–352, https://doi.org/10.2478/popore−2013−0024, 2013.

Czarnecki, K. and Sobota, I.: UAV and photogrammetric techniques to study shoreline changes in the high Arctic as exemplified by the Kaffiøyra region, Svalbard, Earth Surf. Process. Landf., 50, https://doi.org/10.1002/esp.70037, 2025.

Forbes, D. L. and Syvitski, J. P. M.: Paraglacial coasts, in: Coastal Evolution: Late Quaternary Shoreline Morphodynamics, edited by: Carter, R. W. G. and Woodroffe, C. D., Cambridge University Press, Cambridge, 373–424, 1994.

Frydrych, K. and Zagórski, P.: Morphodynamics of Recherchefjorden Accumulative Coasts since the End of the Little Ice Age, Quaestiones Geographicae, 43, 21–43, https://doi.org/10.14746/quageo-2024-0002, 2024.

Geyman, E., van Pelt, W. J. J., Maloof, A. C., Aas, H. F., and Kohler, J.: Historical glacier change on Svalbard predicts doubling of mass loss by 2100, Nature, 601, 374–379, https://doi.org/10.1038/s41586-021-04314-4, 2022.

Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G., and Farris, A. S.: Digital Shoreline Analysis System (DSAS) Version 5.1 User Guide, U.S. Geological Survey Open-File Report 2021–1091, https://doi.org/https://doi.org/10.3133/ofr20211091, 2021.

Kavan, J. and Strzelecki, M. C.: Glacier decay boosts the formation of new Arctic coastal environments—Perspectives from Svalbard, Land Degrad. Dev., https://doi.org/10.1002/ldr.4695, 2023.

Kavan, J., Tallentire, G. D., Demidionov, M., Dudek, J., and Strzelecki, M. C.: Fifty Years of Tidewater Glacier Surface Elevation and Retreat Dynamics along the South-East Coast of Spitsbergen (Svalbard Archipelago), Remote Sens. (Basel)., 14, https://doi.org/10.3390/rs14020354, 2022.

Kavan, J., Strzelecki, M. C., Benn, D. I., Luckman, A., Roman, M., and Zagórski, P.: Glacier surge as a trigger for the fastest delta growth in the Arctic, Commun. Earth Environ., 5, https://doi.org/10.1038/s43247-024-01877-8, 2024.

Kavan, J., Szczypińska, M., Kochtitzky, W., Farquharson, L., Bendixen, M., and Strzelecki, M. C.: New coasts emerging from the retreat of Northern Hemisphere marine-terminating glaciers in the twenty-first century, Nat. Clim. Chang., https://doi.org/10.1038/s41558-025-02282-5, 2025.

Kierulf, H. P., Kohler, J., Boy, J. P., Geyman, E. C., Mémin, A., Omang, O. C. D., Steffen, H., and Steffen, R.: Time-varying uplift in Svalbard - an effect of glacial changes, Geophys. J. Int., 231, 1518–1534, https://doi.org/10.1093/gji/ggac264, 2022.

Kjerfve, B. and Magill, K. E.: Geographic and hydrodynamic characteristics of shallow coastal lagoons, Mar. Geol., 88, 187–199, https://doi.org/10.1016/0025-3227(89)90097-2, 1989.

Kostrzewa, O., Szczypińska, M., Kavan, J., Senderak, K., Novák, M., and Strzelecki, M. C.: A Boulder Beach Formed by Waves From a Calving Glacier Revisited: Multidecadal Tsunami–Controlled Coastal Changes in Front of Eqip Sermia, West Greenland, Permafr. Periglac. Process., 35, 312–325, https://doi.org/10.1002/ppp.2235, 2024.

Li, T., Hofer, S., Moholdt, G., Igneczi, A., Heidler, K., Zhu, X. X., and Bamber, J.: Pervasive glacier retreats across Svalbard from 1985 to 2023, Nature Communications , 16, https://doi.org/10.1038/s41467-025-55948-1, 2025.

Małecki, J.: Elevation and volume changes of seven Dickson Land glaciers, Svalbard, 1960–1990–2009, Polar Res., 32, https://doi.org/https://doi.org/10.3402/polar.v32i0.18400, 2013.

Malenfant, F., Whalen, D., Fraser, P., and Proosdij, D.: Rapid coastal erosion of ice-bonded deposits on Pelly Island, southeastern Beaufort Sea, Inuvialuit Settlement Region, western Canadian Arctic, Can. J. Earth Sci., 59, 961–972, https://doi.org/10.1139/cjes-2021-0118, 2022.

Martín-Moreno, R., Allende Álvarez, F., and Hagen, J. O.: 'Little Ice Age' glacier extent and subsequent retreat in Svalbard archipelago, Holocene, 27, 1379–1390, https://doi.org/10.1177/0959683617693904, 2017.

Nicu, I. C., Rubensdotter, L., Stalsberg, K., and Nau, E.: Coastal erosion of arctic cultural heritage in danger: A case study from svalbard, Norway, Water (Switzerland), 13, https://doi.org/10.3390/w13060784, 2021.

Noël, B., Jakobs, C. L., van Pelt, W. J. J., Lhermitte, S., Wouters, B., Kohler, J., Hagen, J. O., Luks, B., Reijmer, C. H., van de Berg, W. J., and van den Broeke, M. R.: Low elevation of Svalbard glaciers drives high mass loss variability, Nat. Commun., 11, https://doi.org/10.1038/s41467-020-18356-1, 2020.

Norwegian Polar Institute, n.d. TopoSvalbard. https://toposvalbard.npolar.no/, last access: 22 February 2026.

Nuth, C., Kohler, J., König, M., Von Deschwanden, A., Hagen, J. O., Kääb, A., Moholdt, G., and Pettersson, R.: Decadal changes from a multi-temporal glacier inventory of Svalbard, Cryosphere, 7, 1603–1621, https://doi.org/10.5194/tc-7-1603-2013, 2013.

Overeem, I., Nienhuis, J. H., and Piliouras, A.: Ice-dominated Arctic deltas, https://doi.org/10.1038/s43017-022-00268-x, 1 April 2022.

Owczarek, Z.: Spatio-temporal Changes of Svalbard Lagoon Systems in the Post-Little-Ice-Age Period, Permafr. Periglac. Process., 36, 284–301, https://doi.org/10.1002/ppp.2270, 2025.

Planet Labs: Satellite Imagery & Earth Data Analytics, n.d. Planet. https://www.planet.com/, last access: 22 February 2025.

Primo, B., Achete, F., Mahanama, S., Thatcher, M., Hemer, M., Weesakul, S., and Duong, T.: Climate change impacts assessment in coastal 2 lagoons using available modelling tools, https://doi.org/10.20944/preprints201805.0007.v1, 2018.

Rachlewicz, G., Szczuciński, W., and Ewertowski, M.: Post‒"Little Ice Age" retreat rates of glaciers around Billefjorden in central Spitsbergen, Svalbard, Pol. Polar Res., 28, 159–186, 2007.

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A.: The Arctic has warmed nearly four times faster than the globe since 1979, Commun. Earth Environ., 3, https://doi.org/10.1038/s43247-022-00498-3, 2022.

Šiaulys, A., Šaškov, A., Urbański, J. A., Kilmonaitė, G., Lukashanets, D., Politi, T., Samuilovienė, A., Zaiko, A., and Olenin, S.: Dynamic nature of an emerging paraglacial lagoon in Svalbard, Arctic: hydrological and geomorphological features, Polar Sci., https://doi.org/10.1016/j.polar.2026.101363, 2026.

Strzelecki, M. C., Long, A. J., and Lloyd, J. M.: Post-Little Ice Age Development of a High Arctic Paraglacial Beach Complex, in: Permafrost and Periglacial Processes, vol. 28, John Wiley and Sons Ltd, 4–17, https://doi.org/10.1002/ppp.1879, 2017.

Strzelecki, M. C., Long, A. J., Lloyd, J. M., Małecki, J., Zagórski, P., Pawłowski, Ł., and Jaskólski, M. W.: The role of rapid glacier retreat and landscape transformation in controlling the post-Little Ice Age evolution of paraglacial coasts in central Spitsbergen (Billefjorden, Svalbard), Land Degrad. Dev., 29, 1962–1978, https://doi.org/10.1002/LDR.2923, 2018.

Strzelecki, M. C., Szczuciński, W., Dominiczak, A., Zagórski, P., Dudek, J., and Knight, J.: New fjords, new coasts, new landscapes: The geomorphology of paraglacial coasts formed after recent glacier retreat in Brepollen (Hornsund, southern Svalbard), Earth Surf. Process. Landf., 45, 1325–1334, https://doi.org/10.1002/esp.4819, 2020.

Svennevig, K., Hicks, S. P., Forbriger, T., Lecocq, T., Widmer-Schnidrig, R., Mangeney, A., Hibert, C., Korsgaard, N. J., Lucas, A., Satriano, C., Anthony, R. E., Mordret, A., Schippkus, S., Rysgaard, S., Boone, W., Gibbons, S. J., Cook, K. L., Glimsdal, S., Løvholt, F., Van Noten, K., Assink, J. D., Marboeuf, A., Lomax, A., Vanneste, K., Taira, aki, Spagnolo, M., De Plaen, R., Koelemeijer, P., Ebeling, C., Cannata, A., Harcourt, W. D., Cornwell, D. G., Caudron, C., Poli, P., Bernard, P., Larose, E., Stutzmann, E., Voss, P. H., Lund, B., Cannavo, F., Castro-Díaz, M. J., Chaves, E., Dahl-Jensen, T., De Pinho Dias, N., Déprez, A., Develter, R., Dreger, D., Evers, L. G., Fernández-Nieto, E. D., G Ferreira, A. M., Funning, G., Gabriel, A.-A., Hendrickx, M., Kafka, A. L., Keiding, M., Kerby, J., Khan, S. A., Kjaer Dideriksen, A., Lamb, O. D., Larsen, T. B., Lipovsky, B., Magdalena, I., Malet, J.-P., Myrup, M., Rivera, L., Ruiz-Castillo, E., Wetter, S., and Wirtz, B.: A rockslide-generated tsunami in a Greenland fjord rang Earth for 9 days, 2024.

Urbański, J. A.: Monitoring and classification of high Arctic lakes in the Svalbard Islands using remote sensing, International Journal of Applied Earth Observation and Geoinformation, 112, 102911, https://doi.org/10.1016/j.jag.2022.102911, 2022.

Wang, J., Li, D., Cao, W., Lou, X., Shi, A., and Zhang, H.: Remote Sensing Analysis of Erosion in Arctic Coastal Areas of Alaska and Eastern Siberia, Remote Sens. (Basel)., 14, https://doi.org/10.3390/rs14030589, 2022.

Wołoszyn, A., Owczarek, Z., Wieczorek, I., Kasprzak, M., and Strzelecki, M. C.: Glacial Outburst Floods Responsible for Major Environmental Shift in Arctic Coastal Catchment, Rekvedbukta, Albert I Land, Svalbard, Remote Sens. (Basel)., 14, https://doi.org/10.3390/rs14246325, 2022.

Wolper, J., Gao, M., Lüthi, M. P., Heller, V., Vieli, A., Jiang, C., and Gaume, J.: A glacier–ocean interaction model for tsunami genesis due to iceberg calving, Commun. Earth Environ., 2, https://doi.org/10.1038/s43247-021-00179-7, 2021.

Zagórski, P., Gajek, G., and Demczuk, P.: The influence of glacier systems of polar catchments on the functioning of the coastal zone (Recherchefjorden, Svalbard), Zeitschrift fur Geomorphologie, 56, 101–121, https://doi.org/10.1127/0372-8854/2012/S-00075, 2012.

Zagórski, P., Rodzik, J., Moskalik, M., Strzelecki, M. C., Lim, M., Błaszczyk, M., Promińska, A., Kruszewski, G., Styszyńska, A., and Malczewski, A.: Multidecadal (1960-2011) shoreline changes in Isbjørnhamna (Hornsund, Svalbard), Pol. Polar Res., 36, 369–390, https://doi.org/10.1515/popore-2015-0019, 2015.

Zagórski, P., Jarosz, K., and Superson, J.: Integrated Assessment of Shoreline Change along the Calypsostranda (Svalbard) from Remote Sensing, Field Survey and GIS, Marine Geodesy, 43, 433–471, https://doi.org/10.1080/01490419.2020.1715516, 2020.

Ziaja, W. and Haska, W.: The newest Arctic islands and straits: Origin and distribution, 1997–2021, Land Degrad. Dev., https://doi.org/10.1002/ldr.4583, 2023.

Ziaja, W. and Ostafin, K.: Origin and location of new Arctic islands and straits due to glacial recession, Ambio, 48, 25–34, https://doi.org/10.1007/s13280-018-1041-z, 2019.

Ziaja, W., Maciejowski, W., and Ostafin, K.: Coastal landscape dynamics in NE Sørkapp land (SE Spitsbergen), 1900-2005, Ambio, 38, 201–208, https://doi.org/10.1579/0044-7447-38.4.201, 2009.

Ziaja, W., Ostafin, K., Maciejowski, W., and Kruse, F.: Coastal landscape degradation and disappearance of Davislaguna Lake, Sørkappland, Svalbard, 1900–2021, Land Degrad. Dev., https://doi.org/10.1002/ldr.4765, 2023.