CONTEMPORARY DYNAMICS OF GLACIAL LAKES: COMPARISON BETWEEN SELECTED SYSTEMS DEVELOPING IN NORTHERN, CENTRAL AND SOUTHERN REGIONS IN SPITSBERGEN

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Abstract: The study investigates glacial lakes in Svalbard, examining examples from the forelands of Gåsbreen, Crammerbreen, Knivseggbreen, Neppebreen and Ragnarbreen, each representing different classifications of glacial lakes, including ice-dammed, frontal moraine-dammed and medial moraine-dammed. These lakes serve as key indicators of ongoing climate change and the effects of deglaciation processes in polar landscapes. Quantitative analyses reveal notable differences among the selected glacial lakes. For instance, Goësvatnet experienced cyclical glacial lake outburst floods (GLOFs), with a recorded volume of 666,389 m^3 during one event. Conversely, the lake on the Ragnarbreen foreland, while stable, has not encountered any GLOFs, indicating a distinct response to deglaciation compared with other examples. Hydrographic and surface analyses, conducted using digital elevation models (DEMs) and remote sensing data, provide insights into the morphological characteristics and dynamics of the glacial lakes and surrounding landscapes. Longitudinal profiles of glaciers show varied terrains, with Ragnarbreen exhibiting the least variability due to its source zone on the ice cap, while Crammerbreen presents diverse features, including tectonic faults resulting in icefalls with slopes >35°. By including multiple glacial lakes across different locations and classifications, this study offers a comprehensive understanding of the diverse responses of glacial lakes to deglaciation processes in Svalbard, shedding light on the complex interactions between glaciers, lakes and changing environmental conditions in the Arctic region.

Keywords: glacial lakes, GLOF, landscape transformation, Svalbard, high Arctic

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Introduction

Glacial lakes (GL) are becoming an increasingly prominent feature of polar and high mountain landscapes around the world (Bhambri et al. 2018, Buckel et al. 2018, Shugar et al. 2020, How et al. 2021, Andreassen et al. 2022, Carrivick et al. 2022, Rick et al. 2022, Wieczorek et al. 2023). Their presence primarily indicates ongoing climate change (Dye et al. 2022). Glaciers in retreat around the world are revealing entirely new, previously unexplored periglacial zones (Murton 2021). With the right terrain morphology and an existing 'barrier' such as a terminal moraine, water from the deglaciation process is retained (Sakai 2012). The resulting glacial lakes

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are important reservoirs of freshwater and sediments directly from retreating glaciers (Kavan et al. 2022). Dams that stop the drainage of glacial lakes vary in structure. A distinction is made between moraine dams, ice dams and other dams (e.g. debris from landslides) (Emmer et al. 2016, Yao et al. 2018). Lakes dammed by moraines and ice are very fragile elements of the periglacial landscape. This is mainly due to the melting of the ice, which either forms the entire dam of the glacial lake or is a filling element of the moraine (Ewertowski 2014). The transience of glacial lakes described above leads in particular to sudden events such as glacial lake outburst floods (GLOFs). This event, known mainly from regions such as Iceland under the name of *Jökulhlaup*, but also from densely populated mountain valleys in the Himalayas, poses a real threat to infrastructure and above all to human settlements (Russell et al. 2010, Allen et al. 2019). To date, studies of glacial lakes worldwide have focused relatively little on the Svalbard archipelago, which is one of the last undescribed regions in the world in this respect (Shugar et al. 2020, Wieczorek et al. 2023). However, few studies have highlighted the importance of glacial floods in shaping the Svalbard landscape in the context of ongoing climate change. Thus, to fill the gap in the current knowledge of the glacial lakes in Svalbard, selected examples of glacial lake systems representing different types (according to the classification of Emmer et al. 2016), their different locations and the state of research to date were taken into account. Goësvatnet was therefore included, as an example of an ice-dammed lake with documented dynamic (seasonal) fluctuations that resulted in annual GLOFs (Dudek et al. 2023). Examples of glacial lake systems having a significant impact on paraglacial and coastal formations were Knivseggbreen and Nepebreen (endmoraine-dammed lakes), which caused lagoonal lake drainage (Wołoszyn et al. 2022), and Crammebreane (medial moraine-dammed lake), which led to moraine destruction and significant erosion in the runoff zone, as well as sediment transport (Wieczorek et al. 2024). The most recent example chosen was the endmoraine-dammed lake on the Ragnarbreen foreshore, which, despite its size, has been developing very steadily since the Little Ice Age (LIA) and so far there are no indications of catastrophic phenomena such as GLOFs occurring (Ewertowski 2014, Ewertowski, Tomczyk 2020). Based on collected studies on the geomorphology in the surroundings of the indicated glacial lake systems, the aim was to identify similarities and differences in the individual systems and to demonstrate the dynamics of change of the individual glacial lake systems in light of the intensive transformations of the paraglacial landscape (Oliva et al. 2020).

Study area

The study area was limited to catchment areas of selected glacial lakes in the Svalbard Archipelago (Fig. 1A). These are the catchments of two glaciers, Knivseggbreen and Neppebreen, located in the area of NW Spitsbergen with the increased influence of the warm Spitsbergen Current (Fig. 1B), Crammerbreen – SW Bellsund (Fig. 1C), Ragnarbreen – NE Isfjord (Fig. 1D) and Gåsbreen – SW Hornsund (Fig. 1E). Ragnarbreen is more protected from the influence of the marine climate due to its location in the central part of the island (Dallmann et al. 2015).

The climate in the immediate vicinity of Ragnarbreen is significantly drier than the other selected catchments located on the coasts of Spitsbergen (Rachlewicz 2009). It is important to note the sharp climatic differences on Sørkapp Land itself (South Svalbard), where Gåsbreen is located. These differences are due to the influence of the cold East Spitsbergen Current and the warm West Spitsbergen Current, which flow around the peninsula (Ziaja, Ostafin 2015). The location of the Knivseggbreen and Neppebreen glaciers behind the 79°30'N latitude makes the influence of the polar climate very noticeable here (Wołoszyn et al. 2022) (Table 1).

Owing to their distance from each other, each of the indicated areas is characterised by different geology: the Gåsbreen area is mainly composed of phyllite, quartzite, carbonate rocks, dolomite and limestone; Crammerbreen has phyllite, quartzite and diamictite, while in the Knivseggbreen and Neppebreen areas the dominant lithology is migmatite and gneiss, as in Ragnarbreen (Dallmann et al. 2015). Gåsbreen, Knivsggbrenn and Nepebreen are areas with similar morphology, representing glacial valleys fed by several different glaciers in recession. The

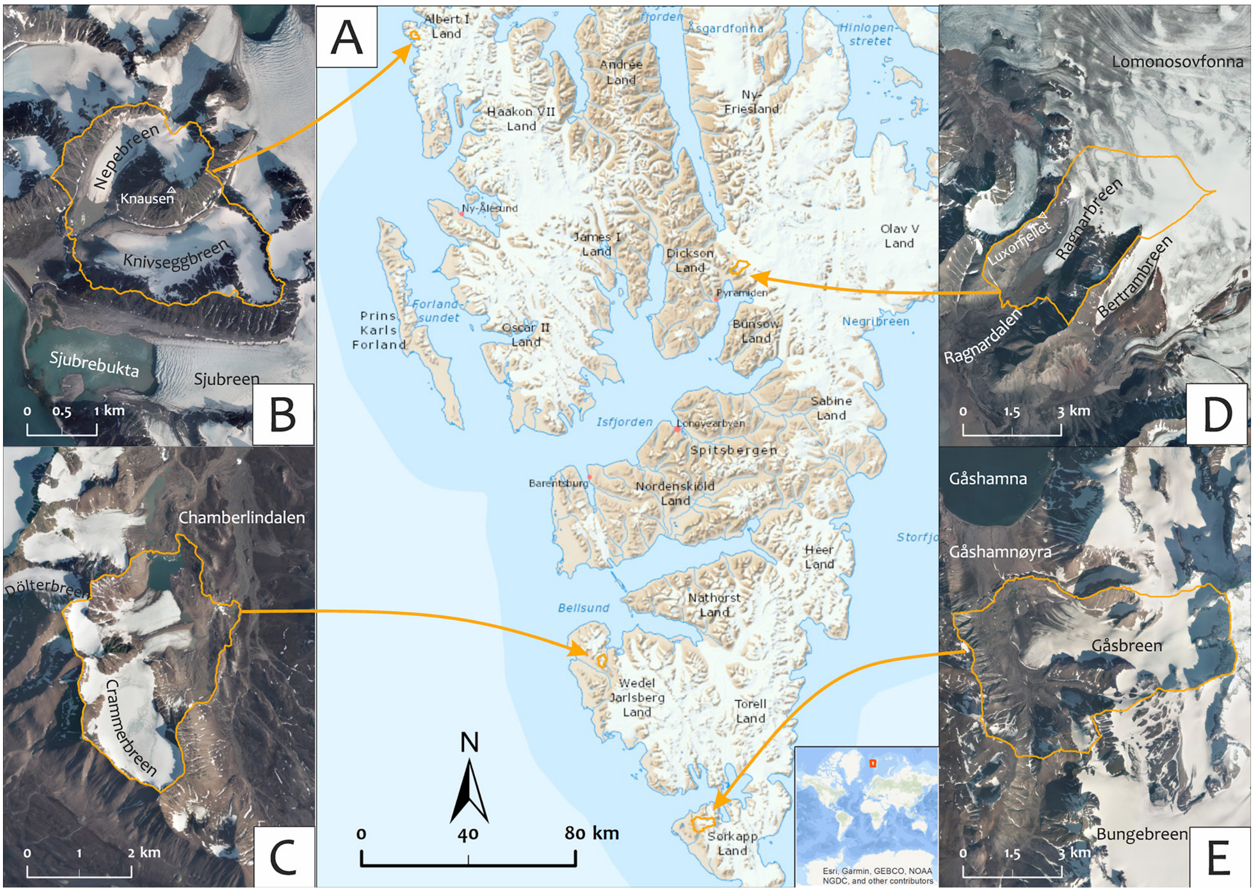

Fig. 1. Selected catchments for case studies of Svalbard glacial lakes. A – Map of Spitsbergen, B – Nepebreen and Knivseggbreen watersheds, C – Crammerbreen watershed, D – Ragnarbreen watershed, E – Gåsbreen watershed. Source: NPI Ortofoto and Basiskart. NPI, Norwegian Polar Institute.

Table 1. Summary of the basic morphometric and meteorological parameters of the selected catchments.

Lake location near the glacier	Catchment area	Glacier area	Annual temperature	Annual precipitation	Altitude min-max	Glacier retreat
	[km²]		[°C]	[mm]	[m a.s.l.]	[m · a⁻¹]
Gåsbreen	30.77	12.59	−4.0 Osuch, Wawrzyniak (2017)	432.9 Błaszczyk et al. (2019)	18–1388	18
Crammerbreen	9.47	5.5	−2.5 Repelewska-Pękalowa et al. (2013)	32.4 Mędrek et al. (2014)	55–820	11
Knivseggbreen and Neppebreen	6.30	2.87	−6.9	200–400	51–716	4
Ragnarbreen	18.22	9.39	>0 Rachlewicz, Styszyńska (2007)	189.1 Bednorz, Jakielczyk (2014)	86–939	9

Crammerbreen area represents a lateral glacier system, which during the LIA was a single glacier fed by four separate sources. As deglaciation progressed, these separated into four smaller glaciers. The Chamberlinvelva, whose drainage area is used by Crammerbreen, is an example of a non-glaciated valley.

Materials and methods

All analyses performed were based entirely on available remote sensing data (Fig. 2). The primary tool was use of the digital elevation model (DEM) from the ArcticDEM Explorer website (Porter et al. 2023). The terrain models available there are represented as stripes and mosaics. An index of the collected terrain models was used to select those that cover the location of the selected study areas. For the present analysis, the mosaics representing the selected study areas in 2015 were selected with a resolution of 2 m. The exception is the DEM representing Gåsbreen in 1990, which originates from the Norwegian Polar Institute (NPI) studies and has a resolution of 20 m. The DEMs were sampled to cover the immediate vicinity of the selected glacial lakes in their entirety. By downloading DEMs with sufficient margin, it was possible to proceed to delineate the catchment area of the individual glacial lakes.

Based on the DEM, hydrographic and surface analyses were performed in ESRI ArcMap 10.8.2. In order to narrow down the study area to the exact catchment boundaries selected on the basis of the DEMs, a series of simple hydrographic analyses were carried out. Hydrographic analyses make use of the elevation information assigned to each pixel of the DEMs, thus demonstrating the theoretical runoff direction (*Flow direction* tool) and then flow rate (*Flow Accumulation* tool) of each liquid located within the catchment. Based on the designated, theoretical watercourses, it is possible to determine where all the streams from our area come into contact with each other, which is designated as a *Pour point* (saved as shapefile). The Pour point is also the end of the catchment area of interest, which, by using its position, can be delineated using the *Watershed* tool. The catchment areas so delineated, in raster form, make it possible to clip the DEMs taken at the outset of their coverage.

With the study areas already delineated, the next step involved conducting morphometric analyses using the DEM. The first was to determine the slope (*Slope* tool) and then to classify the slopes within the catchment based on Sikdar et al. (2004). Longitudinal profiles of the glaciers located within the study areas were also produced and presented using the relevant graphs. Furthermore, the *Surface volume* tool was utilised with DEM to estimate the quantity of water drained during GLOF events. This tool uses DEM to calculate the volume of a specific area. By applying it to an area that was once filled with glacial lake water drained due to a GLOF, the amount of water that flowed during the GLOF can be estimated.

The most recent image data consisted of four multispectral images with a resolution of 3 m, acquired at the turn of July and August 2023 by SkySat satellites launched by Planet Labs PBC (2024). The images have also been processed in ArcMap 10.8.2 software to produce a suitable set of bands. The best performance in identifying water objects was obtained by combining bands

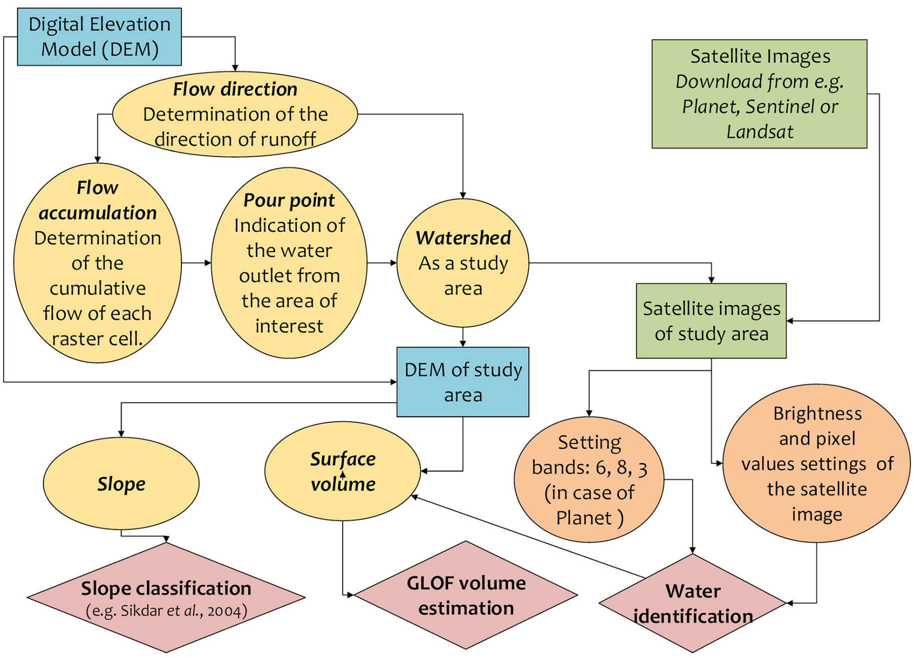

Fig. 2. Methodological process. DEM – digital elevation model; GLOF – glacial lake outburst flood.

6, 8 and 3 (PlanetScope 2024). This allowed areas covered by water (glacial lakes) to be properly highlighted. Remote sensing analysis of high-latitude areas is often hampered by unfavourable weather conditions and overlapping shadows cast by surrounding peaks. While selecting an image with favourable atmospheric conditions was not a problem, it was not possible to avoid the shadow cast over the study area, which is visible at Crammerbreen or Knivseggbreen and Neppebreen. Therefore, the images were additionally brightened and the addition of the Percent clip stretch setting to the default settings enabled more effective analysis of water objects.

Results

The analysed glacial lakes differ mainly in their classification. Goësvatnet was an ice-dammed lake, while the lake at Crammerbreen was initially classified as a frontal moraine-dammed lake, but due to progressive deglaciation, it became a medial moraine-dammed lake. The lakes at Knivseggbreen and Neppebreen and Ragnarbreen are typical examples of frontal moraine-dammed lakes. An important element that allows for comparison between the lakes (apart from their location within a single archipelago) is the documented GLOF phenomenon (Table 2). The lake on the Ragnarbreen foreland is the only one that has not experienced a GLOF, as described in the following paragraphs.

Glaciers and glacial lakes

The selected glaciers vary in surface area and, more significantly, in the altitude of their accumulation zones. The assumed average Svalbard snowline, located at 400 m a.s.l. (see Fig. 2) (Schuler et al. 2014), has been included to facilitate the analysis. According to the calculations based on this assumption, glacier accumulation zones >400 m a.s.l. should effectively resist deglaciation processes, or at least reduce their rate. The lack of visible, permanent snow cover >400 m a.s.l. indicates that the equilibrium line for the indicated catchments is higher. As a result, the analysed glaciers will continue to be subject to deglaciation processes. Deglaciation of Svalbard uncovers paraglacial zones. These zones, such as Ragnarbreen, are occupied by constantly expanding glacial lakes (Fig. 3). Due to the susceptibility of paraglacial zones to landscape transformation, phenomena such as GLOFs are not uncommon, which is related to water provided by melting glaciers – of which Gåsbreen, Crammerbreen or Knivseggbreen and Neppebreen are examples.

The glacial lakes selected for analysis differ primarily in size (refer to Table 1). This size difference is reflected in the GLOF scale, as evidenced by the estimated GLOF volume (refer to Table 1). Each GLOF had a distinct impact on the shape of the runoff zone. Goësvatnet, an ice-dammed lake, experienced cyclical GLOF events, with the first flood in 1956 being the largest. The GLOF on the Gåsbreen forefields in 1990 was the largest on record. The GLOF caused channel changes in the outfall zone and a significant sediment ejection into the bay. Additionally, the GLOF on the Crammerbreen forefield led to increased erosion of the runoff zone, resulting in a change in the outflow of the Crammerbreen catchment. Although the smallest recorded GLOF on the Knivseggbreen and Neppebreen forelands did not result in visible changes, the disappearance of the lagoon lake due to the GLOF wave's water discharge into the bay is noteworthy.

The lakes in the forelands of Knivseggbreen and Neppebreen have developed relatively

Table 2. Comparison of glacial lake outburst flood type, area, and volume for glacial lakes in each watershed.

Classification	Unit	Knivseggbreen Frontal moraine-dammed lake	Nepebreen Frontal moraine-dammed lake	Crammerbreen Medial-moraine dammed lake	Goësvatnet Ice-dammed lake	Ragnarbreen Frontal moraine-dammed lake
Biggest recorded area (date)	[m²]	115,166 (2015)	206,859 (2022)	418,292 (2019)	930,000 (1938)	546,743 (2023)
Area before GLOF	[m²]	49,388	197,264	418,292	370,000	–
Area after GLOF	[m²]	0	145,741	197,395	50,000	–
Estimated GLOF volume	[m³]	666,389	ND	4,624,892	7,391,392	–

ND – no data.

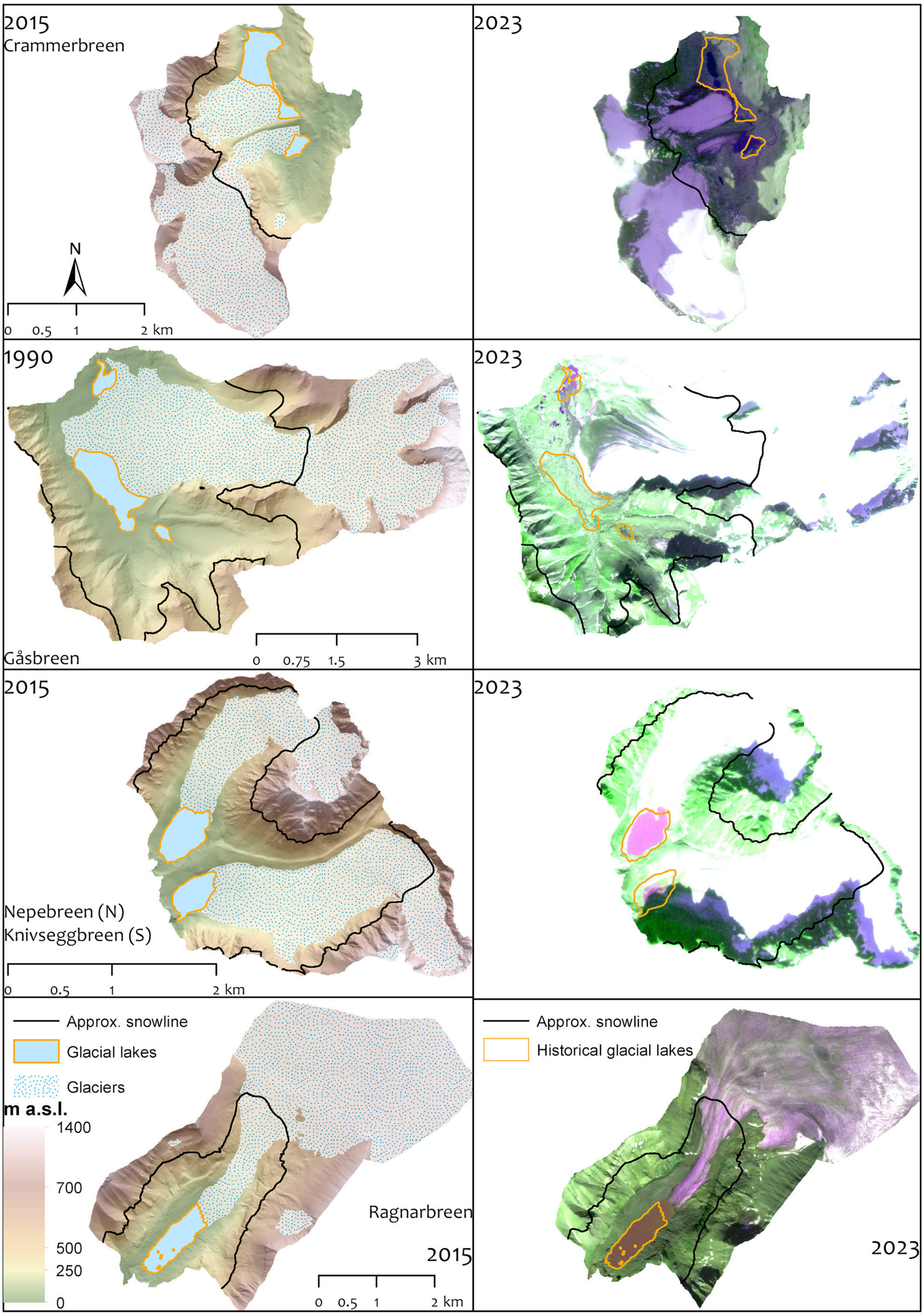

Fig. 3. Catchments of Crammerbreen, Gåsbreen, as well as Knivseggbreen and Neppebreen before GLOF and in 2023 and catchment of Ragnarbreen in 2015 and 2023. The left column shows the DEM of the catchment before GLOF, and the right column shows the current state of the catchment as seen on satellite imagery using settings that emphasise water (glacial lakes) and glaciers. DEM – digital elevation model; GLOF – glacial lake outburst flood. Source: ArcticDEM, Image © 2023 Planet Labs PBC.

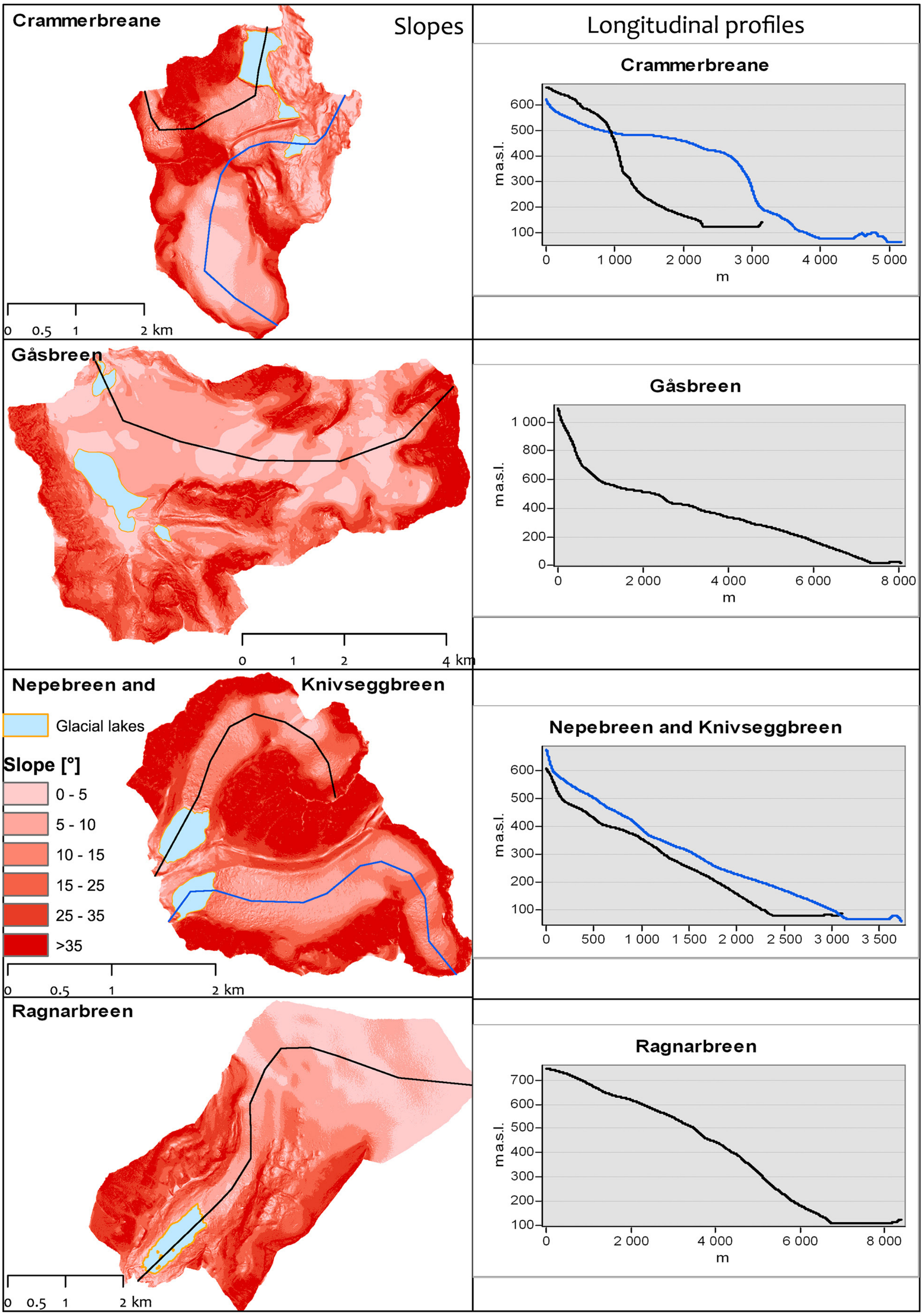

Fig. 4. Comparison of slopes (left column) and the longitudinal profiles (right column) of different glaciers and their slopes. Source: ArcticDEM. DEM, digital elevation model.

symmetrically since the LIA. This is because of their proximity to each other, the location of the glacial accumulation zone at a similar level, and the favourable morphology of the foreland. The frontal moraines that formed effectively blocked the outflow of glacial waters, allowing glacial lakes to form. A significant discovery is that, even though the end moraine overflowed and created a gap in the form, the glacial lakes persist in filling up by using the area left by the retreating glaciers. As a result, they move away from the moraine boundary.

The Crammerbreen glaciers, which consisted of four distinct source zones during the LIA maximum, have undergone significant changes that have impacted the formation of present-day glacial lakes. At the start of the 20th century, all lakes formed in the foreland of the Crammerbreen were classified as frontal-moraine dammed lakes. As deglaciation progressed, the Crammerbreen glacier separated into four distinct catchments, each separated by central moraines. As seen in Figure 2, the lake began to push against a central moraine, which eventually collapsed due to melting ice, resulting in a GLOF phenomenon and the drainage of almost the entire lake in 2019. The morphology of the Crammerbreen foreland does not allow for the re-accumulation of lake water. A gradual deglaciation process will lead to the complete disappearance of this lake. The example of a glacial lake dammed by a central moraine illustrates the absence of cyclicity in glacial flooding.

The lake in the foreland of Ragnarbreen is an example of a stable glacial lake. It is gradually filled by the waters of the glacial lake, an example of the transformation of the paraglacial zone due to deglaciation. No evidence of a GLOF phenomenon has been recorded as there have been no abrupt changes in the surface of the lake waters. The Ragnarbreen glacier has a low gradient slope in the lake contact zone (see Fig. 4) and is not a direct factor that could cause water disturbances, such as an avalanche, which could trigger a wave capable of destroying the moraine dam and resulting in a GLOF event.

Slopes

The longitudinal profiles for each of the selected glaciers exhibit noticeable differences (Fig. 4). The Ragnarbreen longitudinal profile is the least varied, which is due to its source zone on the ice cap. The Ragnarbreen front gradually descends (with a slope of up to 10°) towards Ragnarvatnet. The longitudinal profiles of the Knivseggbreen and Neppebreen and Gåsbreen glaciers consist of steep walls in the glacial cirque at the source zone, followed by gently descending slopes (with a slope of up to 15°) towards the glacial lakes and the terminal moraine. The Crammerbreen glacier is the most varied due to a tectonic fault running through its middle, resulting in icefalls with a slope of >35°.

Discussion

Svalbard's glacial lakes are dynamically changing landforms of the archipelago's landscape. Their modern appearance is a result of the development of glacial lakes since the LIA. Recent inventory studies have shown that these lakes, as dynamically changing landforms, merge at glacier fronts and undergo cyclical or single GLOF events, where, in particular, these single events can lead to the complete drainage of glacial lakes (Urbański 2022, Wieczorek et al. 2023). When glacial lakes merge and lose contact with the glaciers that feed them, these water bodies are often stabilised in the landscape (Loriaux, Casassa 2013). The analysis describes glacial lakes as an example of the changes observed during deglaciation of the glaciers feeding them.

An example of the merging of glacial lakes can be found in the Crammerbreen foreland (Wieczorek et al. 2024). However, the double occurrence of GLOFs has led to the formation of glacial lakes there and, as a result, gradual lake drainage. This example shows how the GLOF phenomenon can lead to the disappearance of a glacial lake from the landscape. Observations of this type are being made in other polar and high mountain regions, indicating the vulnerability of moraine dams to GLOF phenomena (Goswami, Goyal 2021). However, it must be emphasised that global studies assume that ice-dammed lakes exhibit the greatest instability, as exemplified by the Goësvatnet analysis. Cyclic GLOF events, which at one point had almost seasonal occurrences (Walder and Costa 1996, Schöner and Schöner 1996, 1997, Dussaillant et al. 2010, Ziaja et al. 2016, Dudek et al. 2023), indicate the high GLOF activity during the existence of an ice-dammed lake, followed by complete stabilisation or disappearance of the glacial lake (Blown, Church 1985, Kjeldsen et al. 2014). It is therefore generally accepted that ice-dammed lakes pose the greatest threat to human settlements located in their runoff zone (Carrivick, Tweed 2016). This can be precisely linked to the cyclic GLOFs of Goësvatnet, which ceased due to the melting of the ice dam, as also highlighted in other glaciated regions (Veh et al. 2023).

The location of Lake Goësvatnet in southwestern Spitsbergen, which is characterised by higher temperatures and precipitation compared with the rest of Svalbard (Osuch, Wawrzyniak 2017, Błaszczyk et al. 2019), has resulted in a relatively rapid rate of deglaciation and thus the transformation of the glacial lake (Dudek et al. 2023). By contrast, much more stability is observed in the Knivseggbreen and Neppebreen glacial lakes located in northwestern Spitsbergen, where only a single GLOF occurred (Wołoszyn et al. 2022). Based on longitudinal profiles, it can be inferred that the Knivseggbreen and Neppebreen glaciers will soon lose contact with the proglacial lakes due to deglaciation.

A similar situation is occurring with other analysed glacial lakes in the forelands of Crammerbreen and Ragnarbreen, where longitudinal profiles show that the glaciers are retreating to steeper slopes (~5–10°), which will prevent further contact between the lakes and the glaciers. An interesting example is the Crammerbreen area, which features visible icefalls with a slope of ~35°. Ice blocks falling from suspended glaciers are considered as one of the main causes of GLOFs (Emmer et al. 2014, Vilímek et al. 2015, Furian et al. 2021). Although the GLOFs that occurred at Crammerbreen were not caused by these ice blocks, as there are still glaciers directly below the icefalls, the average deglaciation rate of 11 m $\cdot$ a^{-1} suggests that we will observe waves on the lake within the next decade, formed by falling ice blocks from the icefalls.

The DEM analysis for the Crammerbreen foreland indicates that conditions are no longer favourable for the formation of new glacial lakes in this area. The transformation of the Arctic landscape since the LIA has led to the creation of runoff zones that continuously drain the Crammerbreen foreland. The existing glacial lakes are now losing direct contact with the glaciers and are stabilising within the Arctic landscape (Mölg et al. 2021). The Crammerbreen foreland is now a major source of sediment transported to Chamberlindalen Fjord, a phenomenon observed among other Svalbard glaciers (Zagórski et al. 2020, Kavan et al. 2022, Frydrych, Zagórski 2024, Wieczorek et al. 2024). Sediment accumulation in glacial lakes, which is subsequently released due to GLOF events, has been observed in Gåsbreen, Crammerbreen, and Knivseggbreen and Neppebreen, demonstrating the important role of glacial lakes in sediment retention and transport (Kavan et al. 2022, 2023).

The lake in the Ragnarbreen foreland has been the most stable in its development since the LIA. According to Ewertowski (2014) and Ewertowski and Tomczyk (2020), during the maximum of the LIA glaciation, the Ragnarbreen glacier extended up to the terminal moraines visible in the field today. The deglaciation process is assumed to have been similar to that of other Svalbard glaciers, beginning in the early 20th century (Ewertowski 2014, Geyman et al. 2022, Wieczorek et al. 2023). Lake Ragnarvatnet has a maximum depth of −17 m, according to Ewertowski (2014). The symmetrical morphometry of the Ragnarbreen valley, a freeboard of about 10 m, and the Ragnarbreen glacier's low gradient at the contact with the lake suggest that Ragnarvatnet will develop stably and become fixed in the landscape (Mölg et al. 2021). The selected catchments differ primarily in their source areas. The glacial lakes of Crammerbreen, Knivseggbreen, and Neppebreen are fed by relatively small glaciers, which favour the deglaciation process (Paul and Bolch 2019, Wołoszyn and Kasprzak 2023). The Gåsbreen glacier, on the contrary, is much larger than Crammerbreen, Knivseggbreen, and Neppebreen, but due to its location in the southern part of the island and exposure to warm ocean currents, it is retreating rapidly. This also affects the evolution of the glacial lakes in its foreland. The Ragnarbreen is considered to be the most stable due to its sheltered location from the direct influence of the marine climate and the fact that it is fed by a very large ice sheet (Ewertowski 2014, Jia et al. 2019). These differences are reflected in the rate of enlargement of glacial lakes and the frequency of glacial floods. Glaciers that change more rapidly result in larger and more unstable glacial lakes, as exemplified by the now defunct Goësvatnet.

Conclusion

The analysis of the various glacial lakes reveals a spectrum of features and behaviours shaped by their classification and response to deglaciation processes. In this study, an analysis of ice-dammed lake Goësvatnet, medial moraine-dammed lake Crammerbreen, and frontal-moraine-dammed lakes Knivseggbreen and Neppebreen and Ragnarbreen is undertaken. The stability of lake Ragnarbreen, devoid of glacial lake-induced flooding (GLOF) in contrast to the other examples, is attributed to its sheltered location and the influence of a large ice sheet. However, the broader context of ongoing deglaciation on Svalbard highlights the exposure of paraglacial zones where expanding glacial lakes are vulnerable to GLOFs due to changing environmental dynamics. This phenomenon highlights the complexities of glacier-lake interactions in the Arctic landscape. In particular, observations indicate symmetrical lake development in the Gåsbreen and Knivseggbreen and Neppebreen since the LIA, while dynamic changes in the Crammerbreen highlight the separation of the glacier into separate catchments and the subsequent collapse of moraines leading to GLOFs. Longitudinal profiles of the glaciers further illustrate this complexity, with Ragnarbreen showing the least variability due to the source zone on the ice sheet, while Knivseggbreen and Neppebreen and Gåsbreen present diverse terrains with steep cirque walls and gently sloping slopes towards glacial lakes. Location indeed plays a crucial role in the analysis of Svalbard's glacial lakes. Notably, the lakes and glaciers situated in the south-western part of Spitsbergen, such as Gåsbreen and Crammerbreen, have undergone more rapid changes since the LIA compared with those in Knivseggbreen and Neppebreen and Ragnarbreen. This accelerated rate of change is evident in both the dynamics of the lakes themselves and the occurrences of GLOFs. In summary, this comprehensive analysis offers valuable insights into the varied responses of glacial lakes and glaciers to deglaciation, underscoring the importance of understanding their evolving dynamics within the broader context of climate change in the Arctic region. Attention is particularly drawn to spatial distribution, meteorological conditions and classifications, all of which play significant roles in shaping the behaviour and characteristics of these natural features.

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