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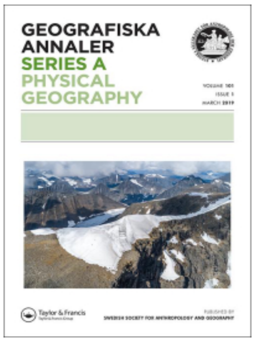

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Proglacial lake expansion and glacier retreat in Arctic Sweden

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ABSTRACT

Proglacial lakes have increased in number and extent in Arctic Sweden since the 1950s/1960s as glaciers have retreated dramatically. Interrogation of Rapid Eye imagery highlights that some lake terminating glaciers had substantial (>100 m) rates of retreat between 2010 and 2018, with one other land terminating glacier also retreating at a similar rate. However, analysis of a regional remote sensing time series suggests that proglacial lake formation in this period across the area has not been uniform. Despite glacier accumulation areas having similar maximum elevations (~2,000 m) and similar alpine topography, proglacial lakes in the southern area (Sarek) were found to be significantly smaller than proglacial lakes in the northern area (Kebnekaise), which had smaller glaciers within corries and more prominent terminal moraines. Therefore, it cannot be assumed that proglacial lake formation will occur as glaciers retreat in response to elevated air temperature, particularly as only 33% of glaciers had proglacial lakes in their forefield. Thus, whilst it cannot be assumed that proglacial lakes will accommodate water currently held in glaciers, the 108 lakes mapped here present a substantial area (4.767 ± 0.377 km^2) of fresh water that has not previously been included in the Global Lakes and Wetlands Database (GLWD). This inventory therefore provides an important dataset that can be used to underpin our understanding of the role of proglacial lakes within the hydrological system in this area of the Arctic.

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Proglacial lake; Arctic Sweden; glacier retreat; ASTER satellite

Introduction

Glaciers are a key component of the hydrological system in many mountainous areas as they can also act as a longer-term deposit of water (due to time taken for mass to pass through the glacial system) than typical non-glacial catchments (Jansson et al. 2003; Fellman et al. 2014). Consequently, water may be accumulated on land in glaciers due to climatic conditions (cooler or wetter) over several decades (or longer) and provide a crucial source of water during periods of drought or in arid areas (Jansson et al. 2003; Farinotti et al. 2016). Glaciers can also act as a depository of water on seasonal and diurnal timescales (Jansson et al. 2003).

As glaciers are sensitive to changes in climate, they have generally retreated since the Little Ice Age cold period finished and are predicted to retreat further with future climate change scenarios (IPCC 2019). If glacier recession continues then this depository of water may eventually disappear and either form or not form proglacial lakes. Where proglacial lakes form in basins exposed as glaciers retreat, they will act as an important store of water in place of glaciers, albeit with different

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characteristics (Carrivick and Tweed 2013). When and where this glacial meltwater from glacial recession is not stored on land (such as proglacial lakes), then it will contribute to sea level rise if it exceeds the snow and ice mass accumulated on glaciers (IPCC 2019). In either case, local hydrological systems will be changed, which will have substantial implications for ecology and human populations downstream (Fellman et al. 2014; Farinotti et al. 2016).

As glacier terminus positions retreat, topographic basins are often left where terminal moraine systems provide a dam or where subglacial erosion into the bedrock has been high. Therefore the extent and topographical restraint on glaciers will influence the potential formation (and depth) of a basin, as well as underlying geology having a strong control on subglacial erosion rates and potential for glacial overdeepenings to form (Cook and Swift 2012). These factors are likely to vary across glaciated mountain areas and will control proglacial lake development through time (as glaciers retreat) across these topographic basins if meltwater input is sufficient and water storage is efficient (Frey et al. 2010; Carrivick and Tweed 2013). Note also that meltwater input to glacial lakes may also originate from groundwater and/or ground ice in the forefield, so meltwater can potentially be an important indicator of permafrost thaw in response to increases in air temperature and heatwaves (Jonsell et al. 2013; Kim et al. 2018).

It is timely to identify the presence of proglacial lakes and study changes in spatial extent individually and across regions, in order to ascertain how they respond to climatic events (e.g. heatwaves) and relate to glacier retreat rates (Kim et al. 2018; Dye et al. 2021). Particularly as there is an increasing body of research which highlights the exacerbation of glacier retreat rates where they are in contact with proglacial lakes, through mechanical and thermo-erosional processes (Lliboutry et al. 1977; Kirkbride 1993; Kirkbride and Warren 1997; Warren and Kirkbride 1998; Warren and Kirkbride 2003; Roehl 2006; Komori 2008; Robertson et al. 2012; Trussel et al. 2013; Tsutaki et al. 2013; Wang et al. 2015; Carr et al. 2013; King et al. 2017, 2018; Minowa et al. 2017; Mallalieu et al. 2020; Watson et al. 2020). Proglacial lake distribution and extent has been mapped at the regional scale in the Alps, Greater Himalaya, Peru, Greenland, Norway, and Patagonia through analysis of multispectral satellite imagery (Buchroithner et al. 1982; Huggel et al. 2002; Gardelle et al. 2011; Loriaux and Casassa 2013; Carrivick and Quincey 2014; Hanshaw and Bookhagen 2014; Yao et al. 2018; How et al. 2021; Kumar et al. 2020; Andreassen et al. 2022). Furthermore, Pierre et al. (2019) called for a global proglacial lake inventory as they found that proglacial freshwater may act as a 'globally relevant' sink for atmospheric CO_2 through chemical reactions in turbid meltwater.

As future predictions of climate change suggest glaciers will retreat further (IPCC 2019), it is vital to assess whether proglacial lakes represent a stable store of water in their place and assess how the spatial extent of proglacial lakes and contact with glaciers has changed in time (Komori 2008; Carrivick and Quincey 2014; Hanshaw and Bookhagen 2014). It is also essential to assess this stability as Glacial Lake Outburst Floods have been observed in many glaciated mountain regions with severe damage and casualties downstream (Clague and Evans 2000; Huggel et al. 2002; Ghimire 2004; Emmer 2018). Further constraining the spatial extent (and persistence) of proglacial lakes and influence on glacier retreat rates at the regional scale would improve future predictions in glacier mass loss (IPCC 2019). Given that smaller glaciers are more sensitive to climate change (Rippin et al. 2011; Paul et al. 2016), this study focuses on an area of the Arctic characterized by relatively small glaciers that have been subject to recent warming trends in air temperatures and heatwaves (Arendt et al. 2012; Jonsell et al. 2013; Dye et al. 2021). The overall aim of this study is to constrain the area of proglacial lakes in Arctic Sweden and assess the changes over time in conjunction with glacier retreat rates.

The objectives of this study are as follows.

(1) Create a proglacial lake inventory for Arctic Sweden and analyse variations in spatial characteristics across the study area.
(2) Quantify the area change in proglacial lake extent since the 1950s/1960s.
(3) Characterize the retreat rates of 24 lake and land terminating glaciers in Arctic Sweden between 2010 and 2018.

Study area

The study area covers ~6,500 km^2 of Arctic Sweden between 67.022806°N and 68.300895°N, with predominantly Caledonian Amphibolite nappe geology (Figure 1) (Goodfellow et al. 2008). The topography extends up to the highest point of northern Scandinavia (Kebnekaise, 2,097 m); with relief commonly of 1,000 m along the elevation axis that runs SW-NE through the study area

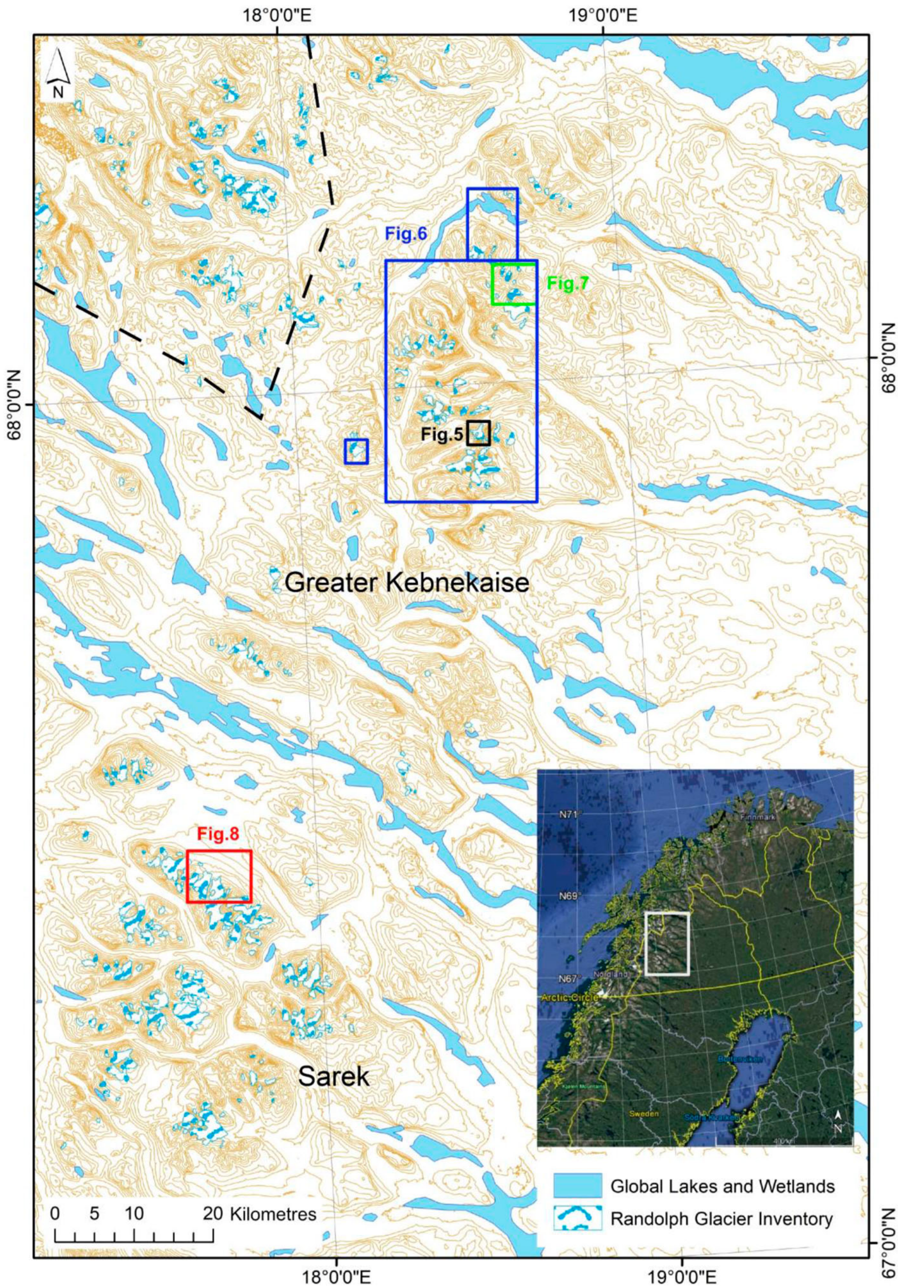

Figure 1. TanDEMX contour (100 m intervals) map for Arctic Sweden. White/blue polygons = RGI glacier areas (Arendt et al. 2012). With boxes to show location of; Figure 5 (black), Figure 6 (blue), Figure 7 (green), Figure 8 (red). Inset image (Google Earth) shows location of the study area (white box). Dashed line marks the border between Sweden and Norway.

(Goodfellow et al. 2008). There is a mixture of plateau areas and alpine peaks along the main mountain crest, with some prominent headwalls that create substantial shading for the neighbouring glacier. The 11-year data record (2001–2011) from a 100 m deep borehole at Tarfalaryggen (1,550 m a.s.l.) indicates there is continuous permafrost above 1,200 m, although there is a significant warming trend that reaches a maximum of 0.047°Cyr^{-1} at 20 m depth (Christiansen et al. 2010; Jonsell et al. 2013). Therefore, some proglacial lakes in the study area may be underlain by permafrost, although this may be degrading (Christiansen et al. 2010).

The glaciers in the northern part of the study area (around Kebnekaise) tend to be of the 'cirque' type, which are situated in deep hollows in the mountainside, and most have developed large terminal moraine systems at the rim of the cirque. In contrast, the glaciers of the Sarek area to the south tend to be larger due to higher rates of precipitation (Karlen et al. 2017). Consequently, they extended beyond the cirque rims at the 'Little Ice Age' maximum and into the larger valley systems below, which has generally resulted in the development of terminal moraine systems with lower crest heights (Ostrem 1964; Karlen et al. 2017). The glaciers in the west of the study area are mostly of the plateau icefield type (Karlén 1973; Goodfellow et al. 2008). Glaciers across the study area have been retreating since reaching a 'Little Ice Age' maximum extent c. 1916, although positive mass balance years have occurred at Storglaciaren (Kebnekaise), particularly between the mid-1970s to mid-1990s (Karlén 1973; Holmlund et al. 1996; Holmlund and Holmlund 2019).

Methodology

The Randolph Glacier (RGI) inventory v3.2 (Arendt et al. 2012) was utilized for identifying the 252 glacial units in the study area from imagery acquired in 2008 (Figure 1). The most extensive snow and cloud free (<7%) imagery available was from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite from 2014 (freely available from https://earthdata.nasa.gov/), which was used for digitizing proglacial lake outlines in ArcGIS (hereafter referred to as; 'manual mapping') to provide the most comprehensive inventory of proglacial lake extent in Arctic Sweden. The relatively high resolution (15 m), wavelength range (three bands across the VNIR and TIR) and availability of ASTER multispectral satellite imagery underpinned their use to map the extent of proglacial lakes from optical imagery in this study. Specifically, ASTER data were favoured over Landsat 8, as the green and red bands have higher spatial resolution (15 m as opposed to 30 m), so the higher resolution is critical in minimizing uncertainty in lake boundary determination and therefore enabling smaller lakes to be identified. The MADAS (METI AIST Data Archive System; https://gbank.gsj.jp/madas/map/index.html) was used to search through the ASTER archive to select Level 1 T images, that are geometrically registered and geo-corrected using ASTER GDEM and supplied as calibrated radiance values. Three ASTER images were downloaded from 8/8/2014 (10:46 UTC+1) and used for manual digitizing of proglacial lake extents.

Mapping proglacial lakes using ASTER data

The extent of the proglacial zone was restricted to the Little Ice Age maximum extent to constrain the climatic period in which these proglacial lakes appeared to the last ~100 years, which tend to be clearly defined by prominent moraine systems across the region (Karlén 1973). The forefields of 252 glaciers (Arendt et al. 2012) were inspected in ASTER multispectral imagery (8/8/2014) to manually detect proglacial lakes within the Little Ice Age maximum limits in Arctic Sweden (Denton and Karlén 1973; Karlén 1973). Water bodies in the proglacial zone were manually digitized using the green (band 1 0.52–0.60 μm), red (band 2 0.63–0.69 μm) and NIR (band 3 0.78–0.86 μm) composite image by drawing polygons around the edges of pixels of water (see Appendix). Where pixels were observed to be a mixture of land and water, the polygon was drawn to dissect such mixed pixels. Manual mapping of proglacial lake polygons was conducted in one batch, with comparison of delineation of lake margins to minimize subjective uncertainty.

The workflow associated with mapping proglacial lake polygons using a raster image with 15 m × 15 m pixels follows the method used in Hanshaw and Bookhagen (2014). They propose that ∼69% of lake pixels will be subject to boundary errors due to proximity to the lake margin and a likely mixture of lake water and land within these pixels (Hanshaw and Bookhagen 2014). The number of pixels along the lake outline was first calculated by dividing the perimeter (P) by the grid size (hereafter referred to as *G;* 15 m for ASTER VNIR) which is then multiplied by 0.6872 (hereafter referred to as *HB;* Hanshaw and Bookhagen 2014). It is assumed that the uncertainty for delineating a lake margin is 0.5 G and therefore the first two terms are multiplied by the area of 0.5 G^2 (Hanshaw and Bookhagen 2014);

$$\text{Lake Area Error}(1\sigma) = (P/G)*0.6872*G^2/2. \tag{1}$$

These calculations give a generic geometric indication of uncertainty in Lake Area determination (L_A) from raster data. They produce a guideline area threshold (L_{AT}) of 0.170 km^2 for geometric errors to be ∼5% of the overall area of the lake (e.g. for G = 15). Given their size, proglacial lakes are likely to have uncertainty in area determination of >5%. However, all proglacial lakes in this category are reported here for completeness of the inventory but have only been recorded where there is a greater than 95% confidence of their presence on data from 2014. All proglacial lakes were mapped in one batch, thereby ensuring the most consistent delineation of boundaries with minimal change in subjective errors. To further assess the uncertainty in manual mapping, the boundary of 26 proglacial lakes (decided by imagery availability) were mapped from ASTER imagery on 29/7/2018 and also from Rapid Eye (5 m resolution) imagery on 27/7/2018 to calculate RMSE between the two datasets.

Mapping proglacial lakes from aerial imagery

The Swedish Lantmateriet historical (1957–1963) aerial imagery catalogue (∼1 m resolution, panchromatic; freely available from Lantmateriet.se) for the Kebnekaise and surrounding areas was searched and 49 tiles (each 5 km × 5 km) were downloaded (metadata currently unavailable). These tiles were manually inspected for suitability for identifying proglacial lakes and 25 tiles were rejected due to snow cover. A total of 24 aerial imagery tiles covering ∼600 km^2 were selected for analysis of proglacial lake extent (see Supplementary).

To minimize erroneous changes in lake extent resulting from differences in resolution between the historical imagery (G ∼1 m) and ASTER imagery (G = ∼15 m), the polygons derived from the ASTER manual mapping were carefully cross-referenced with the historical aerial imagery. Polygons derived from aerial imagery were then only adjusted at the lake-to-glacier ice margin, to purely capture changes in lake size due to glacier recession (see Supplementary). Where the ASTER proglacial lake outlines were visibly covered by ice in historical imagery, they were classed as 'Unborn' or 'Snow Concealed'.

Mapping glacier terminus change using Rapid Eye imagery (2010–2018)

The Rapid Eye satellite imagery catalogue (freely available from Planet.com) was searched for suitable snow/cloud free imagery for mapping glacier termini. A series of 14 Rapid Eye multispectral satellite images (G = 5 m) were downloaded for 2010 and 11 images for 2018, covering Kebnekaise and the northern sections of the study area (Figure 6). A total of 24 glaciers that had suitably snow free margins were selected for analysis and identified alphabetically (Figure 6). To account for the variations in glacier termini geometry (some have a more triangular outline) a reference point [RP] was selected on either side of the glacier where the width was consistent for 2010 and 2018 (Figure 6). The glacier terminus area was then mapped below these width RPs to create terminus polygons for 2010 and 2018 (Figure 6; Lea et al. 2014). The 2018 glacier terminus polygon area was then subtracted from the 2010 glacier terminus polygon area to give the area of ice lost over this period and divided by the width of the RPs, to partly account for glacier thinning and narrowing within the width averaged retreat (Lea et al. 2014).

Results

Glaciers in Sweden from the Randolph Glacier Inventory

The 252 glaciers studied across Arctic Sweden are generally located on northerly to easterly aspects and range in area from 0.052 to 10.2 km^2 (Figure 1). The largest glacier [Parteglaciaren] represents a notable outlier, as the next largest glacier area was 6.63 km^2. Only three glaciers were found to have an area >6.0 km^2 and most (i.e. 89.0% of the inventory used here) tend to be less <2.0 km^2 in area. The total glacier area for Kebnekaise and the northern part of the study area was 45.1 km^2, with a mean glacier area of 0.851 km^2 and median of 0.553 km^2 (Arendt et al. 2012). In contrast total glacier coverage in Sarek was almost double this level, totalling 85.107 km^2 with a mean of 1.637 km^2 and median of 1.360 km^2.

Proglacial lake inventory for Arctic Sweden from ASTER 2014 imagery

A substantial number of glaciers (75 out of 255) in Arctic Sweden had proglacial lakes in the forefield (including 3 not identified in RGI but with visible glacial ice) on 8 August 2014. The boundaries of 108 proglacial lakes were delineated across Arctic Sweden, 42% of which were in visible contact with a glacier terminus on 8 August 2014 with 58% lying within the LIA limit but having no contact with the parent glacier (see Supplementary for Inventory table). The total combined area of proglacial lakes mapped in ASTER imagery (8/8/2014) was 4.767 ± 0.377 km^2. Area uncertainty was calculated for each lake (Equation 1) and included in the inventory (see Supplementary), the RMSE between manual mapping from ASTER (15 m) and Rapid Eye (5 m) was 0.114 (6.68%). The smallest proglacial lake mapped in this study had an area of 0.0001 ± 0.0003 km^2 and the largest lake had an area of 0.6862 ± 0.024 km^2, with a mean of 0.044 ± 0.0035 km^2 and median of 0.008 ± 0.002 km^2 for all lakes mapped in the study area. The majority (89%) of proglacial lakes were <0.1 km^2 and 53% were <0.025 km^2. Indeed, the proglacial lake population size distribution in August 2014 was positively skewed with 71.2% of proglacial lakes being relatively small (<0.03 km^2) (Figure 2).

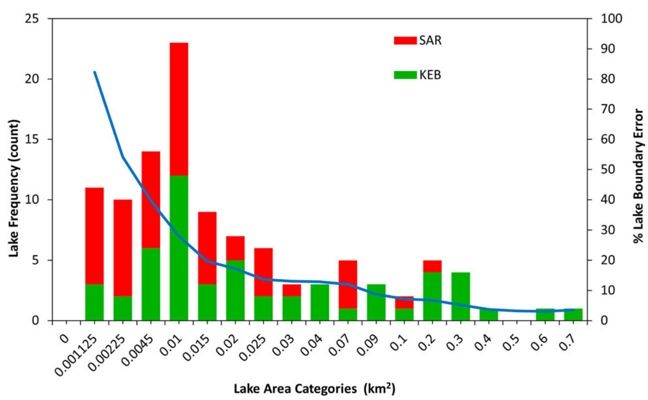

Figure 2. Histogram of proglacial lake area with percentage lake area boundary (average for lakes in each area category/bin) for Arctic Sweden (8/8/2014). Bars are subdivided into lakes in Kebnekaise area (KEB = Green) and Sarek (SAR = Red).

It might be expected that as glaciers retreat and reduce in area, then proglacial lakes will increase in area. However, there was no correlation between glacier area and proglacial lake area ($R^2 = 0.0286$), partly due to the large number of small lakes in the population. The aspect of the glacier associated with each proglacial lake was predominantly (77%) north through to easterly aspects, with 33% of lakes facing east, 25% facing north east and 19% facing north. In contrast only 13% of lakes had neighbouring glaciers facing southeast, 6% facing south and only 5% associated with glaciers facing northwest. Proglacial lake elevations were between 996 and 1620 m, with the majority (95%) lying between 1,100 m to 1,500 m. There was no correlation between proglacial lake area and elevation ($R^2 = 0.0304$).

Variation in geometry of proglacial lakes between sub-regions

There is some notable variation in area of proglacial lakes across the study area (Figure 3). Only 12 out of 108 proglacial lakes were >0.1 km^2 and represent outliers (>1.5 × Inter Quartile Range). The majority (11) of these larger lakes were in the Kebnekaise and surrounding areas, hereafter referred to as 'Greater Kebnekaise area', with separate subpopulations marked a, b, c, d on Figure 3. The very northern limit of the study area (area a, Figure 3) contains 4 smaller proglacial lakes (<0.02 km^2) and two of the 12 large (>0.1 km^2) outliers. The next group of lakes to the south (area b, Figure 3) are smaller (~0.01 km^2) and associated with small corrie glaciers with terminal moraine systems. The Kebnekaise area (area c, Figure 3) has a diverse population of proglacial lakes with a large range in areas, from 0.000744 km^2 to 0.686 km^2 with corrie glaciers, some small valley glaciers and plateau icefields in the west of the region (Karlén 1973). The central region (area d, Figure 3) had proglacial lakes between ~0.05 and 0.15 km^2, with neighbouring corrie glaciers. The southernmost population of proglacial lakes lies in the Sarek area and are generally smaller, although there is 1 larger proglacial lake (>0.1 km^2) (Figure 3).

Analysis of differences between proglacial lakes in Kebnekaise and Sarek

On 8/8/2014 in the Sarek area 23 out of the 54 proglacial lakes mapped had a contact point with a glacier and 28 were moraine dammed (see Supplementary). Proportions were similar in the Greater Kebnekaise area as 21 out of the 54 of the proglacial lakes had contact a glacier and 23 were moraine dammed. The mean proglacial lake size in the Greater Kebnekaise area was 0.073 km^2 and a median of 0.017 km^2. In contrast, the mean proglacial lake area in the Sarek area was 0.016 km^2 and a median of 0.005 km^2. (Figure 3). Both datasets have a positive skew and non-parametric distribution. As U_1 (906) was lower than *Ucrit* (2,238.513) for a two tailed Mann Whitney U test (at 0.05 sig. level) the null hypothesis (H_o) is rejected, therefore the proglacial lakes in the Sarek area had a statistically significant smaller area than those in the Greater Kebnekaise area (Figure 3). So glacial lake formation has not been uniform in extent across the two different areas, despite the mountains being of a similar altitude and relatively close proximity (~50 km apart). Therefore highlighting the complexity of factors controlling proglacial lake formation and spatial extent, which are further explored in the Discussion.

Proglacial lake development since 1950s/1960s

A total of 33 proglacial lakes that were present in the ASTER 2014 imagery were within the area covered by the earlier aerial imagery (covering 1957–1963). There were 7 'snow concealed proglacial lakes' that were present in 2014 but could not be clearly identified in the 1950s/1960s, which ranged in area from 0.002 km^2 to 0.024 km^2 (from ASTER imagery 8/8/2014). The possible presence or absence of these proglacial lakes should be borne in mind as they form a substantial proportion (21%) of the August 2014 proglacial lakes that are within the spatial area covered by the 1950s/1960s imagery.

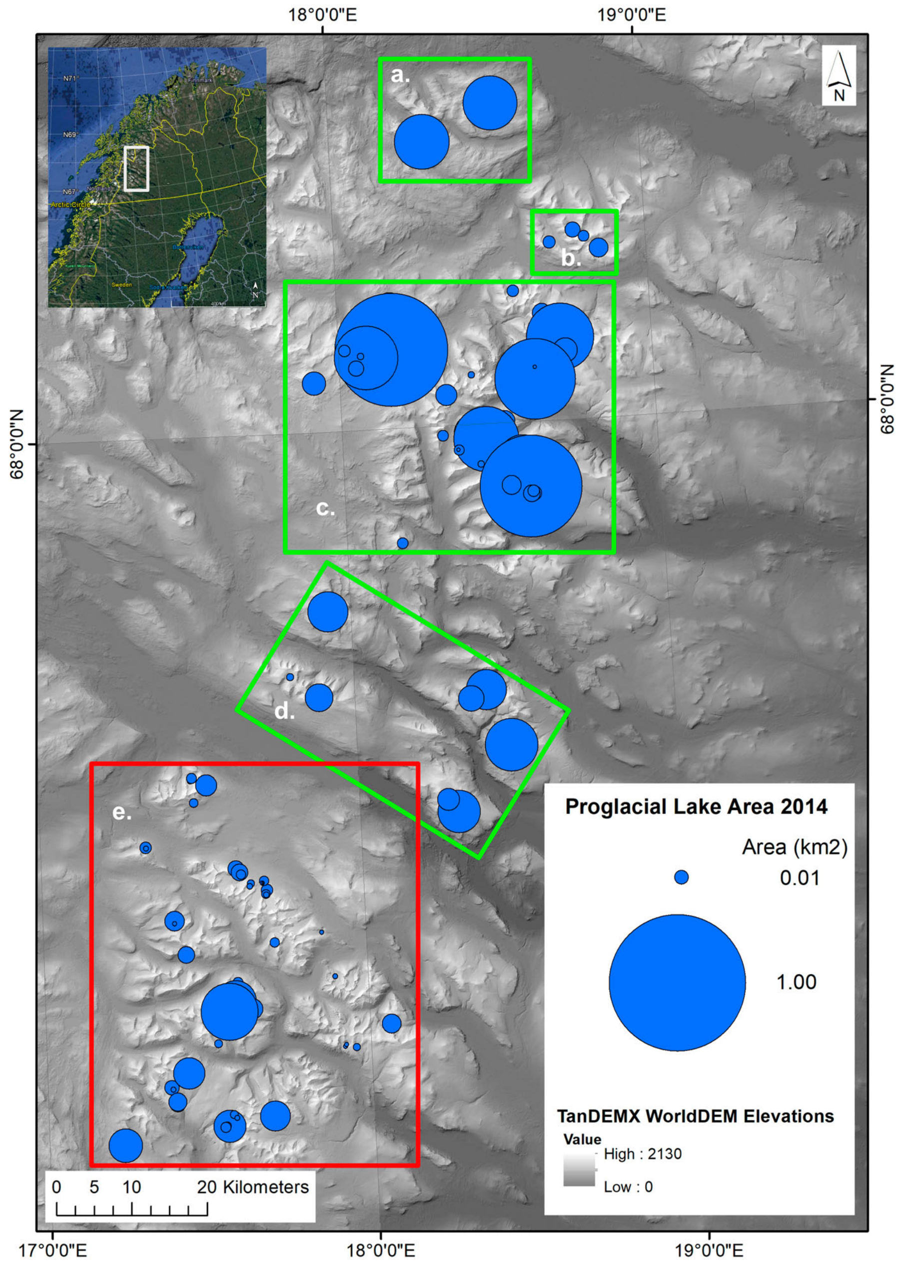

Figure 3. Proportional bubble plot for proglacial lake area (m^2) across Arctic Sweden manually mapped from ASTER satellite imagery (15 m) (8/8/2014). Green boxes denote sub-regions (a, b, c, d) of proglacial lake populations, which are described individually but are treated as 'Greater Kebnekaise area' for statistical analysis. Red box (e.) denotes Sarek area.

There were 15 (45.5%) 'unborn' proglacial lakes (PGL$_{ID}$; 18, 20, 29, 30, 33, 34, 35, 38, 44, 45, 46, 48, 51, 52, 108) that were mapped in the ASTER imagery (26 lakes in total) from 8/8/2014 but were visibly covered by glacial ice in the 1950s/1960s imagery (1957–1963) (Figure 4). These 15 'unborn' proglacial lakes ranged in size from 0.0007 km^2 to 0.086 km^2 with a mean of 0.019 km^2 and median of 0.006 km^2 at elevations between 1,178 m to 1,406 m asl; 12 of them were from corrie glaciers (mostly easterly aspect) and 3 were from plateau icefields. No

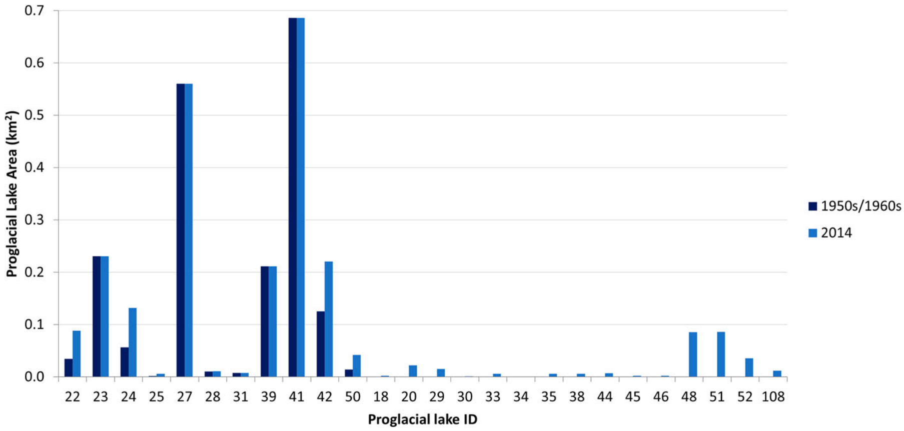

Figure 4. Plot of proglacial lake area from mapping of ASTER satellite imagery (8 August 2014; light blue) and historical aerial imagery (1957–1963; dark blue) across the 'Greater Kebnekaise' area. Lake 41 is covered by an aerial image from 1957, lakes 48, 51 and 52 from 1963 imagery and the remaining lakes are covered in imagery from 1959 or 1960. Note that 'snow concealed' lakes are not plotted.

proglacial lakes that were present in the 1950s/1960s imagery were observed to have a dry bed in August 2014.

Only 11 proglacial lakes from the sample (33 from 8/8/2014) had visibly open water in the 1950s/1960s imagery, with a range in area from 0.002 km^2 to 0.686 km^2 (largest lake in inventory). The mean area of these lakes was 0.176 km^2 with a median of 0.057 km^2, indicating a large positive skew in the dataset. These same 11 proglacial lakes had a mean area of 0.2 km^2 and a median of 0.132 km^2 in August 2014. There was no change in area of the four largest proglacial lakes (in the historical imagery) over this period (lake 41; 1957–2014, lakes 23 and 27; 1959–2014 and lake 39; 1960–2014) (Figure 4).

The remaining 6 proglacial lakes present in the 1950s/1960s imagery all increased in area. The largest absolute increase in proglacial lake area occurred from a plateau icefield glacier (Riukojietna) receding (losing contact with the lake), which increased from 0.125 km^2 in 1960 to 0.221 km^2 in 2014, an increase of 0.096 km^2 (+76.4% of 1960 area). Note that Riukojietna (>1320 m asl) lies ~10 km to the west of the main Kebnekaise mountain chain and therefore experiences a more maritime climate, so the lower limit of continuous permafrost is likely to be higher than that in the Tarfala valley (~1,200 m) (Goodfellow et al. 2008; Christiansen et al. 2010).

The next largest absolute increase (0.075 km^2) in proglacial lake occurred at lake 24 from recession of an alpine/valley glacier (Kaskasapakte glaciar), from 0.057 km^2 in 1959 to 0.132 km^2 in 2014, a 132.8% increase on the 1959 area (Figure 5). Note that Kaskasapakte glaciar still has contact with the proglacial lake and has been actively calving (Dye et al. in prep). There was a comparable amount of area change for lake 22 (0.053 km^2), which represented a 154.2% increase of the 1959 area (0.035 km^2) associated with the retreat of a large corrie glacier (Vaktposten). Lake 50 had a larger proportional change of 192% (0.027 km^2) of the 1963 proglacial lake area (0.014 km^2), associated with the retreat of a relatively small corrie glacier (Figure 4). The largest proportional change of a proglacial lake occurred at lake 25 (265% of 1963 area) (low confidence due to snow cover).

Glacier retreat between 2010 and 2018 from Rapid Eye imagery

The width averaged retreat of the 24 glaciers analysed across the northern part of the study area ranged between 0 and 126 m between 2010 and 2018 (Figure 6); 5 had proglacial lakes in the forefield but no contact, 11 had no proglacial lakes in the fore field and 8 had direct contact with a proglacial lake (Figure 6). The mean width averaged retreat rates was 63 m (median = 55 m) for glaciers

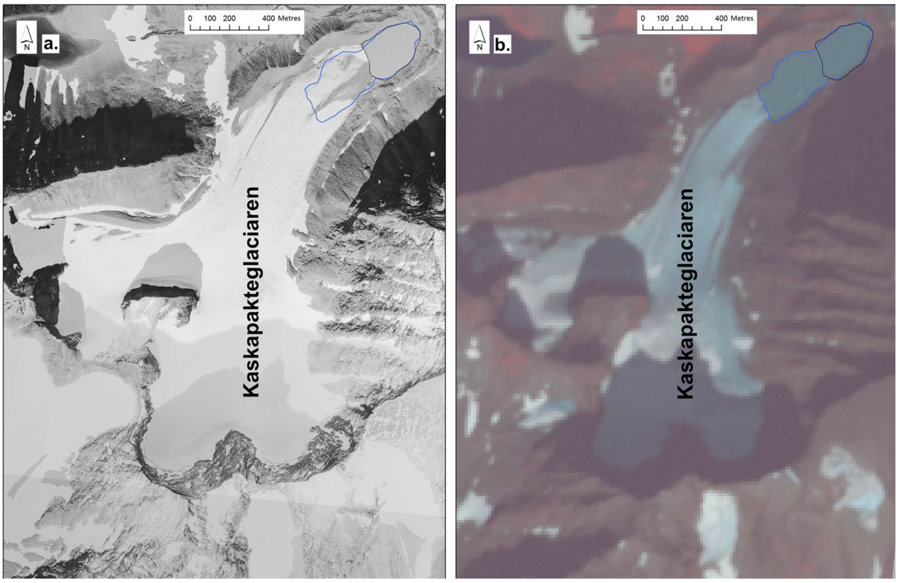

Figure 5. (a) Aerial image (Lantmateriet, 1959) of Kaskapakte glaciar (Sweden; 67.955144°N, 18.565447° E) showing 1959 proglacial lake outline (black) with August 2014 proglacial lake outline (blue). Spatial resolution is unknown but estimated ~1 m. (b) ASTER satellite composite image (G,R, NIR, 15 m resolution) from 8 August 2014 (10.46am) with 1960 proglacial lake outline (black) and August 2014 outline (blue).

with proglacial lakes over this period in the forefield (but no contact), 53 m (median = 39 m) for land terminating glaciers and 53 m (median = 39 m) for glaciers in contact with a proglacial lake. Note that the latter figures change to a mean of 61 m and median of 39 if glacier T is excluded, which is the smallest of these glaciers (area = 0.002 km^2) and was the only glacier analysed that had no change in terminus position between 2010 and 2018 (Figure 6).

The largest width averaged retreat of 126 m occurred at Kaskasapakte glaciaren (glacier X; Figure 6), which is an alpine valley glacier that has contact with a proglacial lake (0.132 km^2 in 2014) across the full width (189 m) of the terminus throughout the period (2010–2018). A similar amount of retreat occurred at Isfallsglaciaren (glacier C; Figure 6), which retreated 122 m between 2010 and 2018 and has no contact with any proglacial lakes. Marmaglaciar (glacier Q; Figure 6) retreated 110 m over this period and there was a 143 m wide proglacial lake in contact with the 412 m wide ice front in 2018. The 3 glaciers with the largest retreat rates discussed above had notably larger retreat rates than the other 21 glaciers analysed for terminus change (2010–2018), with the next (4th) largest retreat being 81 m at the land terminating Rabot's glaciar (Figure 6). The 5th and 6th largest retreats (67 and 63 m) also occurred at land terminating glaciers (Figure 6).

Discussion

Proglacial lake extent across Arctic Sweden on 8 August 2014

This study presents the first proglacial lake inventory in Sweden, with a total of 108 proglacial lakes (covering 4.767 ± 0.377 km^2 in total in 2014) across Arctic Sweden. Whilst this area of water is relatively modest (the neighbouring lake Tornetrask is 332 km^2; Vogel et al. 2013) and depths are largely unknown, the locations of these lakes in the upper reaches of catchments makes them an important part of the hydrological system, particularly for maintaining summer base flow levels. The inventory therefore provides an important dataset, particularly as these lakes (most <0.1 km^2) were previously not included in the GLWD (minimum lake size 0.1 km^2) and largely

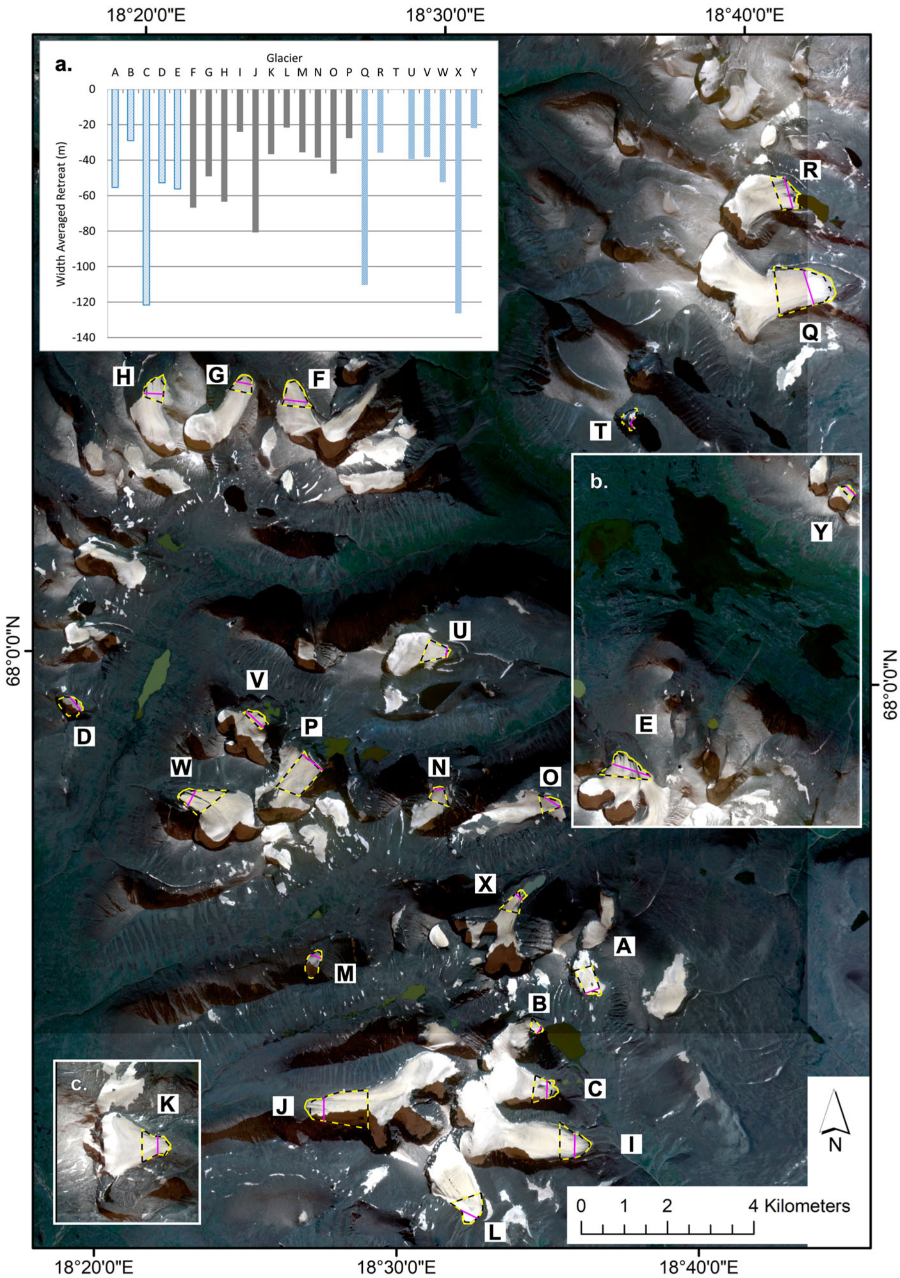

Figure 6. Rapid Eye multispectral satellite image from 27/7/2010 with; yellow outline = 2010 glacier terminus area, dashed black line = 2018 glacier terminus area, purple line = width of glacier terminus area. Inset; a. Plot of glacier terminus position change between 2010 and 2018 from Rapid Eye multispectral satellite imagery. Light blue denotes glaciers with a proglacial lake in the forefield (non-contact), grey bars denoting glaciers with no proglacial lake in the forefield and dark blue bars denoting glaciers with contact to a proglacial lake. For locations of inset b. and c. see Figure 1.

unmonitored (except lake Tarfala; Kirchner et al. 2021) and relatively little is known about their role in local hydrological systems (Birkett and Mason 1995). It is therefore salient to also analyse the spatial extent and distribution of non-ice contact proglacial lakes, as they can be an important store of freshwater (Farinotti et al. 2016). Furthermore, given the presence of discontinuous permafrost in the region (below ~1,200 m) the appearance and persistence of lakes in the proglacial area needs to be monitored carefully, as they may be fed from ground ice and thaw of permafrost in glacier forefields (Christiansen et al. 2010; Kneisel 2010). This is particularly pertinent given the increase in heatwaves in Arctic Scandinavia since 2000, so even the smallest of proglacial lakes should be carefully monitored to assess whether they have originated from melt of ground ice (Sinclair et al. 2019; Dye et al. 2021). The increased availability of high resolution (<10 m) satellite imagery means that these processes can be monitored more carefully and relationship with climatic events be more accurately constrained.

Critically, it cannot be assumed that proglacial lakes will store water where a glacier has disappeared, as not all glaciers form proglacial lakes. The subglacial erosion rates and prominence of terminal moraines will dictate whether a substantial basin for a lake forms, as well as permeability of the substrate and input/output rates determining how long water may be stored in any basin. A substantial proportion (29.4%) of the 255 glaciers in Arctic Sweden had proglacial lakes in the forefield, thereby suggesting a relatively high proportion of glaciers may have been affected by contact with proglacial lakes during their recession/evolution. Indeed, 42% of these lakes were observed to be visibly in contact with a glacier terminus on 2014 and therefore had the potential to directly influence processes of mass loss where they were in contact with a glacier (Carrivick and Tweed 2013). Furthermore, the diversity in glaciers across the study area and recent climatic events make it a valuable region for exploring the relationship with their spatial extent and proglacial lakes. Therefore, improving the understanding of where these lakes are likely to form as glaciers retreat, as well as facilitating further studies into how proglacial lake thermal regimes respond to changes in climate (Dye et al. 2021).

The previous Little Ice Age maximum extent of glaciers across the study area is clearly visible in multispectral imagery, due to prominent moraine systems, glacial deposits and minimal vegetation cover development (Denton and Karlén 1973; Karlén 1973). Furthermore, historical imagery (1910) records the LIA extent of some glaciers in the Kebnekaise region and provides useful validation of the interpretation of past glacier LIA maximum extents (Svenonius et al. 1910; Holmlund and Holmlund 2019). It may be reasonable to postulate that as glaciers retreated from the 1910 LIA maximum and decreased in area, then where they have receded there may be an increase in proglacial lake area. Consequently, decreasing glacier size may be expected to correlate with increasing proglacial lake size. However, there was no correlation between glacier area and proglacial lake area (R^2 = 0.0286). This suggests that the relationship between glacier area and proglacial lake area is more complex than proglacial lakes growing as glaciers retreat, which will be explored further below.

The aspect of the glacier associated with each proglacial lake follows the pattern of glacier locations across the study area, predominantly (76.9%) north through to easterly aspects (Karlén 1973). The predominance of glaciers and proglacial lakes on easterly and northerly aspects is unsurprising in an area where strong positive winter mass balances have been associated with strong westerly flows (positive phases of the NAO), favouring greater accumulation on north easterly aspects (Pohjola and Rogers 1997; Bonan et al. 2019). This suggests that a greater number and extent of glaciers on northerly and easterly aspects have left behind more basins where proglacial lakes have filled after glacial recession. The majority of proglacial lake elevations were between 1,100 m and 1,500 m and there was no correlation between proglacial lake area and elevation (R^2 = 0.0304). This is unsurprising as it is dictated by the extent of glaciers through the Holocene, which have tended to terminate in a relatively narrow elevation band that has been constrained by maximum elevations of ~2000 m and valley levels around ~1000 m around the Greater Kebnekaise (Karlén 1973).

Proglacial lake distribution and style across sub-regions in Arctic Sweden

The distribution of proglacial lakes in Arctic Sweden tends to be focused around the northern area (around Kebnekaise) and Sarek area to the south, with a small number of proglacial lakes in the

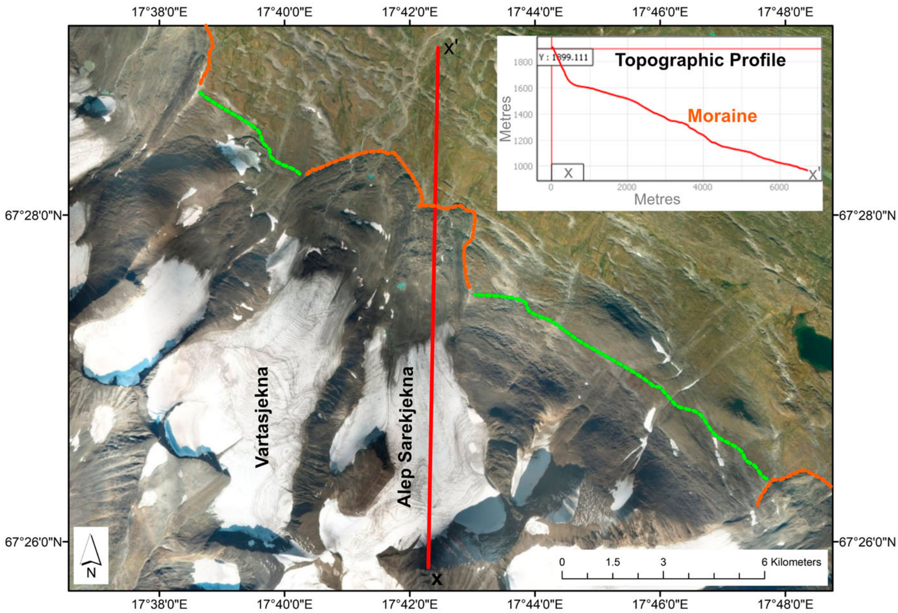

Figure 7. Satellite image from Digital Globe (WV2 0.5 m resolution) 30/8/2014 of Sarek area. The highest peak in the area, Sarektjakka (2,089 m) is in the bottom centre left of the image. Red line denotes the topographic profile (inset). Note the extensive terminal moraine systems (LIA maximum) extending beyond the corrie into the main valley below (orange dashed line). Green dashed line marks the valley side. Small proglacial lakes are clearly visible in the forefields due to the green colour from high suspended sediment load (Amphibolite). Orange dashed line = Little Ice Age Maximum.

central region north of lake Akkajaure (Area d; Figure 3) Whilst the elevation in the Sarek and Kebnekaise areas is similar (maximums of 2089 and 2097 m respectively, although 1800 m is more typical) the glaciers in the Sarek area tend to be larger and extend beyond corrie rims (Figure 7). Also, the topography in Sarek tends to be more open, with wider valleys between mountains and moraine systems that extend further horizontally (Figure 7). Consequently there are less extensive topographic hollows in the Sarek area for proglacial lakes to develop in as glaciers retreat (Figure 7). As a result, proglacial lakes in the Sarek area are significantly smaller (mean 0.016 km^2) than those further north in the central and Kebnekaise regions (mean 0.073 m^2) (Figure 8). A relatively high proportion (43%) of proglacial lakes in the Sarek area had a contact point with a glacier, therefore a substantial number of these lakes have the potential to influence the morphology and retreat rates of glacier termini in the Sarek region.

Glaciers in the Kebnekaise area (area c; Figure 3) tend to be quite diverse. The increase in precipitation rates to the west of the area and plateau topography is reflected in more extensive plateau icefield glacier areas, which would have previously supported more extensive outlet glaciers (Goodfellow et al. 2008). The northern and central regions (areas a, b and d; Figure 3) have maximum elevations of ~1800 m and tend to have smaller corrie glaciers (Figure 8), also partly due to the decreasing amounts of precipitation further north and east (Hock et al. 2002; Goodfellow et al. 2008). In the main area of the Kebnekaise mountain chain, glaciers tend to be more topographically constrained due to narrower/higher valleys and corries (Denton and Karlén 1973) (Figure 8). This combined with more prominent terminal moraine systems (with higher crests), has created topographic niches where proglacial lakes have formed as glaciers have retreated back from their LIA maximum extents (Figure 8) (Karlén 1973).

Proglacial lakes have also formed in the Kebnekaise region in glacial over-deepenings that have been produced through high rates of subglacial erosion on the bedrock, with lake Tarfala being particularly deep at 49.8 m (Kirchner et al. 2019). This is also evident in Figure 8, as lake 14 extends

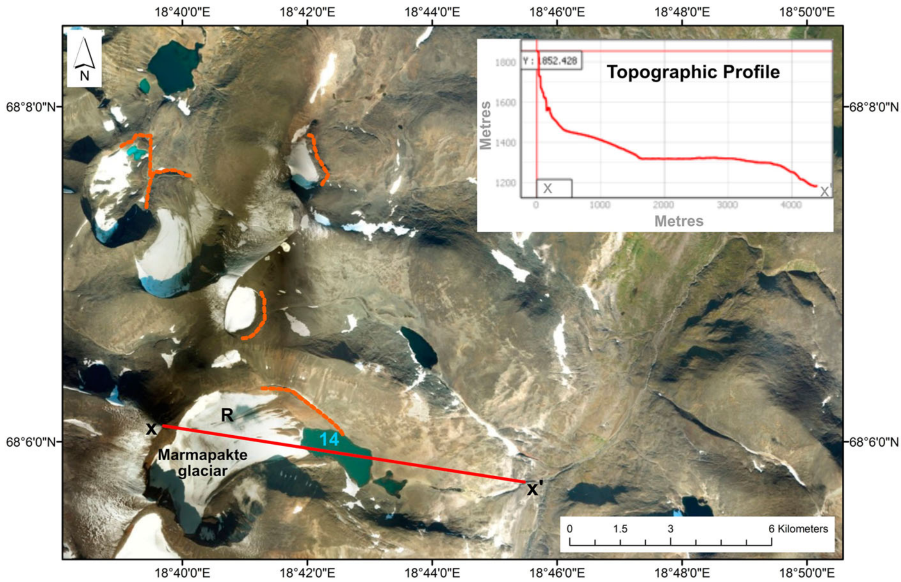

Figure 8. Satellite image from Digital Globe (WV2 0.5 m resolution)25/8/2014 of Marmapakte area. Red line denotes the line of the topographic profile. The highest peak in the image, Marmapakte (1,888 m) is in the lower left hand corner. Marmapakte glaciaren (R) flows north east from the peak to partly terminate in a proglacial lake (PGL_{ID}:14) at 1285 m at bottom centre of image. Orange dashed line = Little Ice Age Maximum.

beyond the terminal moraine from the LIA maximum (dashed orange line) and occupies a topographic depression (Karlén 1973). Although the depth of the lake is unknown, the lack of a damming terminal moraine suggests that this lake is occupying a topographic depression excavated by glaciers previous to the LIA.

The type and extent of glaciation in Arctic Sweden controls the number and size of proglacial lakes. A substantial proportion (38%) of proglacial lakes in the Kebnekaise and surrounding regions have contact with a glacier terminus and therefore have the potential to influence the morphology and subsequent retreat of glaciers. However, it is pertinent to consider the extent of the contact between the lake and the proportion of the glacier terminus as a whole, particularly as small lakes are unlikely to influence the glacier thermally or mechanically and may also quickly lose contact with the ice as the glacier retreats back.

Proglacial lake development since the 1950s/1960s

There has been a notable emergence and expansion of proglacial lakes since the 1950s/1960s in Arctic Sweden. Glaciers in the 1950/1960s covered 45.5% of the proglacial lake sample (33 lakes in total; from 8/8/2014) (Figure 4); 12 were from corrie glaciers (mostly easterly aspect) and 3 were from plateau icefields. On 8/8/2014 six of these 'unborn' lakes were >0.01 km^2 in the ASTER imagery. It is also possible that some of the 7 'snow concealed' proglacial lakes may have been underneath glacial ice, but impossible to confirm due to the snow cover in the available imagery. Substantial increases in proglacial lake area since the 1950s/1960s were observed at the 11 proglacial lakes that were also present in the ASTER imagery (8/8/2014); at Riukojietna plateau icefield (0.096 m^2; 76.4% of 1960 area), Kaskasapakte glaciaren (0.075 km^2; 132.8% of 1959 area) (Figure 5) and at Vaktposten glaciar (0.053 km^2) (Figure 4). Both of the latter two proglacial lake expansions were associated with retreat of large corrie/valley glaciers, which raises the question as to whether the respective proglacial lakes may have enhanced glacier retreat rates in this situation.

Whilst the sample discussed above is relatively limited, it suggests that there has been a substantial increase in number and extent of proglacial lakes in Arctic Sweden between the 1950s/1960s imagery and the snapshot captured by the ASTER satellite imagery (8/8/2014). At the time of writing these findings represent the first report of changes in proglacial lake extent for an Arctic area since the 1950s/1960s. Although it should be noted the study of Carrivick and Quincey (2014) reports an increase of 44% in the number ice marginal lakes on the south west margin of the Greenland ice sheet between 1987 and 2010. Therefore more mapping of proglacial lakes in the Arctic is required, ideally over a large time span to explore the relationship with proglacial lake expansion, glacier retreat and changes in climate.

Glacier retreat between 2010 and 2018 from Rapid Eye

A wide range of terminus retreat (width averaged; 0–126 m) was observed for the 24 glaciers mapped in Arctic Sweden between 2010 and 2018 (Figure 6). This heterogeneity in terminus change suggests that individual glacier characteristics and locational factors play an prominent role on influencing changes in glacier terminus area. The mean retreat rate for glaciers in contact with a proglacial lake was higher (53 m) than for land terminating glaciers without a proglacial lake (44 m) between 2010 and 2018. The highest mean retreat rates (2010–2018) reported in this study are for land terminating glaciers with proglacial lakes in the fore field (but no contact), with a mean retreat of 63 m (7.87 m a^{-1}). This was skewed by the retreat of Isfallsglaciaren (122 m), which has a prominent icefall enhancing mass loss at the terminus (Holmlund and Holmlund 2019). Indeed there is a notable variation in width averaged retreat rates in each of these three datasets, as clearly individual glacier characteristics and situation play a prominent role in response to climate and changes in the terminus area (Table 1).

Kaskasapakte glaciar had the largest width averaged retreat of 126 m between 2010 and 2018, (15.75 m a^{-1}) (glacier X; Figure 6). This is an alpine valley glacier that has contact with a proglacial lake (0.132 km^2 in 2014) across the full width (189 m) of the terminus throughout the period (2010–2018) and also since at least 1959 (Figure 5). A comparable amount of retreat to Kaskasapakte glaciar occurred at Marmaglaciar (glacier Q, Figure 6) (110, 13.75 m a^{-1}), which also had a ~140 m wide proglacial lake in contact with the 412 m wide ice front. Retreat rates at both of these glaciers is comparable to the 10 m a^{-1} reported by Andreassen et al. (2020) for a sample of Norwegian glaciers (1960–2018). In contrast, these rates of lake terminating glacier retreat in Arctic Sweden are substantially lower than reported rates of 46.9 m a^{-1} in Novaya Zemlya (Russian Arctic) (1986–2015) and 80.8 m a^{-1} in Patagonia (mid 1980s to 2010) (Sakakibara and Sugiyama 2014; Carr et al. 2013). The smaller retreat rate of Kaskasapakte glaciaren may be due to the smaller size of the glacier in comparison to glaciers in Novaya Zemlya and Patagonia, which may be due to relatively higher lateral support in proportion to the terminus width (189 m) of Kaskasapakte glaciar resulting in lower calving rates (Boyce et al. 2007). Indeed it is important to note that both areas have much more extensive glaciers than Sweden and different climate regimes, yet remain the most comparable areas for lacustrine glacier retreat rates to date.

Table 1. Summary statistics for retreat of 24 glaciers in Arctic Sweden from Rapid Eye (5 m) imagery mapping from 2010 and 2018. For land terminating glaciers with proglacial lakes in forefield (non-contact), land terminating glaciers with no lake and lake terminating glaciers with contact to proglacial lake water at the terminus.

	Land terminating glacier retreat (m)		Lake terminating glacier retreat (m)
	Non-contact	No lake	Contact
Mean	62.98	44.70	53.05
Mean rate (ma^{-1})	7.87	5.59	6.63
Median	55.37	38.54	38.84
Range	92.57	59.07	126.34
SDEV	34.64	18.97	43.34
Count	5	11	8

The range in retreat rates of the 24 glaciers mapped in 2010 and 2018, would initially suggest that the terminus positions have responded to climatic changes at different rates: albeit with substantial caveats. However, glacier response time must be considered, as particular characteristics of each glacier are clearly paramount (e.g. thermal regime, velocity, bed geometry), which will dictate how a glacier responds to climate change through volume change and/or glacier dynamics (Brugger 2007). The termini of 2 out of 3 glaciers with the largest retreat rates had contact with a proglacial lake, which may have enhanced the retreat rate. These 3 glaciers have notably larger retreat rates than the other 21 glaciers analysed for terminus change between 2010 and 2018, with the next (4th, 5th and 6th) largest retreats occurring at land terminating glaciers (Figure 6). This would suggest that factors other than contact with proglacial lakes have had a substantial influence on the retreat rates of most glaciers sampled in Arctic Sweden between 2010 and 2018. Particularly given increased air temperatures and recent heatwave events in Arctic Scandinavia (Jonsell et al. 2013; Kim et al. 2018; Sinclair et al. 2019). However, detailed analysis and discussion of the characteristics of each glacier is beyond the scope of this study.

Recommendations for future study

Future work should conduct ground penetrating radar surveys to investigate the thermal structure of these glaciers, as well as the profile and properties of the glacier bed (Pettersson et al. 2003; Rippin et al. 2011; Reinardy et al. 2019). If conducted during the winter this may (depending on ice thickness) provide the opportunity to derive proglacial lake bathymetry and therefore volume estimates for the water stored in these proglacial lakes. Proglacial lake bathymetry may be more safely obtained through conducting boat mounted sonar surveys. Furthermore, a suitable sample of proglacial lake bathymetry may facilitate an empirical relationship to be derived for lake area/volume, as has been achieved in the Alps (Cook and Quincey 2015).

Future global remote sensing-based studies [e.g. using data where $G < 5$ m] should work to maximize retrieval of data for lake and land terminating glaciers for terminus change mapping, ideally with imagery over multiple time steps to investigate the nature of change within the context of pervasive climate change. Determining glacier velocity would also be advantageous for understanding any dynamic response to lake development (King et al. 2018). This would work to further underpin our understanding of feedbacks between proglacial lakes and glacier retreat rates at the regional scale. This is particularly important given future predictions of increased air temperatures and heatwaves, which are predicted to increase glacier retreat and lake temperatures (Kim et al. 2018; IPCC 2019; Dye et al. 2021).

Conclusion

This study provides one of the first proglacial lake inventories for an Arctic area, where the development and expansion of proglacial lakes has received relatively little attention to date. The total area of 4.767 ± 0.377 km^2 covered by the 108 proglacial lakes in the inventory represents a considerable area of water that was previously not included within the Global Lake and Wetland Database (GLWD). Therefore the mapping of proglacial lakes reported in this study has important hydrological implications for assessing how currently glaciated catchments will respond to climate change (Fellman et al. 2014). Furthermore, the increase in number and extent of proglacial lakes since the 1950s/1960s reported in this study emphasizes the increasing prevalence and importance as part of the hydrological system in Arctic Sweden.

Proglacial lakes in the Sarek region are significantly smaller (mean = 0.016 km^2) than the Kebnekaise and surrounding areas (mean = 0.073 km^2). This is an important result as it cannot be assumed that proglacial lakes will provide replacement stores of water for retreating/disappearing glaciers. Proglacial lake extent is highly variable due to the differing extent and characteristics of glaciers between the two regions. A substantial proportion (29.4%) of glaciers inspected in Arctic

Sweden had proglacial lakes in the forefield. A large proportion (42%) of the 108 proglacial lakes mapped in Arctic Sweden were classed as being in contact with glacier termini and therefore had the potential to influence glacier retreat rates through enhancing mass loss. The largest retreat rate of 15.75 m a^{-1} reported in this study was at a lake terminating glacier (Kaskasapakte). This further supports the body of evidence of glacier retreat rates being enhanced where the terminus is in full contact with proglacial lake water. This retreat rate is substantially lower than has been reported for lake terminating glaciers in Arctic Russia and Patagonia, which are much larger glacier systems. The large range in retreat rates amongst the 24 glaciers analysed emphasizes the heterogeneity in glacier responses to climatic changes.

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Data availability statement

Data is currently under embargo as part of PhD thesis on the White Rose repository. Embargo ends July 2022 and data will be uploaded to a repository after this.

Disclosure statement

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Appendix

Glacier Index for Figure 6

A = Syostra Kaskatjakkaglaciaren, B = Kebnepakteglaciaren, C = Isfallsglaciaren, D = Rygglaciaren, E = Goduglaciaren, F = Ostra Bossosglaciaren, G = Vastra Bossosglaciaren, H = Norra Riehppiglaciaren, I = Storglaciaren, J = Rabots glaciar, K = Sealggaglaciaren, L = Bjorlings glaciar, M = unnamed, N = Pyramidglaciaren, O = Nipalsglaciaren, *P* = Vastra Knivglaciaren, Q = Moarhmmaglaciaren, R = Moarhmmapakte glaciaren, T = unnamed/unmarked, U = Raitajakkaglaciaren, V = Vaktpostglaciaren, W = Reaiddaglaciaren, X = Kaskapakteglaciaren, Y = unnamed.