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# Inventory and classification of the post Little Ice Age glacial lakes in Svalbard

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**Abstract.** Rapid changes of glacial lakes are among the most visible indicators of global warming in glacierized areas around the world. The general trend is that the area and number of glacial lakes increase significantly in high mountain areas and polar latitudes. However, there is a lack of knowledge about the current state of glacial lakes in the High Arctic. This study aims to address this issue by providing the first glacial lake inventory from Svalbard, with focus on the genesis and evolution of glacial lakes since the end of the Little Ice Age. We use aerial photographs and topographic data from 1936 to 2012 and satellite imagery from 2013 to 2020. The inventory includes the development of 566 glacial lakes (total area of 145.91 km$^2$) that were in direct contact with glaciers in 2008-2012. From the 1990s to the end of the 2000s, the total glacial lake area increased by nearly a factor of six. A decrease in the number of lakes between 2012 and 2020 is related to two main processes: the drainage of 197 lakes and the merger of smaller reservoirs into larger ones. The changes of glacial lakes show how climate change in the High Arctic affect proglacial geomorphology by enhanced formation of glacial lakes, leading to higher risks associated with glacier lake outburst floods in Svalbard.

## 1 Introduction

Glacial lakes constitute a significant part of many glacial landscapes (Carrivick and Tweed, 2013). In recent years, there has been an increasing focus on the rapid growth observed in the number, size and volume of glacial lakes worldwide related to climate-forced glacier retreat. There is also increasing attention on the potential hazards of glacial lake outburst floods (GLOFs). This interest has led to the compilation of glacial lake inventories in many glacierised regions such as parts of the Himalayas (Aggarwal et al., 2017; Chen et al., 2017; Govindha Raj et al., 2013; Jain et al., 2012; Khadka et al., 2018; Prakash and Nagarajan, 2017; Raj and Kumar, 2016; Ukita et al., 2011; Wang et al., 2020; Worni et al., 2013; Zhang et al., 2015), the Karakoram Range (Mal et al., 2020; Senese et al., 2018), the Tibetan Plateau (Luo et al., 2020), the European Alps (Buckel et al., 2018), Greenland (Mallalieu et al., 2021; How et al., 2021), Alaska (Post and Mayo 1970), and the Andes (Loriaux and Casassa, 2013; Wilson et al., 2018). However, detailed inventories and quantification of the changes of glacial lakes in the High Arctic, where climate amplification is strongest, are still missing.

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Glacial lakes are defined as 'bodies of water that are influenced by the presence of glaciers' (Fitzsimons and Howarth, 2018). Although this definition of glacial lakes includes supraglacial and subglacial lakes, it is common to apply the term 'glacial lakes' as synonymous to lakes located in proglacial environments. Glacial lakes are often divided into (1) ice-contact lakes and (2) ice-distal lakes (that is, not in direct contact with the glacier). Both types of glacial lakes are fed by glacial meltwater or melting of inactive glacier ice and/or formed by glacial erosion or damming (Yao et al., 2018). In a warming climate with glacier retreat, it is also expected that ice-contact lakes will develop into ice-distal lakes as glaciers retreat (Fitzsimons and Howarth, 2018; Shugar et al., 2020).

This study presents an inventory and classification of glacial lakes in Svalbard that have developed since the termination of the Little Ice Age (LIA) and have direct contact with glaciers. We provide information on spatial distribution and temporal changes in the number and size of Svalbard glacial lakes. This inventory is a significant contribution to the existing monitoring of glacial lakes, as the global synthesis of glacier lake evolution by Shugar et al. (2020) excluded Svalbard due to insufficient remote sensing data (cloud-free satellite scenes).

## 2 Study area

The Svalbard archipelago lies between 74° N and 81° N and is surrounded by the Greenland Sea to the west and the Barents Sea to the east (Figure 1). Svalbard is among the regions of Arctic where climate warming progress in the fastest pace, as the mean annual air temperature has increased by 4°C over the last 40 years (Isaksen et al., 2016; Nordli et al., 2014; Wawrzyniak and Osuch, 2020). The current mean annual air temperatures range from -5.2°C (Ny-Ålesund, north Spitsbergen) to -4.6°C (Longyearbyen, central Spitsbergen) and -4.3°C (Hopen island, southeast Svalbard) (Førland et al., 2011). The mean annual precipitation measured at Svalbard weather stations is between 190 and 525 mm, and with progressive climate change it is increasingly in a liquid or mixed (liquid-solid) state than in a solid state (Førland and Hanssen-Bauer, 2000). Climate projections indicate that the annual air temperature will increase by 4-7 ˚C, while the annual precipitation is expected to increase by 45–65% (Moreno-Ibáñez et al., 2020).

Glaciers cover approximately 57% of the total area of Svalbard (Nuth et al., 2013). Reduction of the total glacier area has been going on continuously since the maximum extent of the LIA, which occurred in the late 19th and early 20th centuries (Farnsworth et al., 2016; Humlum et al., 2003; Malecki, 2016). The archipelago is dominated by polythermal glaciers (Hagen et al., 1993) containing cold and temperate ice (i.e. ice at the pressure melting point), where subglacial water remains liquid during the winter season (Schuler et al., 2020).

There is limited knowledge on glacial lakes and their changes in Svalbard. Lake Goësvatnet, situated in northern Sorkappland, is the best documented glacial lake, but it ceased to exist in 2001 because of the retreat of Gåsbreen, followed by a glacial flood (Grzes and Banach, 1984; Schoner and Schoner, 1997; Ziaja et al., 2016). Up to date, there is no data on the number and area of glacial lakes, and their spatial distribution and temporal changes.

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## 3 Methods

### 3.1 Data compilation

To make an inventory of the glacial lakes in Svalbard, we used various sources of remote sensing data (Table 1).

*1936-1938*

The oldest of the data series used are archival aerial photos taken during the 1936–1938 NPI campaign. The photos are available on TopoSvalbard (Norwegian Polar Institute). They were taken at variable angles from a plane, and they allow for a descriptive analysis of the state of the landscape at that time. They do not cover the entire area of Svalbard and do not always make it possible to determine the state of the proglacial zones due to the distance from the plane, the angle of the photo taken, as well as the weather conditions and the presence of terrain forms that obscure the view of a specific area.

*1990*

We gained access to vectorised data for the 1990s from Norwegian Polar Institute. The data cover the entire area of Svalbard, including the state of the glacial lakes in the late 20th century.

*2008-2012*

We examined the collection of aerial photos of Svalbard, taken by the Norwegian Polar Institute (NPI) during the 2008–2012 campaign, available on TopoSvalbard (Norwegian Polar Institute). Data from this period is a reference for whole inventory. This campaign covers almost the entire archipelago with the exception of Torell Land, Wedel Jarlsberg Land, Nathorst Land, Heer Land, and the south-eastern part of Sabine Land, for which no vector data for lakes from 2008 to 2012 are available. Instead of missing vector data, we analysed the available aerial photographs to obtain information about presence of lakes during this period.

*2013-2019*

Newer data from Google Earth Pro allow obtaining information about the state of the Svalbard landscape from 2013 to 2019. This dataset provides additional information, although good-quality photos, which also meet the time criterion, do not cover the entire area of Svalbard.

*2020*

The newest data in this study are from satellite photos available from the Copernicus Sentinel mission (Sentinel Hub). Due to good weather conditions (little cloud cover), we chose photos taken in August 2020 to gain information about the state of the Svalbard landscape during the warmest month. The downloaded images were converted into one raster image and then vectorised.

### 3.2 Data processing

Data processing was executed in five consecutive steps. In the first step, the vector data, which allowed the landscape condition to be analysed and the research basis to be created, were selected using ArcMap 10.7.1 software. This selection was based on location –ice-contact lakes are characterised by seasonal variability among all of the glacial lakes. The automatic selection (ArcMap selection by attributes) was followed by a manual selection, which involved ground-truthing the results with the help of aerial photos. This procedure enabled an exclusion of supraglacial lakes from the inventory, and hindered the potential mistake of including non-glacial lakes (e.g. coastal lakes, thermokarst lakes, post-glacial valley lakes with nivo-pluvial regime), which could be a significant problem when analysing remote sensing data alone, particularly in case of poor-quality imagery.

In the second step all the glacial lakes for the period 2008–2012 were verified to show whether they were present in the 1930s and had contact with glaciers at that time. This procedure made it possible to determine the state of the glacial lakes just after the termination of the LIA in Svalbard which occurred approx..at the turn of 19th and 20th century.

In the third step, the vectorised data from the 1990s (Table 1) were applied to selected glacial lakes located in the same places as lakes from the reference period (2008–2012) and those located within 50 m of them (the buffer tool ¬ this tool decrease number of lakes which shouldn't be in analyse) with the use of ArcMap 10.7.1 software. The selected glacial lakes were then checked using the data from the research base and aerial photos from 2008 to 2012.

The next step was to check the glacial lakes selected from the reference period database using Google Earth Pro. If the quality of the photos allowed for analysis, the areas of glacial lakes were measured. The measurements made on satellite images may contain a large margin of error (of the order of +/- 5 m), which is related to the resolution of the images. They can thus be used to determine certain trends in changes related to the development of glacial lakes.

Final step of the data compilation involved vectorising glacial lakes based on photos from the Sentinel mission of August 2020. Appropriately collected data (areas and perimeters) were added to the integrated attribute table, which allowed the inventory to be completed with last year's data.

### 3.3 Measurement error

For estimating the measurement error of glacial lake area estimation, error propagation was conducted for data from the 1990s, 2008–2012 and 2020 (Eq. 1). The measurement uncertainty was different for individual periods depending on photograph precision and data source. As the data for the 1990s and 2008–2012 came from NPI and were based on accurate cartographic measurements and aviation data, the error uncertainty was assumed at the level of +/- 1 m . Due to manual vectorisation, sometimes based on low-resolution images (a margin of error >5 m), the Sentinel data received a measurement uncertainty of +/- 20 m .

$$s = \sqrt{((a^2) + (b^2) + (c^2))} \qquad (1)$$

where:

s – error propagation;

a, b and c – measurement uncertainty for the 1990s, 2008–2012 and 2020, respectively,

Using equation 1, we obtained the average measurement uncertainty for the entire area of Svalbard at a level of 0.05 $km^2$ for each of lakes . Additionally, the average measurement uncertainty was differentiated to individual regions of Svalbard (Figure 2).

### 3.4 Inventory features

The information extracted from data sources was collected and grouped in the final inventory. We extended the metadata by including information about the administrative regions in which the individual lakes are located (Atakan et al., 2015) and about the lithology based on geokart.npolar.no – Geology. Based on the numerical terrain model provided by NPI, the heights above sea level of the individual lakes and their dams were noted by creating the appropriate centroids of the measured objects in ArcMap 10.7.1, as well as the approximate length of the runoff of each glacial lake using the measure tool. Based on the Glacier Atlas of Svalbard and Jan Mayen (1993) and TopoSvalbard, information on each of the glaciers that came into direct contact with the lakes was noted (Hagen et al., 1993).

Finally, all lakes were classified based on their dam construction. To do this, the classifications by Emmer et al. (2016) and Yao et al. (2018) were applied. The classification by Emmer et al. (2016) is simple compared to that by Yao et al. (2018) because it divides lakes according to classes, while the latter also divides them into sub-classes (Table 2). Applying this classification scheme makes it possible to properly group glacial lakes into those that potentially show increased seasonality of changes and those that will be drained only in catastrophic, sudden events.

### 3.5 GLOF risk assessment

An important part of this study is to identify glacial lakes that pose a threat of GLOF due to their morphological conditions. For this purpose, we compared the heights above sea level of the surfaces of the lakes relative to the heights above sea level of their dams in reference period (2008-2012). If the difference between the lake's surface and the dam's top was less than 1 m (based on DTM with resolution of 20 m – reference points were taken minimum 5 for each dam), the glacial lake was considered as a potential threat. Based on the quantitative data obtained, we also identified those lakes that had drained completely, or their area had decreased by more than half over the entire period (1936–2020). With the indicated assumption that a lake blocked by a 1 high dam is considered a potential flood risk, it should be taken into account that this would require additional dam width calculations. This is due the fact that high, but very narrow barriers can pose an equally great threat. However, without more detailed material (e.g. high-resolution DEM) or field research, we cannot estimate the exact risk. Therefore, these results indicate the approximate scale of the research problem which are GLOF on Svalbard.

## 4 Results

### 4.1 Glacial lake classification

The inventory contains 566 ice –contact glacial lakes in the reference period (2008-2012), table 2 classifies 560 lakes and the remaining six have been described as unclassified due to the selected criteria for comparing lakes according to the classifications by Emmer et al. (2016) and Yao et al. (2018). They unclassified glacial lakes constitute a definite minority and have therefore not been considered in the following analysis.

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According to the applied lake classifications, moraine-dammed lakes are the most common in Svalbard (290) (Figure 4), followed by ice-dammed lakes (157) (Figure 5), while bedrock-dammed lakes are the least numerous (113) (Figure 6). Ny-Friesland (northeast Spitsbergen) is the region with the greatest number of glacial lakes, while the region with fewest glacial lakes is Bünsow Land (Figure 3). Moraine thaw lakes (Figure 4D), which are mostly formed in the marginal zone of glaciers, are the most common type of moraine-dammed lakes with a total of 152 lakes. The 99 end-moraine-dammed lakes (Figure 4A) and 39 lateral moraine-dammed lakes constituted the smallest subgroup of moraine-dammed lakes (Figure 4C) (Table 2). The next group according to the classification by Emmer et al. (2016) includes ice-dammed lakes (Figure 5A), whose counterpart in the classification by Yao et al. (2018) is ice-blocked lakes. Of all Svalbard lakes, a total of 157 of ice-blocked lakes were detected, and they are located mainly in the north-east parts of Spitsbergen and between the two ice caps on the island of Nordaustlandet (Figure 5A). The ice-dammed lakes (157) could be categorised into 38 advancing glacier-blocked lakes (Figure 5B) and 119 other glacier-blocked lakes (Figures 5C-D; Table 2). The last group of glacial lakes includes bedrock-dammed lakes, which posed the greatest challenge when recognised with remote sensing tools. In the classification by Emmer et al. (2016), these glacial lakes are referred to as bedrock-dammed lakes while the term glacial erosion lakes is used by Yao et al. (2018). A total of 113 lakes of this type were detected in Svalbard, the vast majority of which are located on the island of Nordaustlandet and in the northern part of Ny-Friesland (Figure 6A). As it is often difficult to identify bedrock-dammed lakes from remote sensing data, some of these should be verified and carefully classified during field research. Using Yao et al. (2018) 's classification, we distinguished ten cirque lakes (Figure 6B), three glacial valley lakes (Figure 6C) and 100 other glacial erosion lakes (Figure 6D; Table 2).

### 4.2 Post-LIA glacial lake changes

Our analyse shows that between 1990's and 2020 is observed 0.9 times increase of area of glacial lakes on Svalbard (50.9 km$^2$). The greatest changes of number of glacial lakes were observed on the Nordaustlandet island (Figure 7), where 54 lakes existed in the 1930s, then 83 lakes in the 1990s and as many as 112 between 2008 and 2012. Due to lack of adequate quality data for the entire island of Nordaustlandet, only 61 of the 112 glacial lakes were identified from 2013 to 2019. However, the Sentinel data showed that there were 97 lakes on the island in 2020. Also, the total area of glacial lakes increased by approximately 1.48 km$^2$ from the 1990s to 2020.

Table 3 compares quantitative data for the glacial lakes with full range of data (1936–2020), showing that the total area of glacial lakes increased in most regions from the 1990s to 2012. The analysis shows that the greatest changes in area of glacial lakes took place on Edgeøya and James I Land, where the area of glacial lakes increased by over 10 km$^2$ (3.8 and 13.5 times higher respectively) compared to the 1990s. In contrast, the largest decrease in glacial lake area was recorded in Orvin Land and Wedel Jarlsberg Land by over 0.5 km$^2$ loss (0.2 and 0.09 times lower respectively). The relative comparison of the increment and total area of lakes is slightly different. In this comparison, the highest values have: James I Land (14 times higher), Andrée Land (5.6 times higher) and Oscar II Land (5 times higher) in contrast to Kong Karls Land (0.6 times lower), Nathorst Land (0.4 times lower) and Orvin Land (0.2 times lower).

Due to the diverse bedrock geology of Svalbard, we prepared basic spatial statistics showing some dependencies between the lithology and the type of glacial lakes (Figure 8). Moraine-dammed lakes, which are found primarily on the west coast of Spitsbergen, lie mainly on unconsolidated and sedimentary rock substrate. Ice-dammed lakes predominate on the metamorphic rock substrate and dominate in the north-east part of Spitsbergen and the central part of Nordaustlandet. The last type of rock we have distinguished is of igneous nature, on which mostly bedrock-dammed lakes have been formed, primarily on Nordaustlandet.

Comparing the available quantitative data from 1936 to 2020 has made it possible to show the historical occurrences of GLOFs or at least fast drainage of lakes. An important aspect was also to show the lakes which pose a threat to Svalbard due to their morphological conditions (the difference in height between the water surface and the dam surface). In total, there were ten GLOFs between 1936 and 1990, 63 between 1990 and 2008-2012 and 183 between 2008-2012 and 2020 (Figure 9). The analysis of the spatial distribution of glacial floods indicates that it is a geohazard with the similar frequency of occurrence in the entire analysed area. Nordaustlandet is currently the most likely place for potential large-scale GLOF events to occur as the lakes located there are characterised by being larger compared to other ice-dammed lakes in Svalbard (Figure 9).

Lake Gandvatnet on the island of Edgeøya (Figures 1 and 10A) is an end-moraine- dammed lake. It is characterised by a rapid increase in area and a relatively low stability of the dam, which is the terminal moraine. Given the pace at which this lake develops (Figure 10), it is classified as a potential GLOF threat (Figure 10). Trebrevatnet Lake (Figure 10B) is the largest lake in Svalbard. It receives meltwater from three separate ice tongues, which further intensifies the process of water accumulation. Between 2013 and 2014, a GLOF took place at Trebrevatnet Lake, which is evident by reduction of the area of the lake (Figures 9 and 10B). Another example of a potential GLOF lake is Vetterndammen, located at the mouth of Isfjorden on the northern coast. It is a prime example of an end-moraine-dammed lake and, due to the morphology of the area, its development indicates a risk of GLOF. Its accelerated increase in size may be affected by the milder climate in this part of Svalbard and the southern exposure (Figure 10C). Although GLOF events may be more common in Svalbard than previously known, the societal consequences of GLOFs are not as great as, for example, in the Himalayas, due to the limited access for people and few settlements in Svalbard.

## 5 Discussion

### 5.1 Spatial distribution of glacial lakes

Most of the moraine-dammed lakes are located on the west coast of Spitsbergen. Based on the geology and climate gradients on Svalbard, we hypothesize that this might be linked to the number of factors. First of all, western coast is characterized by stronger retreat of ice margins when compared to e.g. northeast which led to the development of larger lakes in proglacial zones exposed by deglaciation. This greater glacier dynamic along the west coast is linked with a milder climate associated with the West Spitsbergen Current. The oceanic current not only causes relatively higher air temperatures in the western part of Svalbard, but also higher precipitation than in central and eastern sector of the archipelago, what may influence the higher

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availability of water supply to the lakes. It is also important to note, that glaciers developing along western coasts of Spitsbergen had higher availability of debris and clastic sediments to build moraines, which is related to the sedimentary lithology of bedrock.

Moraine-dammed lakes show seasonal runoffs, which is related to the instability of their dam material (Emmer, 2017; Worni et al., 2014). The greatest amount of water in glacial lakes is at the beginning of the winter season and this state usually does not change until the summer season (Emmer, 2017; Worni et al., 2014). In the summer season, when water runoff exceeds the retention capacity, water begins to flow over moraine dams or creates holes in them, causing lake drainage which could occur in catastrophic manner as GLOF event (Clague and Evans, 2000; Harrison et al., 2018; Thompson et al., 2012; Veh et al., 2019). Referring to the results of this article, moraine-dammed lakes are distinguished by the dynamic of changes during the analysed periods which is directly related to their seasonal variability. It is especially visible on west side of the Spitsbergen where the number of moraine-dammed lakes is the biggest as the potential as the potential of GLOF events.

Ice-dammed lakes are mostly located in the north-east parts of Spitsbergen and on Nordaustlandet. Similar to moraine-dammed lakes, they are characterised by seasonal changes related to glacier changes. Goësvatnet is the best documented ice-dammed lake in Svalbard (NW Sørkapp Land). During the summer season, the lake drained through a tunnel located in the transition zone between dead ice and active glacier ice of Gåsbreen – Goësvatnet was observed for the last time in 2000 (Grzes and Banach, 1984; Schoner and Schoner, 1997; Ziaja et al., 2016; Ziaja and Ostafin, 2007). Observations of ice-dammed lakes in satellite and aerial photographs indicate that considerable GLOF events can be expected in the coming years due mostly to the large amounts of water accumulated behind ice dams which according to the glaciers retreat on Svalbard will gradually vanish (Huss et al., 2009; Sobota, 2014; Zemp et al., 2012).

Bedrock-dammed lakes are represented by the lowest number of glacial lakes. Most of these lakes is located on Nordaustlandet, where there are fewer moraines, likely due to a lower availability of sediment on the island (the lithology dominated by resistant igneous and metamorphic rocks) and, most importantly, lack of supraglacial debris delivery to glacial systems of large ice caps (Figure 8). GLOFs in the case of bedrock-dammed lakes might only occur in response to catastrophic events such as avalanches, mass movements or glacial floods from higher lakes (domino effect) that dam up water (Carey et al., 2012; Emmer et al., 2016; Vilímek et al., 2015).

### 5.2 Temporal changes of glacial lakes

The first work to present the global changes in glacial lakes was by Shugar et al. (2020). Until then, a series of inventories of glacial lakes and GLOFs on regional scale areas had been created, which of course has a higher accuracy than aforementioned world-scale article. The Himalayas and Tibet have been thoroughly described regions (Govindha Raj et al., 2013; Luo et al., 2020; Thompson et al., 2012; Ukita et al., 2011; Wang et al., 2020; Zhang et al., 2015). The majority of studies that have compiled glacial lake inventories have been published over the last decade, which is directly related to the intensified climate change in the 21st century compared to the 20th century (Cook et al., 2014) and to the increasing amount of high resolution

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satellite images (Abdalla et al., 2021). Climate-forced development of glacial lakes and GLOFs often has a direct societal impact in populated regions (Carey et al., 2012; Clague and Evans, 2000; Wang et al., 2020). In high mountain areas, this risk of GLOF events is usually associated with moraine-dammed lakes (Ding Yongjian and Liu Jingshi, 1992; Bat'ka et al., 2020; Thompson et al., 2012; Veh et al., 2019). A slightly different situation is observed in the polar regions, where all classes of lakes occur due to regional differences in the intensity of the impact of climate change (depending on local climatic and morphological conditions). This is due to the relatively short time since these areas have been free of ice and thus the possibility of developing various types of lake dams. Ice-dammed lakes are presumably the greatest threat in Svalbard mostly due to the significant volume of water that collects behind these ice dams (Bhambri et al., 2020; Prakash and Nagarajan, 2018).

Of the regions for which inventories of glacial lakes have been carried out, Greenland is located closest to Svalbard. Based on remote sensing data, How et al. (2021) show a continuous increase in the number of glacial lakes throughout Greenland, which is similar to the trend in the inventory of glacial lakes in Svalbard. In Greenland, the east coast has the largest number of glacial lakes (How et al., 2021), which is in line with our study showing the largest number of lakes on the west coast. The number of glacial lakes formed may be influenced by the local milder climatic conditions related to the direct influence of the warm sea current – the Gulf Stream (Pavlov et al., 2013). A detailed inventory of glacial lakes in Alaska has shown that this region has a different hierarchy of lake types compared to Svalbard: moraine-dammed > bedrock-dammed > ice-dammed (Rick et al., 2021). In high mountain regions such as the Himalayas, the Andes, the Karakoram, and the Alps, where inventories of glacial lakes have been compiled, glacial lakes are primarily restricted to u-shaped valleys. This is in contrast to Svalbard, where glacial lakes are located mainly within moraines (Buckel et al., 2018; Viani et al., 2016; Wilson et al., 2018; Zhang et al., 2015). As climate change progresses in Svalbard, the landscape will likely undergo rapid geomorphological and glacier changes affecting the future changes of glacier lake system. This trend is visible as an evolution of glacial lakes from ice-dammed to moraine-dammed lakes (Table 4).

## 6 Conclusions

The compiled inventory presents a record of 566 glacial lakes (total area of 145.91 km$^2$) in Svalbard. Of the 290 documented moraine-dammed lakes, the vast majority are located on the west coast of Spitsbergen, the 157 ice-dammed lakes recorded dominate in the north-east part of the archipelago and the 113 bedrock-dammed lakes prevail on the Nordaustlandet island. The spatial distribution of glacial lakes in Svalbard is related to local climatic conditions and associated glacier dynamics, as well as abundance of glacial geomorphology features (moraine arcs) and the bedrock lithology.

The temporal changes of glacial lakes on Svalbard shows that number of lakes increase form 1930's till period 2008-2012 (120-566), then decreased till 2020 (566-370), importantly the total area since 1990's till 2020 increased continuously (110-169 km$^2$). It shows, that glacial lakes evolve by merging with each other or in some cases, growth in area is significant. Based on changes of area and number of glacial lakes between 1936 and 2020, we showed the potential places of the GLOF events or big-scale drainage events. In total, between 1936 and 2020 we have mapped 256 lake systems which experience at least partial drainage.

*Data availability*

Sentinel-2 imagery is available from the SentinelHub (available apps.sentinel-hub.com, last access: 27 November 2021). The topographic data of Svalbard are available from the Norwegian Polar Institute (https://toposvalbard.npolar.no/, last access: 27 November 2021 and https://geodata.npolar.no/, last access: 27 November 2021).

*Supplement*

The supplement includes table with data of each of glacial lake included in the inventory and as additional, shapefiles showing spatial distribution of lakes in different periods. The supplement related to this article is available online at https://doi.org/10.5281/zenodo.5744359

*Author contributions.*

Conceptualisation of the work presented in this paper was done by IW, MCS, LS and JCY. The problem investigation and methodology was done by IW, who also carried out GIS analyses. As far as the writing and manuscript preparation are concerned, IW prepared the draft and the data visualisation with JCY, JM, LS doing the first reviews and editing. MCS was the project PI responsible for funding acquisition and IW supervision.

*Competing interests.*

The authors declare that they have no conflict of interest.

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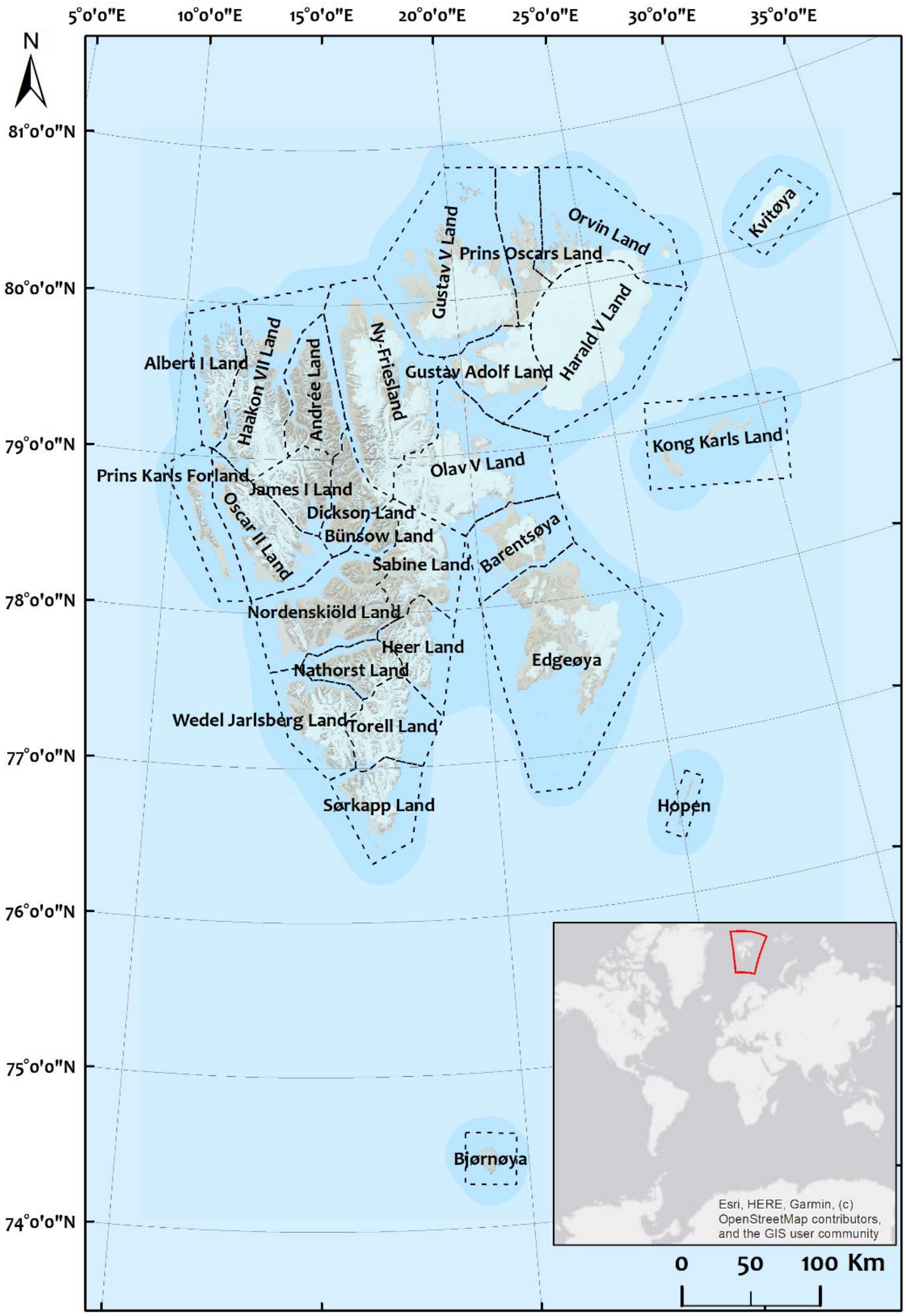


475 **Figure 1 Map of Svalbard showing the regions used in this study. Based on ESRI map.**

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**Table 1 Summary of data sources and types used in the inventory of glacial lakes**

| Year | Source | Type of remote sensing data |
|---|---|---|
| **1936-1938** | NPI | Aerial images |
| **1990's** | NPI | Digitalised data |
| **2008-2012** | NPI | Aerial images and digitalised data |
| **2013-2019** | Google Earth | Satellite images |
| **2020** | Sentinel satellite | Satellite image |

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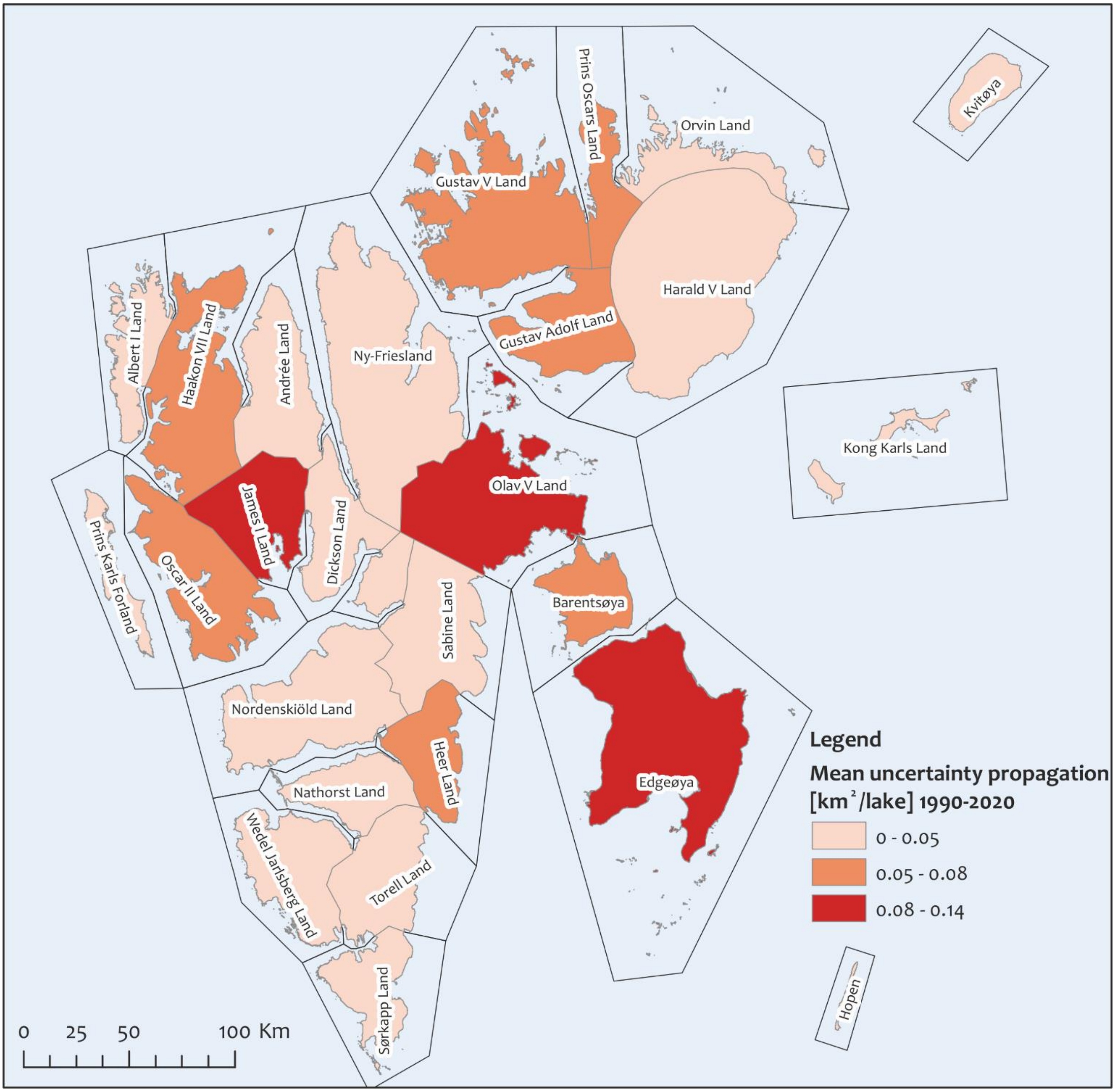


**Figure 2 Uncertainty of lake area assessment for: 1990-2020. Based on Norwegian Polar Institute map.**

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**Table 2 Glacial lakes types in Svalbard (2008-2012)**

| **Emmer's (2016)** | **Class** | **Bedrock-dammed lakes** | | | **Ice-dammed lakes** | | **Moraine-dammed lakes** | | | **Unclassified** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Yao's (2018)** | | Glacial Erosion lakes | | | Ice-blocked lakes | | Moraine-dammed lakes | | | - |
| | | Cirque lakes | Glacial valley lakes | Other glacial erosion lakes | Advancing glacier-blocked lakes | Other glacier-blocked lakes | End moraine-dammed lakes | Lateral moraine-dammed lakes | Moraine thaw lakes | |
| **Number** | | 10 | 3 | 100 | 38 | 119 | 99 | 39 | 152 | 6 |
| **Total number** | | 566 | | | | | | | | |

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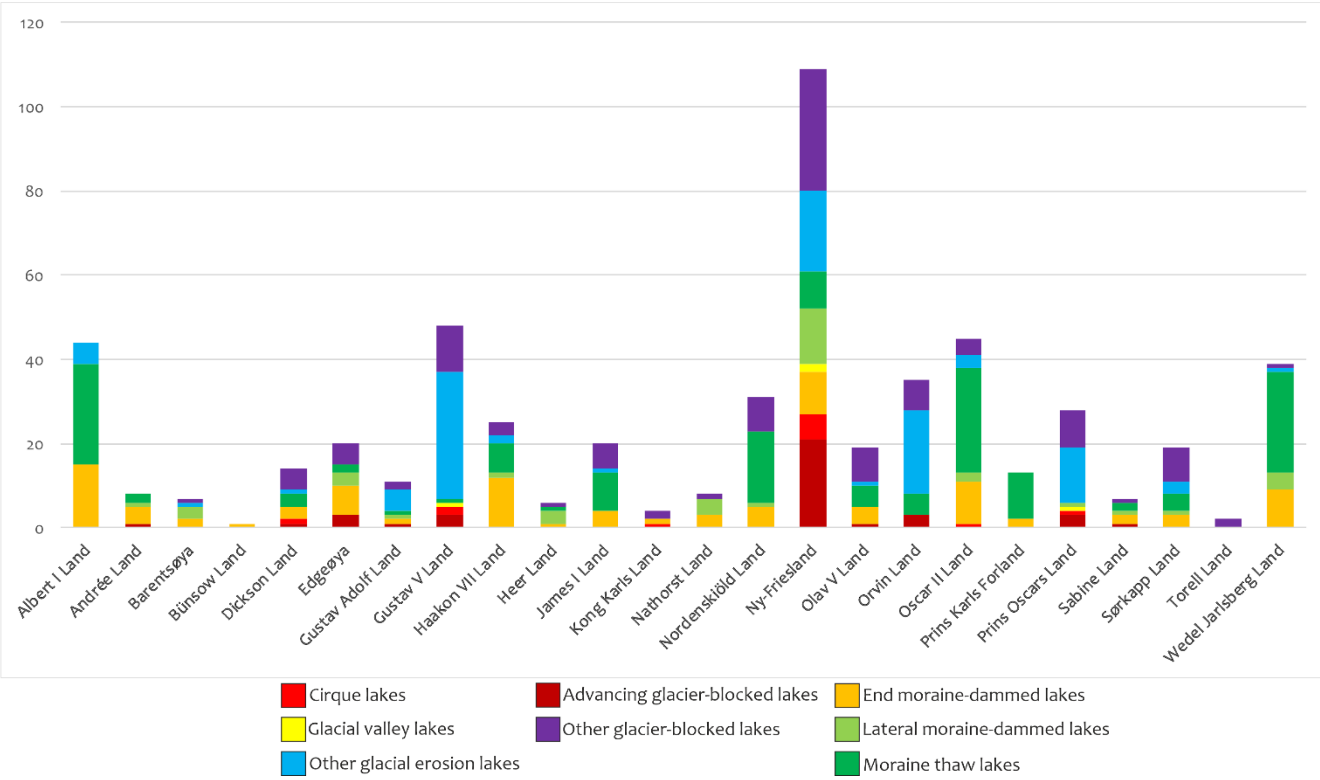


**Figure 3 Classification of glacial lakes, according to regions of Svalbard**

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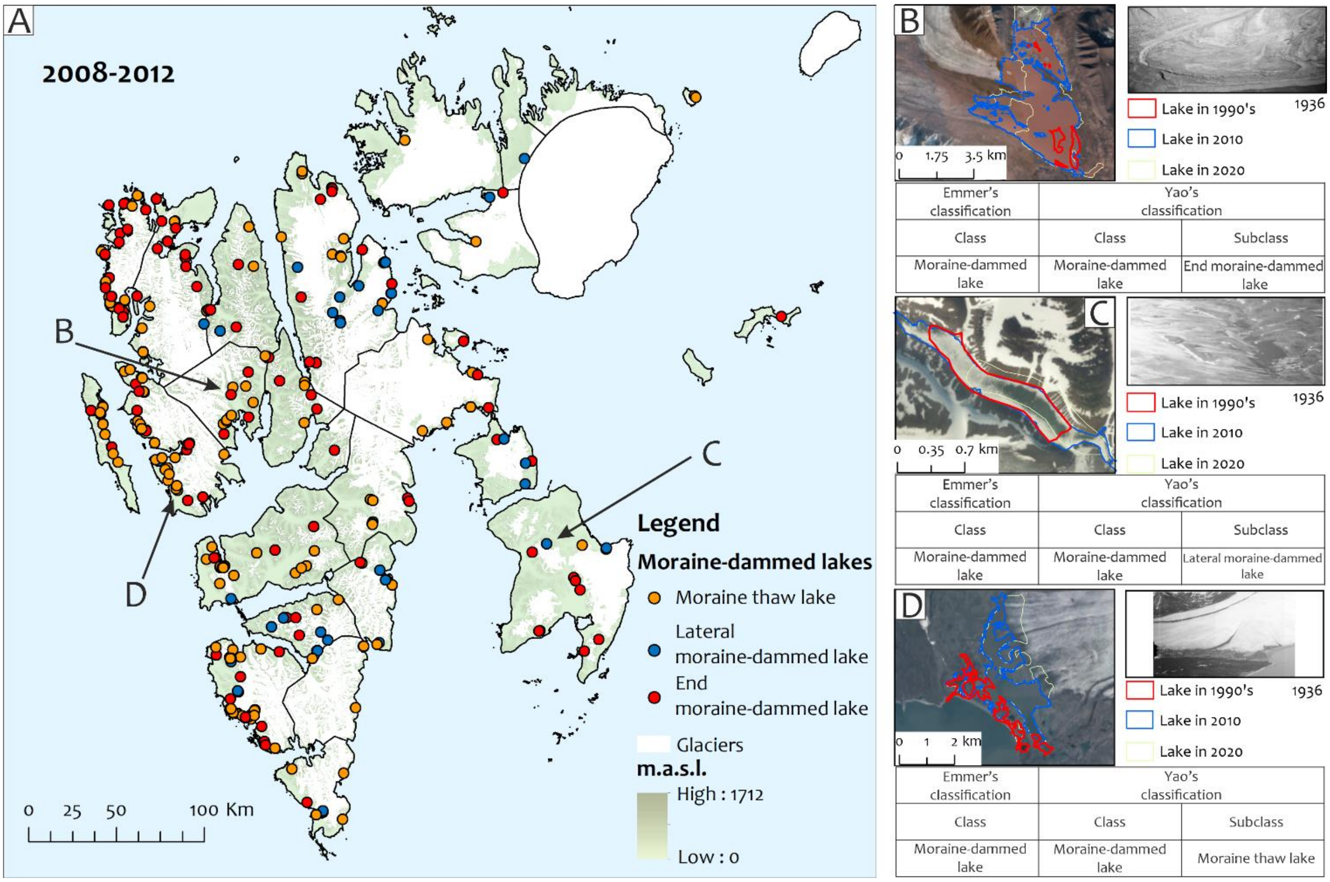


490 **Figure 4 A) Spatial distribution of moraine-dammed lakes on Svalbard, B) end moraine-dammed lake at: Holmströmbreen, Morabreen and Orsabreen, C) lateral moraine-dammed lake at Storskavlen, D) moraine thaw lake at Eidembreen. Based on Norwegian Polar Institute.**

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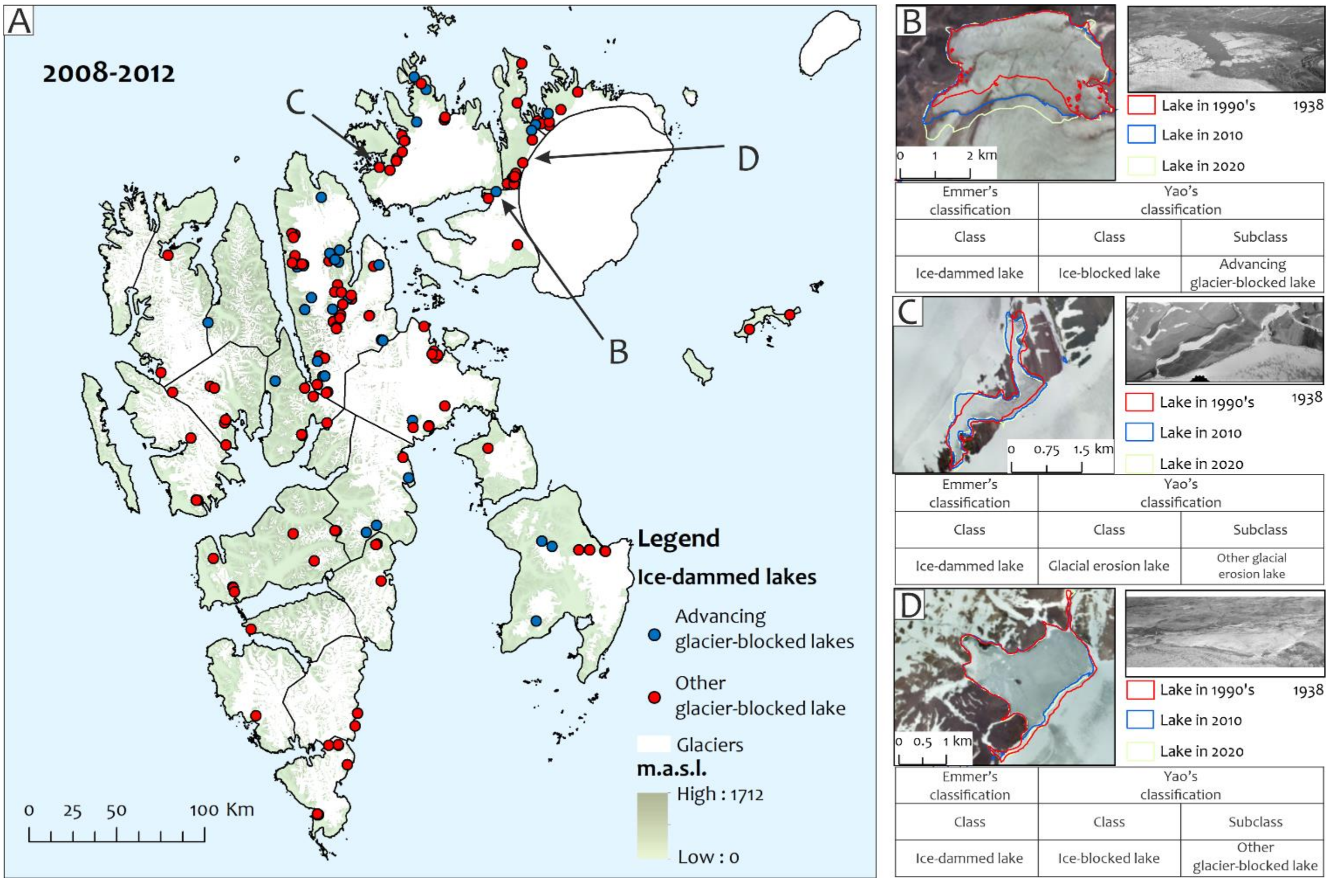


495 **Figure 5 A) Spatial distribution of ice-dammed lakes on Svalbard, B) advancing glacier blocked lake at Etonbreen, C) other glacier-blocked lake at Backabreen, D) other glacier-blocked lake at Flòtbreen. Based on Norwegian Polar Institute.**

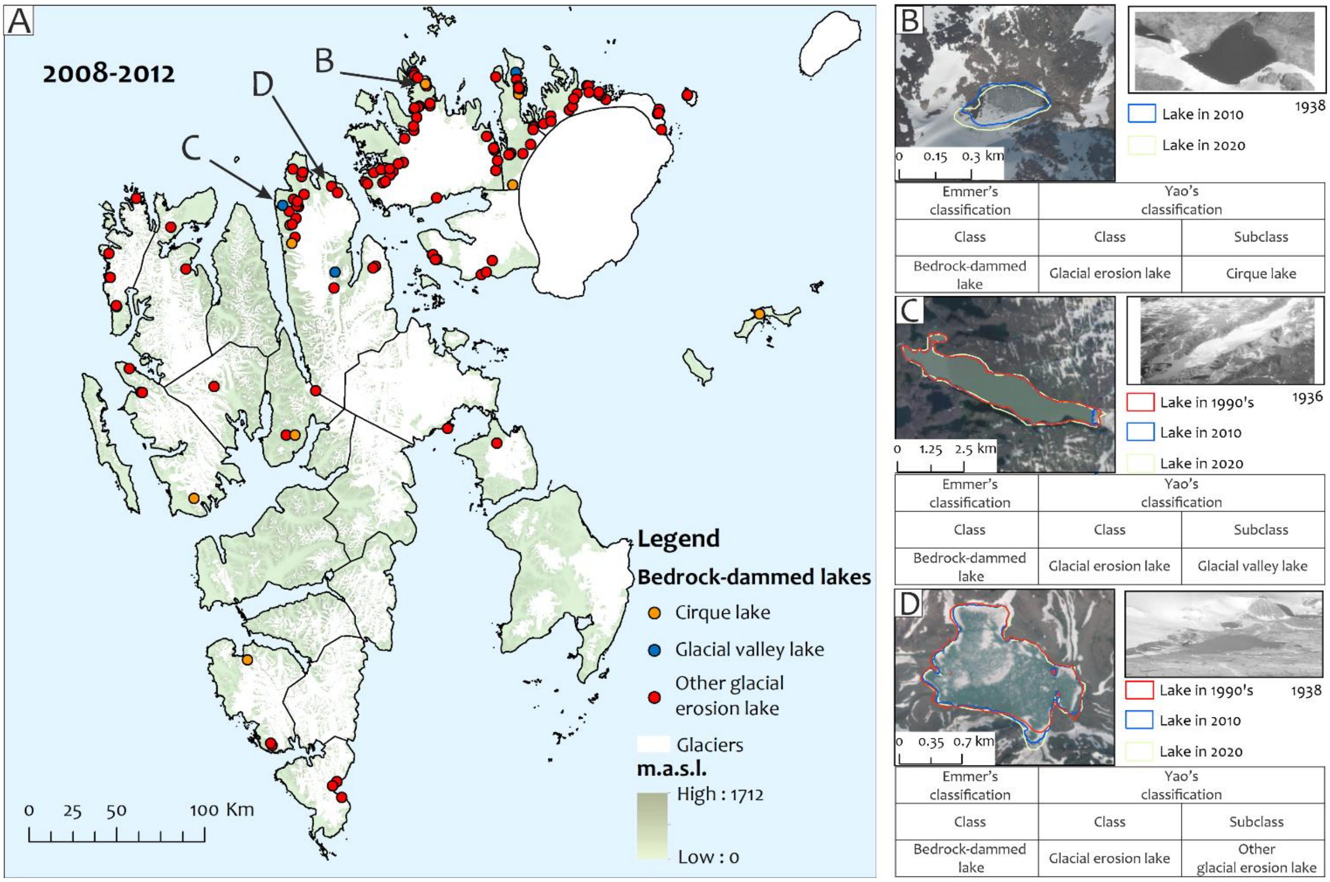


**Figure 6 A) Spatial distribution of bedrock-dammed lakes on Svalbard, B) cirque lake, C) glacial valley lake at Longstaffbreen, D) other glacial erosion lake at Buldrebreen. Based on Norwegian Polar Institute.**

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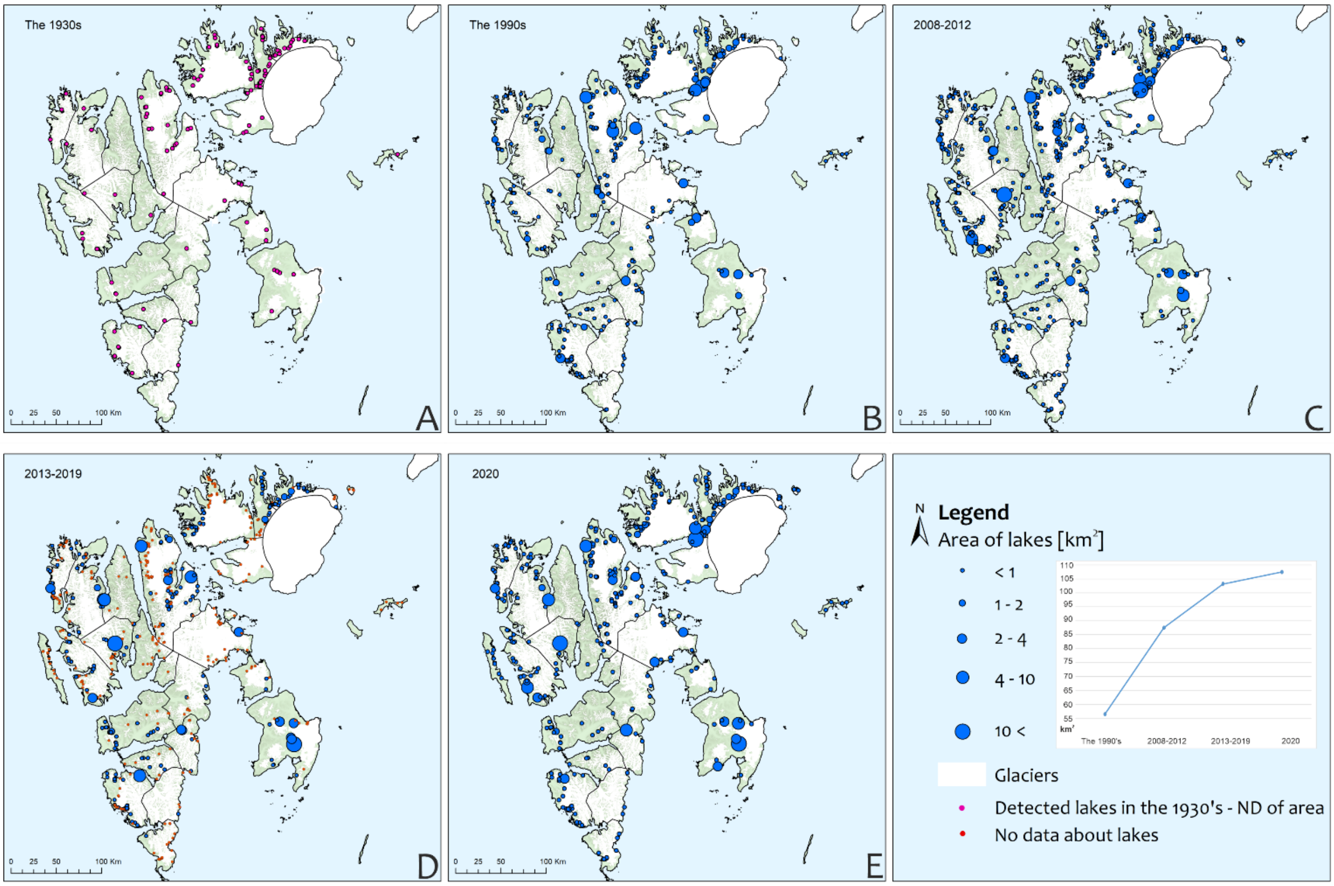


**Figure 7 Changes of glacial lakes on Svalbard detected in years: C) 2008-2012 in comparison to: A) 1930's, B)1990's, D) 2013-2019, E) 2020. Based on Norwegian Polar Institute.**

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**Table 3 Long-term changes of glacial lakes on Svalbard which have full record (1936-2020) of data for analysed time periods. ND – not determined (for details see 3.2 – Data processing)**

| Region | Number of observed lakes in 1936-1938 | Total area in 90's [km²] | Total area in 2008-2012 [km²] | Total area in 2013-2019 [km²] | Total area in 2020 [km²] | Difference between 90's and 2020 [km²] | Difference between 90's and 2020 [%] |
|---|---|---|---|---|---|---|---|
| Heer Land | 1 | 3.26 | ND | 0.26 | 4.57 | +1.31 | +40% |
| Nathorst Land | 2 | 0.85 | ND | 0.64 | 0.44 | -0.41 | -49% |
| Torell Land | 1 | 0.26 | ND | 0.37 | 0.46 | +0.21 | +80% |
| Wedel Jarlsberg Land | 7 | 5.85 | ND | 6.71 | 5.33 | -0.52 | -9% |
| Dickson Land | 0 | 0.00 | 0.02 | 0.03 | 0.00 | 0.00 | — |
| Sørkapp Land | 0 | 0.00 | 0.02 | 0.24 | 0.00 | +0.00 | — |
| Gustav Adolf Land | 1 | 0.10 | 0.09 | 0.10 | 0.11 | +0.01 | +10% |
| Barentsøya | 2 | 0.00 | 0.16 | 0.11 | 0.58 | +0.58 | — |
| Sabine Land | 1 | 0.62 | 0.39 | 1.16 | 0.57 | -0.05 | -8% |
| Kong Karls Land | 1 | 0.43 | 0.43 | 0.00 | 0.16 | -0.27 | -63% |
| Haakon VII Land | 1 | 0.18 | 0.98 | 0.92 | 1.10 | +0.93 | +520% |
| Gustav V Land | 2 | 1.65 | 1.69 | 0.80 | 1.73 | +0.08 | +5% |
| Nordenskiöld Land | 3 | 1.95 | 2.04 | 2.15 | 2.00 | +0.05 | +2% |
| Prins Oscars Land | 12 | 3.03 | 2.90 | 2.58 | 3.18 | +0.14 | +5% |
| Albert I Land | 1 | 1.52 | 2.96 | 2.70 | 2.93 | +1.40 | +92% |
| Olav V Land | 2 | 3.36 | 3.77 | 3.75 | 4.13 | +0.77 | +23% |
| Oscar II Land | 1 | 0.88 | 4.11 | 4.99 | 5.37 | +4.49 | +508% |
| Andrée Land | 0 | 1.15 | 6.97 | 7.23 | 7.59 | +6.44 | +562% |
| Orvin Land | 13 | 7.18 | 7.93 | 5.37 | 5.73 | -1.45 | -20% |
| Ny-Friesland | 15 | 17.28 | 15.38 | 15.49 | 17.20 | -0.07 | +0.4% |
| James I Land | 1 | 1.06 | 17.85 | 21.38 | 15.41 | +14.35 | +1352% |
| Edgeøya | 5 | 5.92 | 19.79 | 26.14 | 28.84 | +22.92 | +387% |
| Total | 72 | 56.52 | 87.48 | 103.12 | 107.43 | +50.91 | +90% |

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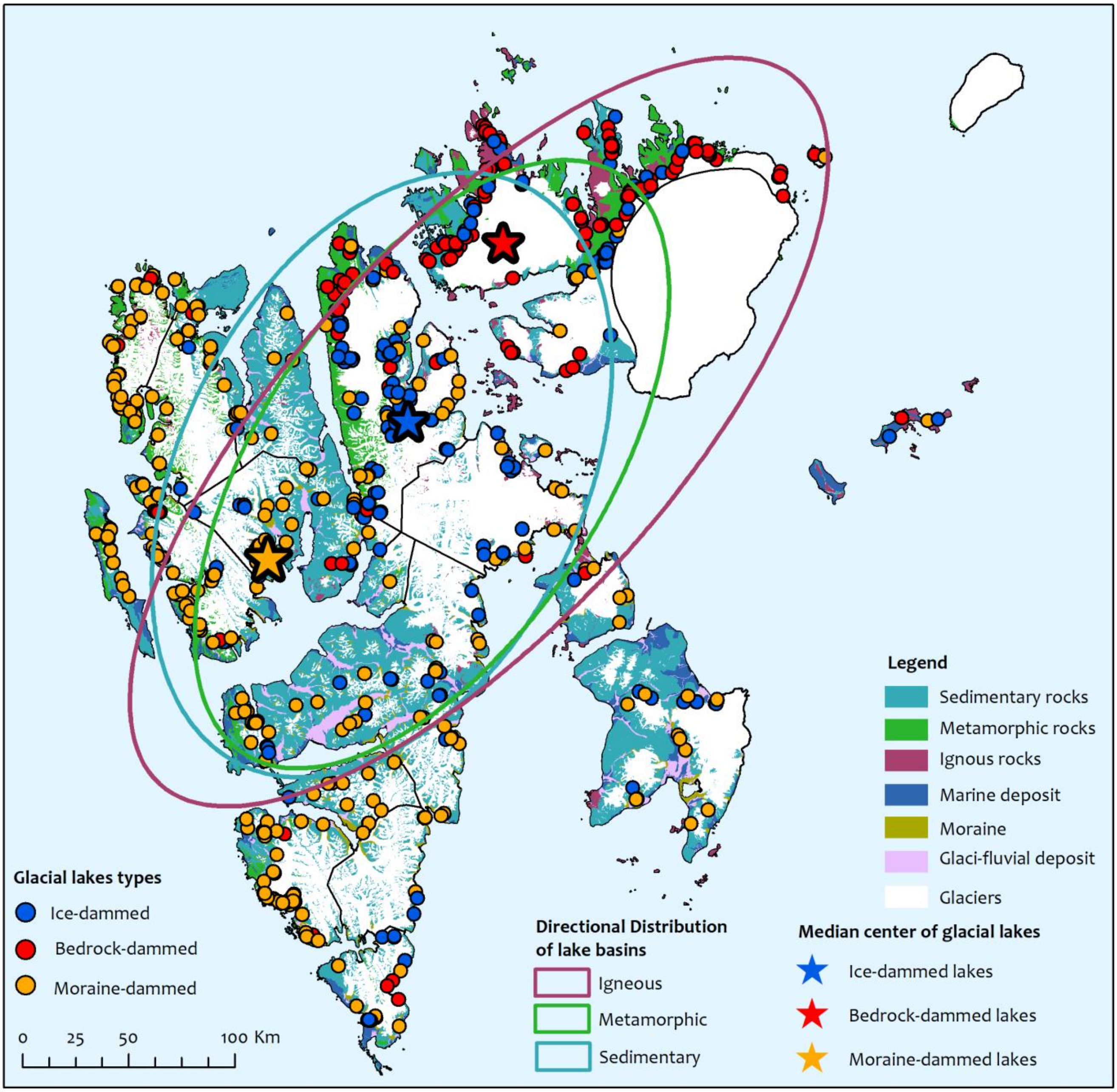


**Figure 8 Statistical approach of median center of glacal lakes types and and their relationship with directional distribution of lakes basins. Based on Norwegian Polar Institute.**

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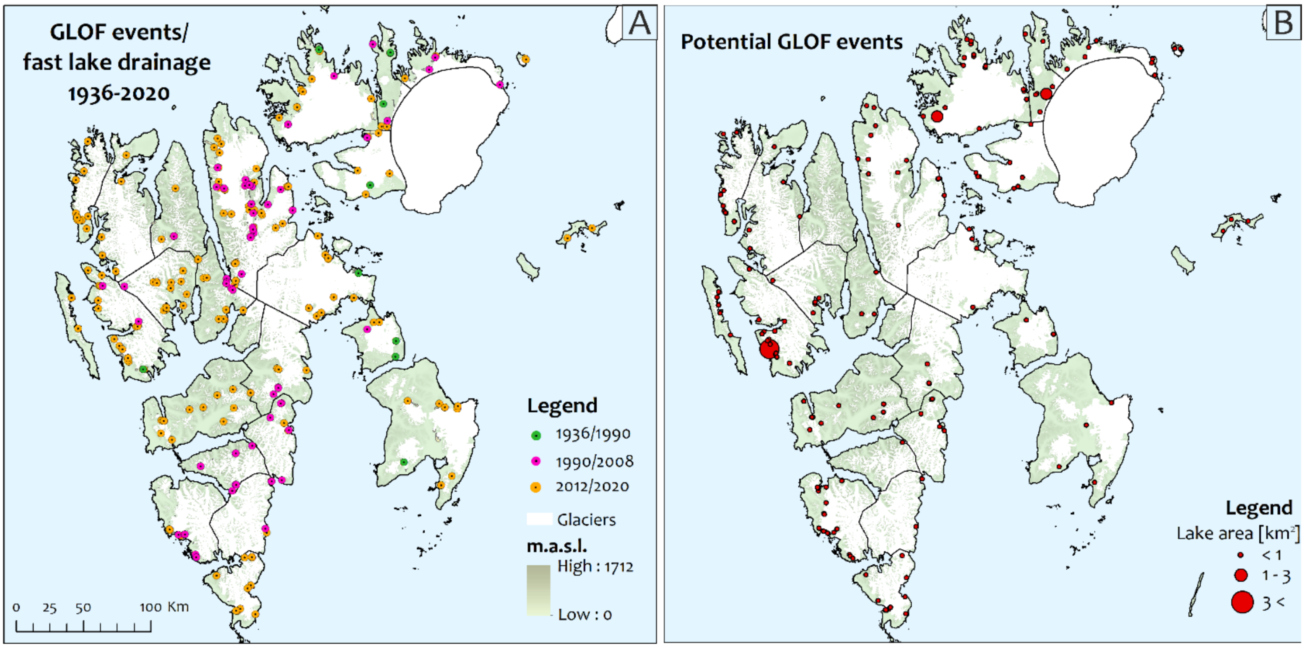


515 **Figure 9 Identified glacial lake outburst floods (GLOF) and fast lake drainage in Svalbard: A) historical (1936-2020), B) potential occurrence in the future. Based on Norwegian Polar Institute.**

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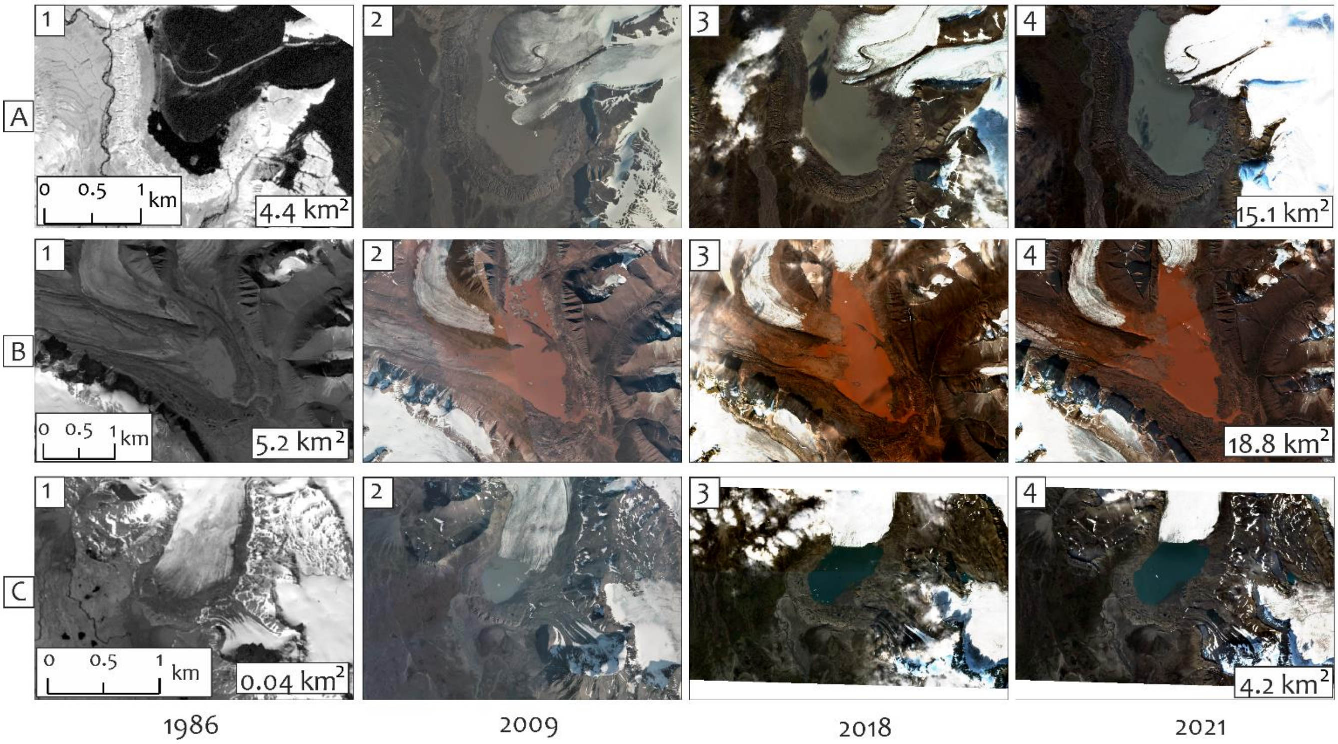


520 **Figure 10 Examples of rapid changes of glacial lakes in Svalbard: A) Gandvatnet, B – Trebrevatnet, C) Vetterndammen. Based on U.S. Geological Survey.**

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**Table 4 Changes of glacial lakes in Svalbard in 1936-2020. ND – not determined (for details see 3.2 – Data processing).**

| Year | Number of all detected lakes | Area of all detected lakes [km²] | Number of detected lakes with full record of data (1936-2020) | Area of detected lakes with full record of data (1936-2020) [km²] |
|---|---|---|---|---|
| **1936-1938** | 120 | ND | 72 | ND |
| **1990's** | 314 | 110 | 148 | 57 |
| **2008-2012** | 566 | 146 | 240 | 87 |
| **2013-2019** | 264 | 111 | 188 | 103 |
| **2020** | 370 | 169 | 152 | 107 |