

## A satellite perspective on jökulhlaups in Greenland

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### ABSTRACT

Methods by remote sensing techniques were developed to locate potential jökulhlaup lakes and to assess the volume of water discharged. To locate potential jökulhlaup lakes, a time sequence of LandSat satellite imagery covering the area was investigated with spectral mapping techniques. The investigations showed how LandSat images can be used to map surface water, glacial ice, and surface temporal anomalies, and when combined with geographic information system (GIS) analysis, potential jökulhlaup lakes could be identified. For assessing the volume of the water discharged, the bottom topography for the jökulhlaup lakes were mapped from stereo images acquired by the ASTER satellite sensor and thereby defining the relations between the lake surface areas and the volumes of water stored in the lakes. Annual lake areas outlined from LandSat images were combined with the area-volume relations to describe the change over time in the volume of water in the lakes and thereby the volume released during jökulhlaups. The results of the volume assessments were validated against recordings from a hydrological station in the downstream lake. The validation underpinned the credibility of the method and as it relies on satellite data that are readily available, the method is applicable for use in many areas of the world.

**Key words** | arctic, Greenland, hydrology, jökulhlaup, remote sensing

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### INTRODUCTION

Ice-dammed lakes are a very common phenomenon in Greenland. The lakes are formed where water collects in depressions under a glacier or along a glacier margin. When the water level in the lake reaches a critical level, it is possible for a jökulhlaup to occur. A jökulhlaup (an Icelandic term that has been adopted by scientists) is a very intense flood where a subglacial or proglacial water reservoir releases a large amount of water abruptly. Jökulhlaup physics and dynamics are further described in [Röthlisberger \(1972\)](#), [Tweed & Russel \(1999\)](#), [Roberts \(2005\)](#) and [Walder \*et al.\* \(2005\)](#).

The local topography, glacier dynamics and climate will determine the frequency and magnitude of jökulhlaup events at a given site. Ice-dammed lakes that release water in a jökulhlaup every year or every second year are also known of, as well as lakes where a jökulhlaup occurs as seldom as every 10 years. The jökulhlaup causes the water

level in the ice-dammed lake to drop considerably; water level changes of 40–100 m are common.

Jökulhlaups influence ecosystems and human activities in downstream areas. Settlements or towns are potential catastrophe areas if hit by a jökulhlaup. In Greenland, this is luckily not the foremost concern as no permanent settlements are located in areas of potential jökulhlaup drainage. That said, the ability to identify and estimate the risk of a jökulhlaup and thereby protect human life is always crucial.

This work was initiated by a hydropower project. There are a number of potential hydropower areas in Greenland where jökulhlaup lakes exist close by or within the catchment area. During the design process of hydropower plants, the consequence of a jökulhlaup or the possible exploitation of the water resource has to be considered. This could be in the design of the dam and an overflow construction or by connecting a jökulhlaup lake to a reservoir in

order to drain the lake in a controlled way. It is therefore important to identify and estimate the magnitude of jökulhlaups in each area.

The aim of the work presented here is therefore to develop methods to handle two different concerns:

- how to identify jökulhlaup lakes; and
- how to estimate the volume of water released during a jökulhlaup from a specific lake.

The vastness of the remote and unexploited areas in Greenland means that local catastrophic events such as a jökulhlaup can easily go unnoticed by humans. It is therefore not trivial to consider how to identify jökulhlaup lakes in an area contemplated for future development whether the plan is to build a hydropower plant, establish a mine or bring in tourists. Potential jökulhlaup lakes may be spotted manually on a detailed map and/or an aerial photo of the area as ice-dammed lakes with no river outlet. Additional evidence is however needed to confirm that such a lake does in fact drain by jökulhlaup. This could be by observations in the field of a jökulhlaup or signs of a jökulhlaup having taken place, measurements in affected areas or a series of satellite photos that show a sudden, large change in the lake area. As stated above, historical evidence or measurements of jökulhlaup does not exist for many areas in Greenland. In these cases, satellite data may be the only way to confirm the existence of jökulhlaup lakes. In the work presented here, a method to identify jökulhlaup lakes based on satellite data alone is described.

When a jökulhlaup lake has been identified, any further evaluation of the hazard or resource that it might constitute will typically include an evaluation of the frequency and magnitude of jökulhlaups. A method to estimate the volume of water released during a jökulhlaup based on satellite data alone is presented here. If ground observations from the site exist, they can be used to enhance the accuracy of the result, but they are not needed for the method to be applied. For almost all jökulhlaup lakes in Greenland, the bathymetry of the lake is unknown and time series of the water level do not exist. To start such field measurements at a new site is both expensive and practically challenging, and several years will pass before the frequency and magnitude of the jökulhlaup can be evaluated. In comparison, the available archive of satellite images implies that both the

occurrence and magnitude of a jökulhlaup can be easily evaluated. However, the satellite approach requires that the areal footprint of the jökulhlaup event is large compared to the pixel size of the chosen satellite data. Further, it is required that the frequency of jökulhlaup events is low compared to the frequency of suitable satellite images.

In the development of the methods described in the following, we aim to use well-tested remote sensing techniques from a jökulhlaup point of view instead of developing new remote sensing techniques.

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## STUDY AREA

The project area consists of a large area in the vicinity of Nuuk and a smaller area referred to as the ISTA (Isortuarsuup Tasia) area. Several jökulhlaup lakes are already known of in the project area, but the area is well suited for the development of methods to identify lakes with jökulhlaup potential. The ISTA area contains two known ice-dammed lakes, Lake North and Lake South, in connection with the reservoir lake known as Isortuarsuup Tasia or Lake ISTA. It is known that Lake North and Lake South regularly empties into Lake ISTA and, as Lake ISTA is a potential reservoir for hydropower, hydrological investigations has been carried out in the area and several of the jökulhlaups have been monitored. The area of interest for the assessment of volumes is Lake North and Lake South in the ISTA area. The project area and the ISTA area together with Nuuk can be seen in [Figure 1](#). The method for identifying jökulhlaup lakes is used over the whole project area, while the volume assessment method is only applied to the ISTA area.

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## LOCATING POTENTIAL JÖKULHLAUP LAKES

In order to locate potential jökulhlaup lakes, a four-task approach was used. Most parts of Greenland were last mapped in the 1970s. As glacier margins are dynamic, new mapping of lakes and glaciers were necessary. In the first three tasks, a lake theme, a glacier theme and a surface anomaly theme were mapped using well-tested remote sensing classification techniques. The mapping was based on a time series of LandSat satellite data acquired in the late summers

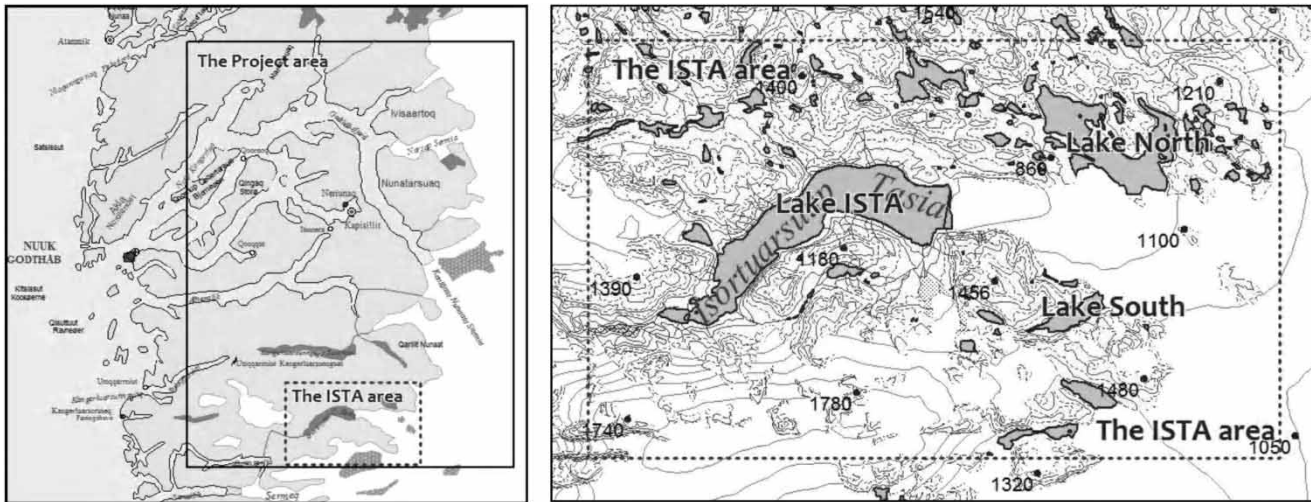


Figure 1 | The project area and the ISTA area.

from 2003 to 2009. In the fourth task, a spatial location analysis using the three maps was performed in a geographic information system (GIS) to find potential jökulhlaup lakes.

### Mapping lakes

For the lake mapping, the Tasseled Cap transformation was used to perform an orthogonal transformation of the original Landsat data into a new 3D space consisting of a brightness index, a greenness index and a third component related to soil moisture or wetness (Chuvieco & Huete 2010). The Tasseled Cap transformation is a commonly used technique in land cover mapping. The Tasseled Cap transformation is a standard function in some remote sensing software and can be easily executed. The output of the transformation, especially the brightness and the wetness, are strongly associated with water surfaces. A simple threshold was used to classify water as any surface area with a brightness index less than 0.4 and a wetness index greater than 0. The threshold was found empirically and can vary with the sediment content in the water. The lake classification was enhanced by a simple rule stating that a pixel could only be water if classified as water in 5 out of 6 years in the Landsat time series.

### Mapping glaciers

The mapping of glaciers from multi-spectral imagery involved discriminating between ice and other surface

types. It was difficult to map glaciers for an individual year due to difficulties in separating glacier ice from other types of ice and snow. In addition, debris-covered ice was confused with non-ice areas. The areas of confusion tend to differ from year to year, so it was assumed that a better glacier classification could be achieved by using the surface long-term spectral characteristics as given by the Tasseled Cap parameters.

In the approach to map glaciers, an output image was produced as the average of the Tasseled Cap parameters from the Landsat time series. The output image was used as input for an unsupervised classification with 50 spectral classes. In an unsupervised classification, an image is classified into spectral classes based on natural groupings of the spectral properties of the pixels in the image. The unsupervised classification is a common function and is relatively easy to perform using any remote sensing software.

The spectral classes from the image of the averaged Tasseled Cap parameters were thematically coded into glacier-ice and non-glacier-ice. After labelling, a median filter was applied to the classified image in order to remove speckle noise.

### Mapping surface temporal anomalies

A vegetation index approach was used for the mapping of surface temporal anomalies. A vegetation index is a simple numerical indicator that can be used to estimate a large

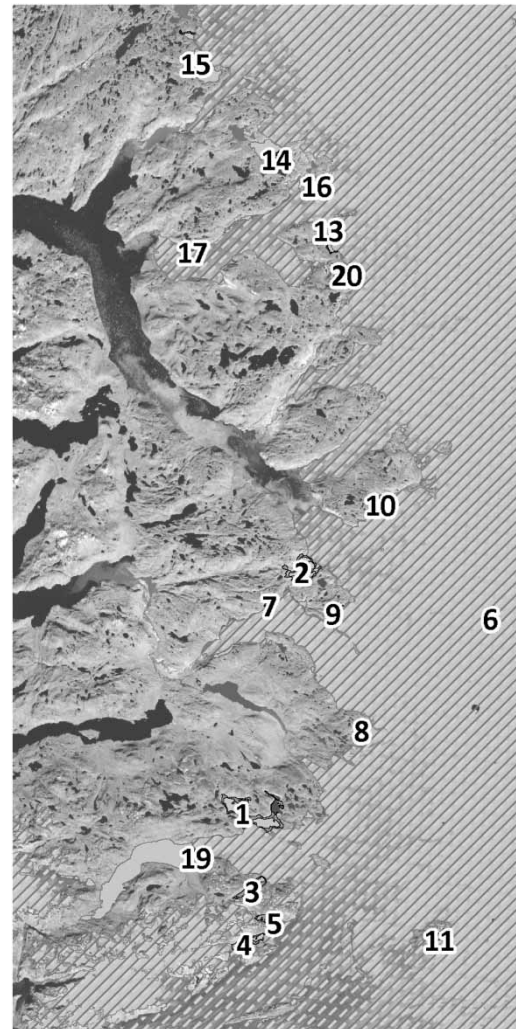
number of land surface properties. The most commonly applied vegetation index is the Normalized Difference Vegetation Index (NDVI), which is computed as the difference between near-infrared (NIR) and red (RED) reflectance divided by their sum. It has been shown that NDVI is sensitive to the presence, density and condition of vegetation (Tucker 1979; DeFries & Townshend 1994; Huete *et al.* 2002). Furthermore, NDVI provides valuable indications of land cover categories. By design, the NDVI varies between  $-1.0$  and  $+1.0$ . Areas containing a dense vegetation canopy will have positive values ( $0.3$ – $0.8$ ), while soils tend to generate rather small positive NDVI values ( $0.1$ – $0.2$ ). Free standing water will tend to have very low positive or even slightly negative NDVI values. Clouds and snow fields will be characterized by negative NDVI values.

Since NDVI relates to the present land cover, multi-temporal NDVI images were used to identify surface temporal anomalies, i.e. surface areas that change over time. NDVI anomalies were calculated from the difference between NDVI at a given date and the long-term mean NDVI. The long-term mean NDVI was calculated from the time series of Landsat satellite data acquired in the late summers from 2003 to 2009.

Potential jökulhlaup lakes were mapped using NDVI anomalies based on the assumption that a lake that empties will have strong positive or negative anomalies due to discharge or refill. Yearly anomalies for two known jökulhlaup lakes were compared with anomalies for two reference lakes where jökulhlaups are known not to occur. The comparison showed significant difference between the anomaly for the jökulhlaup lakes and the reference lakes.

### Spatial location analysis

For the GIS analysis, the mapped lake theme, the glacier theme and the surface anomaly theme were converted to polygons. By definition, the potential jökulhlaup lake borders the glacier margin. In the GIS analysis, all lake polygons located in the vicinity of a glacier which also shared area(s) with a surface anomaly were selected. Without any restrictions, such a selection returned many hundreds of potential jökulhlaup lakes; this meant that it was necessary to include an area size threshold to filter out smaller and less significant anomalies. Only lakes



**Figure 2** | Surface anomalies (with a threshold of  $250,000 \text{ m}^2$ ) with the potential of being significant jökulhlaup lakes. Labels rank the anomalies 1–20, with 1 being the largest and 20 the smallest area. The hatched area is ice.

associated with a surface anomaly larger than  $250,000 \text{ m}^2$  were considered as likely significant jökulhlaup lakes, a threshold which returned 20 potential jökulhlaup lakes in the project area east of Nuuk. The potential jökulhlaup lakes can be seen in Figure 2.

### Discussion of the method for locating jökulhlaup lakes

The method showed good results for the project area although some known jökulhlaup lakes were not identified due to ice cover. Ice-covered lakes were difficult to classify in the remote sensing approach. Further development in

discriminating between glacier and lake ice is therefore advisable. Setting the threshold for the area anomaly is of great importance and it must be defined according to the goal of each project. The time series, i.e. the number of years to be analyzed, is also significant. A jökulhlaup for a given lake can occur only every 10th year or even less frequent. For this reason, we must consider data from a longer time series. In this project, however, the remote sensing approach with a time series of 6 years did not demonstrate any problems in locating Lake North, which is known to empty every 9 years.

The use of images from different sensors was investigated in the method development and collection of reliable data from several years took time. Since only Landsat images were used in the approach, the data collection can be made more efficient by the use of online Landsat image search tools.

## ASSESSMENT OF THE WATER VOLUMES

The method for assessing the volumes of water discharged quantifies the volume of water contained in the lakes from just before and just after the jökulhlaups. For this purpose, lake bottom topographies, surface areas and area–volume relations for the lakes were needed.

The discharged water volumes were estimated for Lake North and Lake South in the ISTA area.

### Determining lake bottom topographies

Measurements of the lake bottom topographies for most lakes in Greenland have not been carried out, including Lake North or Lake South. Lake bottom topographies were instead determined from a digital elevation model (DEM) extracted from satellite stereo images (a set of ASTER stereo images from 8 August 2004 where the water level was low). The DEM for Lake North can be seen in Figure 3.

The ASTER sensor system is designed to allow along-track optical stereo data acquisition at a 15 m spatial resolution for each ASTER scene. These stereo pairs were used to create a DEM using a stereo autocorrelation procedure and applying the principle of the parallax effect. The

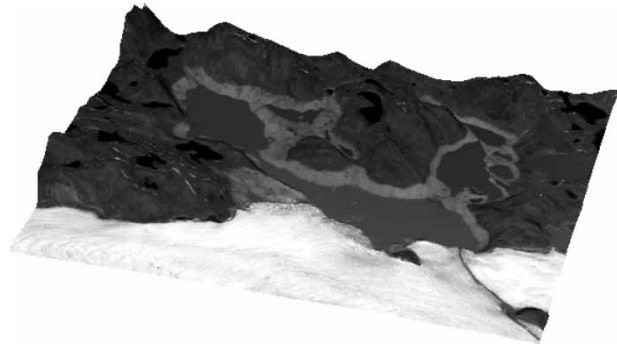


Figure 3 | DEM for Lake North.

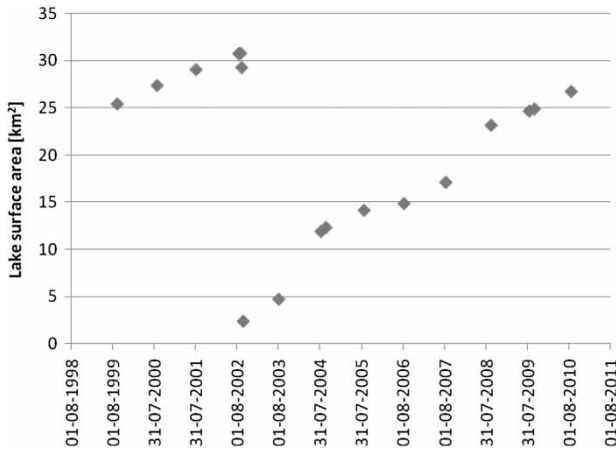
parallax effect is based on the fact that the image stereo pair will show a pixel displacement in the satellite flight direction that is proportional to the pixel elevation (Welch *et al.* 1998). A cross-correlation method was used to evaluate this displacement and transform it into elevation values.

### Determining surface areas of the lakes

In the determination of the lake surface areas, a higher accuracy of the surface areas was needed than in the mapping of the lakes. Three different pixel-based classification techniques and a manual digitization of lake borders were therefore tested. The pixel-based classification techniques included unsupervised classification, supervised classification and an index-based classification.

A semi-automatic index-based classification, where regions with problems were corrected manually, was the most consistent and fastest method. The index-based classification was based on the brightness index and the wetness index from the Tasseled Cap transformation.

Lake surface areas for the two lakes were determined for a time series of Landsat satellite data in the late summers of the period 1999–2010. The determined lake surface areas for Lake North are seen in Figure 4. In the figure, a jökulhlaup is indicated by the abrupt change in the lake surface area in September 2002. The accuracy of the estimated surface area depends on shadows and clouds in the images and the lake ice conditions. These conditions vary with different lakes and different satellite images. The geometric shape of the lake also influences the accuracy of the surface area. As the lake shorelines were mapped from images, the accuracy of the shorelines was not better than the pixel size in



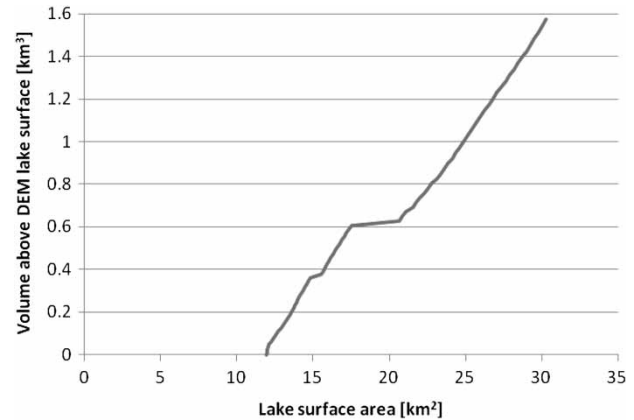
**Figure 4** | Digitized lake surface areas for Lake North.

the image. The accuracy of mapping shorelines was estimated as the relation between the number of pixels defining the shoreline and the total number of pixels in the surface area. The accuracy of the surface areas was estimated to be within 3–5%.

### Determining the area–volume relations

An area–volume relation is a site-specific empirical relation which describes the volume of water stored in the lake as a function of the lake surface area. The area–volume relations were derived by calculation of surface areas and volumes from the lake bottom topographies (DEM) for potential water levels at 1 m increments. The surface areas were found as the total area of cells in the lake bottom topographies with elevations below the potential water level. The volumes were calculated as the surface areas multiplied by the difference between the potential water level and the average elevation of cells below the potential water level in the lake bottom topographies.

By deriving the area–volume relation from the DEM, it was assumed that the water surface area increases with the water level and that the volume in the lake increases with the water surface area, i.e. the volume of water ‘hidden’ under an overhanging or floating glacier front is assumed negligible. Furthermore, as the DEM was not extracted when the water level in the lakes was at its absolute minimum, the estimated volumes only represent the volume above the water level in the lakes when the DEM was extracted. The area–volume relation for Lake North is



**Figure 5** | The area–volume relation for Lake North.

seen in [Figure 5](#). This relation contains a couple of steps, where an increase in surface area only induces a very small increase in volume. The form of the area–volume relation reflects the geometry of the lake bottom. At low water levels, Lake North is divided into several smaller lakes with different water levels (see also [Figure 3](#)). At those water levels, only the main lake adjacent to the glacier is included in the area–volume relation. The steps in the relation occur at the water levels at which the other lakes are included as part of the main lake and the length of a step reflect the surface area of the lake engulfed.

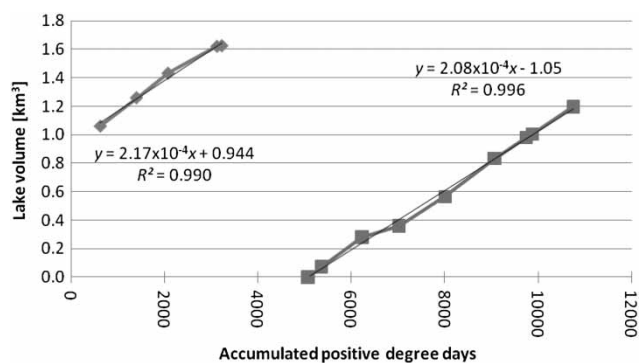
The accuracy of the area–volume relation depends on the quality of the extracted DEM. The area–volume relation was compared with an area–volume relation derived from an existing DEM extracted from orthophotos by the National Survey and Cadastre in Denmark. From the comparison, the accuracy of volumes obtained from the area–volume relation was estimated to be within 10%.

In order to estimate the total volume of water released during a jökulhlaup, it was necessary to evaluate the volume between the absolute minimum water level in the lake and the water level in the DEM. This volume was estimated by determination of the inflow of water to the lake. For this purpose, the fill rate for the lake was determined as the slope of the relation between the lake volume and the accumulated number of positive degree-days (i.e. the sum of mean daily temperatures above 0 °C) for above-DEM water levels. As the slope of the relation defines the fill rate, the start date for the accumulation of positive

degree-days is not important as long as it is before the start of the period investigated (here 01.01.1999 was used). As the main part of water inflow to the lake is glacier meltwater, the fill rate based on accumulated number of positive degree-days was assumed to be constant. The inflow of water to the lake was estimated, for the period from when the jökulhlaup occurred until when the water level was equal to the DEM water level, using the number of positive degree-days in that period and the fill rate. The inflow of water was assumed to be equal to the volume stored between the water level just after the jökulhlaup and the minimum water level in the DEM.

Lake North volumes were estimated from the surface areas seen in Figure 4 and the area–volume relation seen in Figure 5. The relation between the volume of water in Lake North and accumulated positive degree-days is seen in Figure 6. A good correlation between the estimated lake volumes above the DEM and the accumulated number of positive degree-days is seen. By the slope of the linear regression lines, a fill rate of  $2.17 \times 10^5 \text{ m}^3$  per positive degree-day is seen before the jökulhlaup and a fill rate of  $2.08 \times 10^5 \text{ m}^3$  per positive degree-day is seen after the jökulhlaup. The accuracy of the water volume below the water level in the DEM is estimated from the difference between the two fill rates and the correlation coefficients in Figure 6 to be within 10–15%.

From the determined lake surface area just before the jökulhlaup and the area–volume relation, the water volume above the water level in the DEM was estimated. The total volume of water discharged from the jökulhlaup



**Figure 6** | Volume of water in Lake North as a function of accumulated positive degree-days.

was estimated as the sum of the volume below and above the water level in the extracted DEM.

### Validation of the volume assessment

The two jökulhlaup lakes are connected downstream with the reservoir lake (Lake ISTA); see Figure 1. Hydrological investigations of Lake ISTA were initiated in 1975 and, since 1976, the water level has been continuously monitored by an automatic hydrometric station. During the monitoring period, a number of jökulhlaup events have been registered. A jökulhlaup from Lake South typically increases the water level in Lake ISTA by 3–4 m in 2–4 days, whereas a jökulhlaup from Lake North gives a 15–20 m increase in the water level in 4–5 days in Lake ISTA. The water level in Lake ISTA is back to normal 10–30 days after the peak.

The water released during a jökulhlaup was estimated by integration of the water balance equation for Lake ISTA from the start to the end of water inflow from the jökulhlaup lake. Three terms were calculated: the discharge from Lake ISTA; the change in water accumulated in Lake ISTA; and the inflow from other sources. Evaporation and exchange of water with the groundwater storage was assumed negligible due to the relative short integration period (a few days), the high latitude position of the lake and the limited storage capacity of the bedrock and shallow soil layer surrounding the lake. The discharge from Lake ISTA was calculated based on the measured water level time series (data point every 3 h) and the stage–discharge relation. The upper part of the stage–discharge relation has been established from the recession curve of one of the larger jökulhlaup events where water level was measured every hour, whereas the lower part of the stage–discharge relation is based on manual discharge measurements.

The accumulation of water in Lake ISTA during the integration period was found from the measured water level and the DEM of the lake. The inflow of water from other sources, which is primarily meltwater from the glacier, was estimated by a degree-day approach.

Of the three terms mentioned above, the inflow from other sources has the least accuracy. As the integration covers a short time period, this term was however relatively small; for the three events used for validation (see below) the inflow from other sources comprises 2–9% of the water

**Table 1** | Estimated volumes of water (m<sup>3</sup>) released during jökulhlaups

	Lake North September 2002	Lake South August 2003	September 2007
Water balance equation	$1.85 \times 10^9$	$0.28 \times 10^9$	$0.18 \times 10^9$
Remote sensing method	$1.98 \times 10^9$	$0.29 \times 10^9$	$0.19 \times 10^9$
Difference (%)	7	0.4	2

balance. The accuracy of the calculated volume of water released by the jökulhlaup is evaluated to be within 10%.

During the period 1999–2010, three jökulhlaups occurred in the ISTA area. Lake North was emptied once in September 2002. Lake South was emptied twice, in August 2003 and in September 2007. The volumes of water discharged from the three jökulhlaups were estimated by the developed remote sensing method and by the water balance equation for Lake ISTA; see Table 1. By the estimations from the remote sensing method, about 80% of the water volumes were above the water level in the DEM in each of the three jökulhlaup events. The remaining 20% were estimated by extrapolating the rate filling method. The validation with the water balance equation showed that the method gave very reliable results for the two test lakes in the ISTA area.

### Discussion of the volume assessment method

A method for assessing the volumes of water discharged during a jökulhlaup based on satellite data alone has been described above. The method was validated for a total of three jökulhlaup events from two lakes and, when taking the uncertainty of the methods into account, the results in each case were in good agreement with an independent estimate. Even though only three events were quantified, the importance of the validation is increased by the difference in characteristics (lake size, topography and time between jökulhlaups) between the two test lakes; see Table 2. A validation that covered more jökulhlaup lakes with other characteristics would have been optimal. That has not been practical however, since the ISTA area is one of the very few places in Greenland where jökulhlaup outbursts

**Table 2** | Characteristics for Lake North and Lake South in the ISTA area

Characteristic	Lake North	Lake South
Maximum lake area (km <sup>2</sup> )	30	6
Minimum lake area (km <sup>2</sup> )	2.4	0.7
Mean slope of lake bottom (°)	13	15
Change in water level during jökulhlaup events (m)	c. 80–100	c. 50
Time between jökulhlaup (years)	9	4–6

have been measured and can actually be quantified based on *in situ* data.

The rarity of *in situ* monitoring of jökulhlaup lakes in Greenland together with the practical and economical challenges in establishing such measurements emphasizes the usefulness of this method, which is based on satellite data alone and does not require any field measurements. The method as described here is based on Landsat and ASTER images that are free or can be obtained at a low cost, respectively. Further, the satellite data archive enables analysis that readily covers the last 10 years; by including sources other than Landsat and ASTER, this period may be extended even further.

The method does however require a set of ASTER stereo images which were acquired immediately after a jökulhlaup event (i.e. when the lake water level is low) in order to extract the best possible DEM. Further Landsat images are required from just before and after the jökulhlaup to determine the change in lake surface area due to the jökulhlaup. If a DEM cannot be obtained for the lowest water level in the lake, a series of Landsat images can be used to estimate the rate at which the lake fills up. The volume below the DEM released during the jökulhlaup can be estimated from this. The optimal satellite data to assess lake volumes and to classify lake areas are:

- cloudless images obtained immediately before and after the jökulhlaup event;
- images obtained at the end of the melting season, where snow and ice cover and seasonal lake ice are minimal; and
- images obtained in mid-summer, where cast shadows are minimal.



In reality, selecting images to outline lake areas or to generate a DEM is almost never optimal due to adverse weather conditions (frequent clouds, early snow) and the narrow time window with optimal conditions. Shadows also influence the quality of DEM extraction and make the assessment of lake volumes challenging. Cloud covers, debris-covered glaciers and floating ice on lakes are additional challenges in outlining lake surface areas.

For the three events considered in the evaluation, the accuracy of the results was estimated to be within 10–15%. For general application of the method, the accuracy of results may differ from this depending on the characteristics of the jökulhlaup lake. The accuracy will decrease for smaller lake sizes, for increased steepness of the lake bottom/banks and for shorter time intervals between jökulhlaup events.

The smaller the lake compared to the grid size of the DEM and spatial resolution of the images used to evaluate the surface area, the higher the uncertainties of the results. For potential jökulhlaup lakes with steep lake bottom topography, the method is less accurate as a difference in lake surface areas over time would be small even when the volume of the water in the lake changes dramatically. A small error in the lake surface area will therefore give a large error in the calculated volume. When the time between jökulhlaup events is short, it becomes more important to obtain images immediately before and after the jökulhlaup in order to precisely evaluate the change in volume of water stored in the lake. It might also become difficult to obtain enough images to evaluate the filling rate, if this is needed for extrapolation of below-DEM volumes. If the jökulhlaup events at a given site occur frequently compared to the frequency of suitable images, the method might not be useful.

## CONCLUSION

The primary aim of the project was to develop methods to locate potential jökulhlaup lakes and to determine the quantity of water discharged by jökulhlaups from satellite data. Remote sensing is a suitable and cost-efficient way to provide temporal, consistent and synoptic land surface information. The present study has demonstrated how

satellite images, in combination with relatively simple analytical techniques, can comply with the primary aim of the project.

## Identifying lakes with jökulhlaup potential

The work showed how multi-temporal Landsat image data can be used to map surface water, glacial ice and surface temporal anomalies (i.e. surface areas that change over time). When combined with a GIS, the mapped themes can be used to identify potential jökulhlaup lakes characterized as surface water bodies that border a glacier while also being associated with a surface area change. Ice-covered lakes are difficult to classify in the remote sensing approach. Further development in discriminating between glacier and lake ice is advisable.

## Assessing the volume of water released during jökulhlaup

The magnitude of a jökulhlaup depends largely on the quantity of water draining the ice-dammed lake, i.e. the water discharge volume. In this work it was shown how the lake bottom topography for a jökulhlaup lake can be mapped from stereo images acquired by the ASTER satellite sensor, thereby defining the relation between the lake surface area and the volume of water stored in the lake.

The stereo images obtainable for the project area were not in the immediate time after a jökulhlaup, making it necessary to develop a method to extrapolate the volume to the lowest observed water level (i.e. the smallest lake surface area). Annual lake areas outlined from Landsat images were combined with the area–volume relation to describe the change over time in the volume of water in the lake and thereby the volume released during jökulhlaup.

The results from three known jökulhlaup events were validated against recordings from a hydrological station in the downstream Lake ISTA. As the validation underpins the credibility of the method, and as the method relies on satellite data that are readily available for many parts of the world, we recommend its application in a wider context, i.e. Greenland, as well as other locations.

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## REFERENCES

- Chuvieco, E. & Huete, A. 2010 *Fundamentals of Satellite Remote Sensing*. CRC Press, Boca Raton, USA.
- DeFries, R. S. & Townshend, J. R. G. 1994 [NDVI-derived land-cover classifications at a global-scale](#). *International Journal of Remote Sensing* **15**, 3567–3586.
- Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X. & Ferreira, L. G. 2002 [Overview of the radiometric and biophysical performance of the MODIS vegetation indices](#). *Remote Sensing of Environment* **83**, 195–213.
- Roberts, M. J. 2005 Jökulhlaups: a reassessment of floodwater flow through glaciers. *Reviews of Geophysics* **43**, 1–21.
- Röthlisberger, H. 1972 Water pressure in intra- and subglacial channels. *Journal of Glaciology* **11** (62), 177–203.
- Tucker, C. J. 1979 [Red and photographic infrared linear combinations for monitoring vegetation](#). *Remote Sensing of Environment* **8**, 127–150.
- Tweed, F. S. & Russel, A. J. 1999 Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* **23** (1), 79–110.
- Walder, J. S., Trabant, D. C., Cunico, M., Anderson, S. P., Anderson, R. S., Fountain, A. G. & Malm, A. 2005 [Fault-dominated deformation in an ice dam during annual filling and drainage of a marginal lake](#). *Annals of Glaciology* **40**, 174–178.
- Welch, R., Jordan, T., Lang, H. & Murakami, H. 1998 [ASTER as a source for topographic data in the late 1990s](#). *IEEE Transactions on Geoscience and Remote Sensing* **36**, 1282–1289.

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