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Glacier lake mapping with Sentinel-2 imagery in Norway

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Forsidefoto: Uranosbreen glacier lake and glacier front, 24/08/2019. Photo: Teodor Nagy

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Summary: In this report, we summarize work carried out to map glacier lakes in mainland Norway from Sentinel-2 satellite imagery from 2018. In total, more than 400 lakes were mapped and categorized based on the nature of damming and contact with the ice interface. Glacier dammed lakes and jøkulhlaup events were identified. This report also discusses advantages, and limitations in mapping of glacier lakes with Sentinel-2 imagery.

Keywords: Glacier lake, Sentinel-2, inventory, NDWI, lake area, jøkulhlaup, GLOF, lake change, glaciers

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Preface

The project Copernicus Glacier Service ('Copernicus bretjeneste' in Norwegian) is a cooperation between the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Polar Institute and the Department of Geosciences, University of Oslo. The project is partly funded by the Norwegian Space Centre through the Copernicus programme of the European Space Agency (ESA). The project mainly focuses on using optical imagery from Sentinel-2, but also Landsat-8 and other sensors are considered.

In this report Sentinel-2 imagery has been used to map glacier lake outlines in mainland Norway. This is a follow up on previous glacier lake inventories made by NVE using Landsat imagery. Teodor Nagy has analysed the Sentinel imagery, produced the lake outline dataset and written the report with contributions from Liss M. Andreassen. The glacier lake outlines are available for viewing and download from NVEs website.

We would like to thank ESA for providing freely available Sentinel-2 imagery. We also want to thank Kartverket, the Norwegian mapping authority, for providing freely available high resolution orthophotos for mainland Norway via www.norgeibilder.no. Landsat 8 imagery was acquired via Earth Explorer tool built by USGS. Sentinel Hub Playground tool (https://apps.sentinel-hub.com/sentinel-playground/) was used for quick visualization of Sentinel-2 imagery.

Oslo, October 2019

Svein Taksdal
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Summary

In this report, we use Sentinel-2 optical satellite imagery to map glacier lakes in mainland Norway. Mapping of the lake outlines was conducted using optical satellite imagery from 2018 by calculating the Normalized Differential Water Index (NDWI), applying a threshold, and manually correcting outlines when necessary. The total number of the glacier lakes mapped was 414. The lakes were categorized according to the nature the contact with the ice interface and lakes within ca. 100m of the glacier perimeter were included. Sites where lake emptying (jøkulhlaup) events happened were identified. The advantages, limitations and challenges in the mapping of the lakes using Sentinel-2 optical imagery are discussed. The glacier lake outline inventory is a follow up on previous Landsat lake inventories and can be used as a reference for monitoring glacier lake changes, in particular for glacier and moraine dammed lakes with a history or a potential of outburst floods.

Sammendrag

I denne rapporten har vi kartlagt bresjøer ved hjelp av Sentinel-2 optiske bilder. Bresjøkartleggingen ble foretatt ved bruk av Sentinel-2 optiske bilder fra 2018, ved bruk av NDWI terskling og manuell redigering av sjøene. Totalt, ble 414 bresjøer kartlagt. Bresjøene ble kategorisert basert på kontakttype med bre og sjøer inntil ca. 100m fra dagens brekant ble inkludert. Lokaliteter hvor det har skjedd plutselig tømming av sjøer (jøkulhlaup) ble identifisert. Fordeler og begrensinger ved bruk av Sentinel-2 bilder til å kartlegge bresjøer er oppsummert i rapporten. Denne nye oversikten over bresjøer i Norge kan være verdifull for overvåkning av endringer i sjøer ved breer, særlig for sjøer med tidligere eller mulige jøkulhlaup hendelser.

Abbreviations

DEM Digital Elevation Model

Et al. And others

ESA European Space Agency

GAO Glacier area outline

GLO Glacier lake outline

GIS Geographical information system

GLOF Glacial lake outburst flood (jøkulhlaup)

NDWI Normalized differential water index

NVE Norges vassdrags- og energidirektorat (Norwegian Water Resources and Energy Directorate)

UAV Unmanned aerial vehicle

Abbreviations used in figures

L Landsat

S Sentinel

O Orthophoto

1 Introduction

1.1 Background

Glacier lakes in alpine regions are sensitive to climate change and their mapping and monitoring improves our understanding of regional climate change and glacier-related hazards (Li and Sheng, 2012). Proglacial lakes can increase mountain glacier ablation via mechanical and thermal stresses, but very large lakes can moderate summer air temperatures and relatively retard summer ice ablation (Carrivick and Tweed, 2013). Mapping of glacier lakes with optical satellite sensors has become common and has been applied to detect both proglacial and supraglacial lakes (Nie et al., 2017; Watson et al., 2018; Williamson et al., 2018). Mapping has been undertaken on both regional (Nie et al., 2017) and national scale (Ukita et al., 2011). Mapping of changes in lake surface area has been done on both seasonal (Watson et al., 2018) and a near-daily scale (Cooley et al., 2019). Glacier lake outburst floods (GLOFs) are the major hazard directly related to glacier lakes and can often lead to both personal and material losses. Glacier lakes in mainland Norway have long posed a threat due to frequent outburst floods, which were fatal in the past and resulted into material losses (Liestøl, 1956; Jackson and Ragulina, 2014). With continuing glacier shrinking, existing lakes can change and new lakes can develop or disappear. Having an updated glacier lake outline dataset can be used as the basis for investigation of future changes in lakes on a local or a national scale. An updated glacier lake outline can be equally helpful for differentiation of ice-water interface in glacier area outline mapping.

With the onset of Sentinel-2 satellite missions, we are able to use medium resolution optical satellite imagery that is freely available to create glacier products, such as lake outlines, glacier area outlines, transient snowlines and datasets of surface velocities. High acquisition frequency of the Sentinel-2 satellites and a dense satellite orbit overlap over mainland Norway provides a better potential for working with useful imagery in a region with notorious cloud and snow cover problems. Availability of bands at 10m ground resolution and a high revisit time compared to previous Landsat missions provide basis for an improved glacier lake inventory and glacier lake monitoring.

1.2 Report aims

This report aims to present a glacier lake outline inventory for mainland Norway acquired by using Sentinel-2 optical imagery. The focus in the report is the mapping methods, accuracy and the advantages and limitations of using Sentinel-2 optical imagery to map the glacier lakes. Challenges in the processing chain including image selection are described in detail. Last, the jøkulhlaup sites with events in the period 2015-2019 are identified and presented together with other glacier and moraine dammed lakes.

2 Glacier lakes in Norway

In total, glaciers in mainland Norway (hereafter referred to as Norway) cover an area of 2692 ± 81 km^2 and are divided into 3143 units (Andreassen et al., 2012) across southern Norway (1575 units) and northern Norway (1568 units) (Figure 1). Glacier lakes in Norway have been a target of several studies. Liestøl (1956) gives one of the first comprehensive reports on glacier dammed lakes in Norway with detailed description of outburst floods from as early as 1890's. Elvehøy et al. (1997) provide a detailed overview of Nedre Demmevatnet and jøkulhlaup scenarios. Engeset et al. (2005) analyse the first jøkulhlaup event at Blåmannsisen and evaluate its implications for future events. Kjøllmoen (2018) reports the history of jøkulhlaups from Blåmannsisen. Jackson and Ragulina (2014) provide a summary of the glacier lake outburst floods and other glacier-related hazardous events in Norway. According to Jackson and Ragulina (2014), there were at least 20 glacier dammed or supraglacial lakes in Norway in 2014.

Three previous glacier lake outline inventories done by NVE using Landsat imagery are available. The first complete inventory was made using Landsat 5 and Landsat 7 imagery from 1999-2006 and a semi-automatic approach using NDWI (Winsvold and Andreassen, 2012). The glacier lakes were defined as water bodies that either intersected, were within a distance of <50m or were completely within the glacier boundary/glacier area outline (GAO). Lakes smaller than 0.001km^2 were removed. The lakes were post-processed and validated with aerial photographs, 1:50 000 maps, and earlier registered lakes from edits done on the glacier area inventory. In total, 398 lakes were mapped. Using this as a basis, a second inventory consisting of 195 glacier lake outlines was made by manual digitization using Landsat 5 imagery from the period 1988-1997, but due to severe cloud conditions some glacier regions were not mapped (Winsvold and Andreassen, 2012). The most recent inventory was done using manual digitization of Landsat 8 imagery from 2014. Glacier lake outlines (GLO) were identified as water bodies that either intersected, were within a distance of <50m, or were completely within the GAO of 1999-2006 (Andreassen et al., 2012). The lake inventory of 2014 includes 636 glacier lake outlines, but due to glacier retreat between 1999-2006 and 2014 several of the glaciers are further away then 50m of the 2014 glacier outline. The previous lake inventories are available in NVEs digital glacier atlas (NVEs Breatlas).

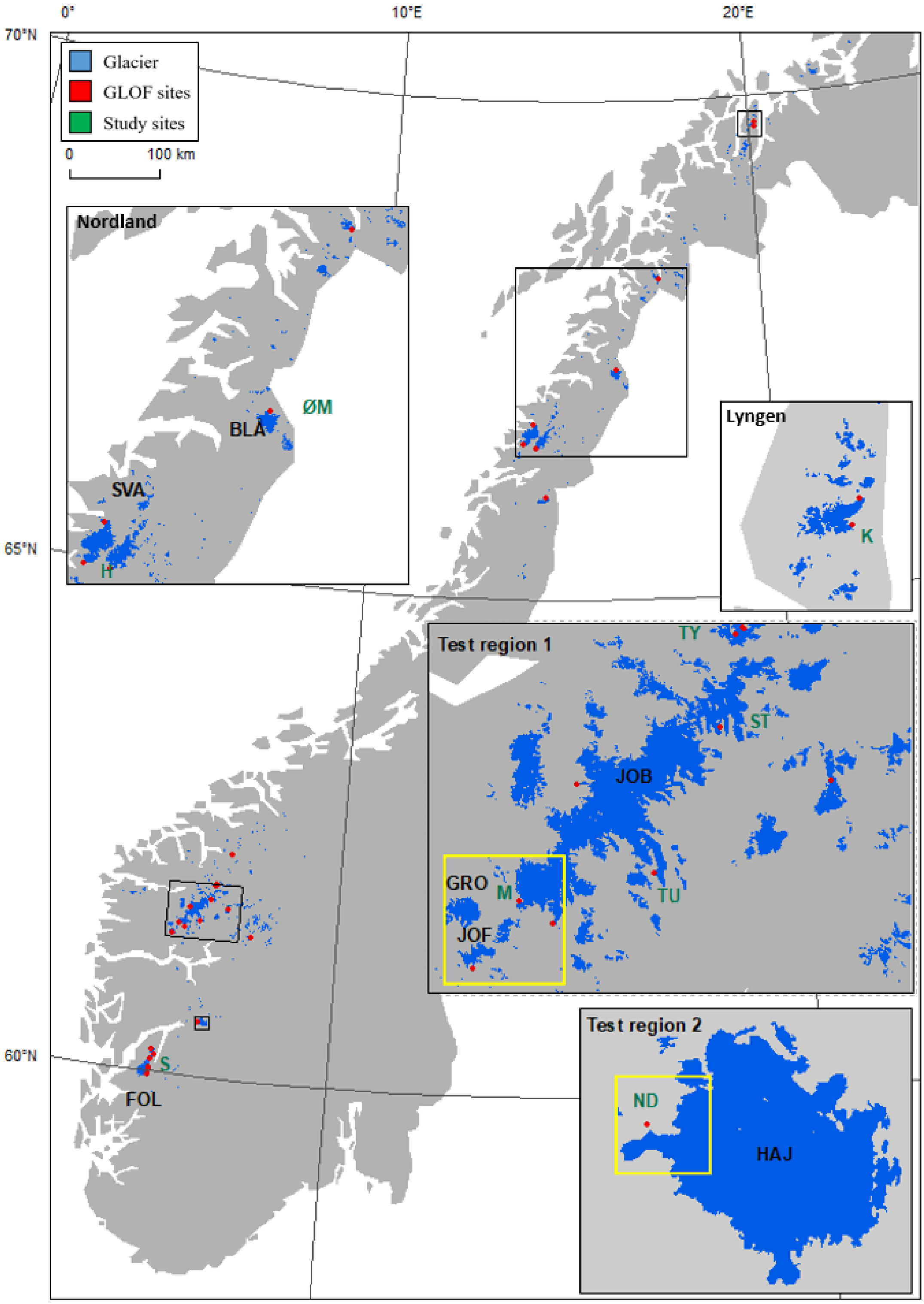

Figure 1: A map of Norway showing subsets in test regions 1-2 (yellow boxes), lake sites (green font), and main glaciers (black font) referred to in the report. Regions Nordland and Lyngen are also shown as close-ups. All GLOF sites recorded in NVEs Breatlas up to and including 2018 are shown in red. Abbreviations: FOL: Folgefonna; HAJ: Hardangerjøkulen; JOF: Jostefonni; GRO: Grovabreen; JOB: Jostedalsbreen; SVA: Svartisen; BLÅ: Blåmannsisen; S: Sauvatnet; ND: Nedre Demmevatnet; M: Marabreen lake; TU: Tunsbergdalsbreen lake; ST: Styggevatnet; TY: Tystigbreen lakes; H: Heiavatnet; ØM: Øvre Messingmalvatn; K: Koppangsbreen lake.

3 Data and methods

A number of methods and data sources can be employed for glacier lake outline mapping. As discussed in the following chapter, Sentinel-2 optical satellite imagery has a better potential to be used on a nation-wide scale, when compared to orthophotos, drone acqusitions, and high-resolution satellite imagery. For the new glacier lake outline inventory, we used exclusively optical imagery from the Sentinel-2 missions. Imagery was downloaded from Colhub (https://colhub.met.no/#/home) and was processed with ArcGIS 10.5.1 software. We used Sentinel Hub Playground tool (https://apps.sentinel-hub.com/sentinel-playground) to quickly visualize Sentinel-2 imagery available as either separate bands or as band combinations.

3.1 Glacier lake outline mapping methods

There is a number of methods that can be used for glacier lake outline mapping (Table 1). Field mapping with a UAV can be time flexible and results in high resolution orthophotos. Therefore it is well-suited for detailed investigations, but suffers from a low spatio-temporal coverage and can be time-consuming (e.g. Andreassen and De Marco, 2018). The plane-acquired orthophotos for mainland Norway provided by Kartverket are a good alternative for the lake outline mapping, can be used for validation and are invaluable source for improved catalogization of the lake outlines in a large inventory. However, the multi-temporal revisit time is ca. 5-6 years depending on the region and the individual orthophotos that can be taken early in the season with remaining snow and ice cover. The very high resolution optical satellite imagery of less than 1m ground resolution provided by satellites such as Ikonos, Pleiades or Quickbird, or 3m such as Planet can be purchased, but are expensive for non-academic users and often too costly to map areas beyond a span of a single glacier or a glacier valley. The Landsat missions have been excellent in providing freely available imagery covering mainland Norway for decades now and were key to mapping glacier lake extents prior to the Sentinel era as used for the previous glacier and glacier lake outline inventories (Andreassen and Winsvold, 2012; Winsvold et al., 2014). The Landsat imagery at the 30m ground resolution for the bands needed for NDWI calculations and false and natural image composites show nine times less detail when compared to corresponding Sentinel-2 imagery and NDWI maps from the 10m ground resolution imagery (Figure 2). Nevertheless, both Landsat and Sentinel optical satellite imagery for glacier lake outline mapping suffer from severe cloud cover and may have difficult snow and lake ice conditions. The improved revisit time of Sentinel-2 (5 days) compared to 16 days of Landsat increases the chances of working with useful imagery.

Table 1: Advantages and disadvantages of different methods and image sources that can be used for mapping of glacier lake outlines.

Mapping method	Advantages	Disadvantages
Airplane orthophotos from Kartverket	Very high accuracy. Relatively large spatial coverage.	Infrequent repeated observations on a scale of ca. 5-6 years. Quality depending on the snow conditions at a given date.
UAV orthophotographs	Very high accuracy. Temporal and spatial independency. Good for mapping of the events such as jøkulhlaups.	Low spatial and multi-temporal coverage potential. Laborious fieldwork and additional data processing. Costs associated with fieldwork, UAV purchase and maintenance.
Landsat 5, 7, 8 optical imagery	Large spatial coverage. Good multi-temporal coverage. Freely and readily available data.	Too coarse to observe fine changes. Quality depending on weather and snow/ice conditions. Positional accuracy can be unsatisfying.
Sentinel-2 optical imagery	Large spatial coverage. Improved multi-temporal coverage. Highest freely available imagery resolution. Freely and readily available data.	Quality depending on weather and snow/ice conditions. Need improved positional accuracy with DTERRENGDATA imagery as original orthorectification can be unsatisfying.
Very high (<1m) resolution optical imagery	Flexible spatial coverage. Good multi-temporal coverage. Reasonable flexibility in the image date choice.	Very high cost. Quality partly depending on weather and snow/ice conditions.

3.2 Satellite imagery

The Sentinel-2A satellite was launched into orbit on 23/06/2015 (Paul et al., 2016). After the launch of the Sentinel-2B satellite on 07/03/2017, the amount of data has doubled (Castriotta and Knowelden, 2017). The combination of the Sentinel 2A-2B constellation yields an observation every five days at the equator and more frequently at higher latitudes, which makes the Sentinel 2A-2B constellation superior to other missions including Landsat 8 with longer revisit times (Li and Roy, 2017). Sentinel-2A and Sentinel-2B satellites also currently provide the highest ground resolution freely-available imagery at a 10m ground resolution. The Sentinel-2A and Sentinel-2B missions carry a multi spectral instrument (MSI), which provides 13 reflective wavelength bands; four 10m visible and near-infrared (NIR) bands, six 20m near-infrared and short-wave infrared (SWIR) bands, and three 60m bands (Zhang et al., 2018). In comparison, the most recent Landsat mission, the Landsat 8, carries an operational land imager (OLI) and thermal infrared sensor (TIRS) and has nine reflective wavelength bands designed for land use, with the highest panchromatic band ground pixel resolution being 15m, compared to the Sentinel 2A-2B constellation's 10m (Loveland and Irons, 2016). Sentinel-2 provides improved details of glacier outlines and crevasses (Paul et al., 2016, Nagy et al., 2019). The green and NIR bands (3 and 8) of Sentinel-2, often used to compute the NDWI, are provided at a 10m ground resolution (Zhang et al., 2018), whereas the corresponding bands 3 and 5 of Landsat 8 are provided at a 30m ground resolution. Effectively, this results in a nine times sharper imagery of Sentinel-2 compared to Landsat 8 enabling to capture more detailed information of the lake outlines (Figure 2).

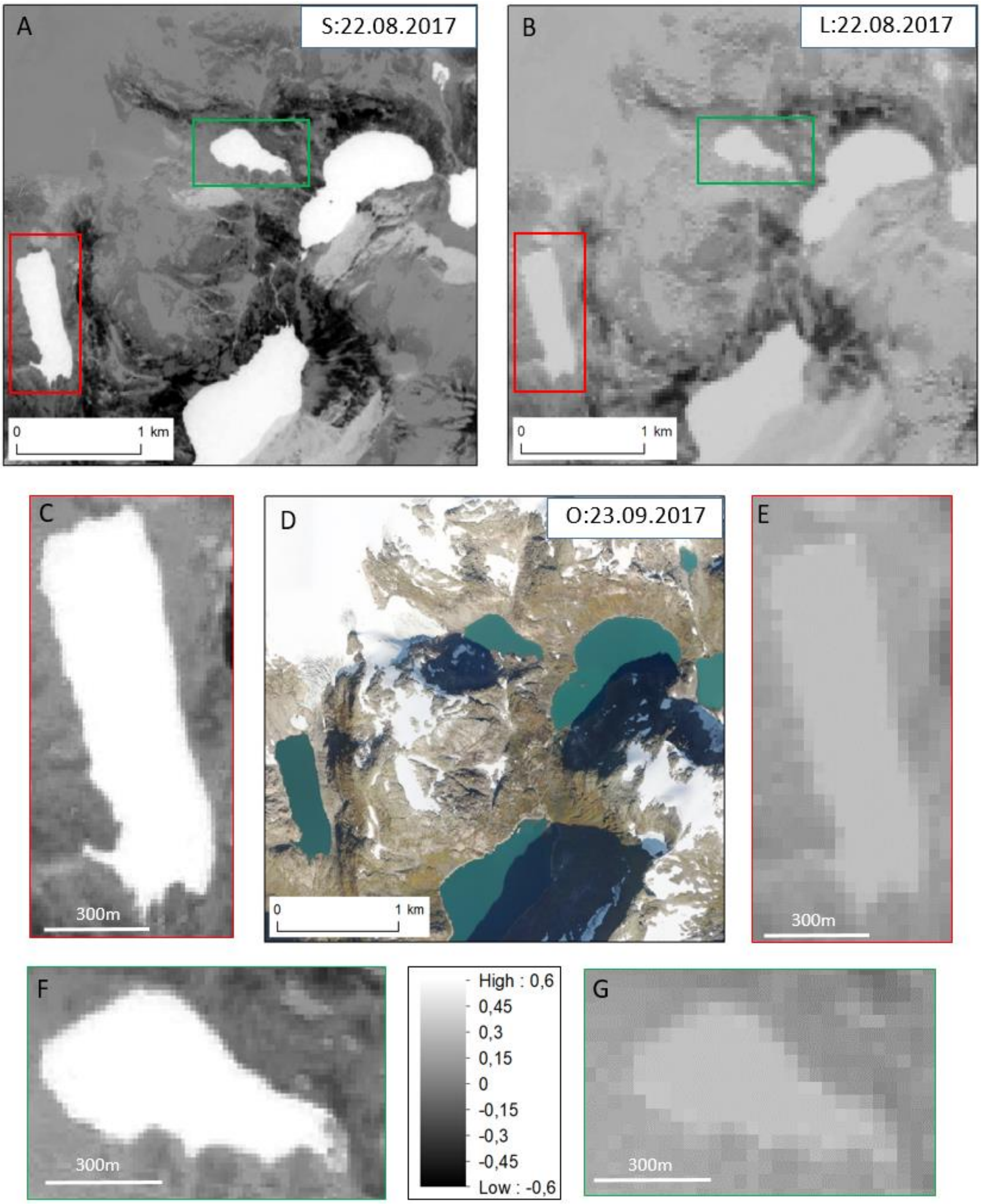

Figure 2: NDWI maps of Sentinel-2 (S) and Landsat 8 (L) scenes, as well as orthophoto (O) of lakes at southern Jostefonni glacier (part of test region 1, see Figure 1) showing varying level of observable lake outline detail. Close-up of the NDWI maps of the lakes of southern Jostefonni from 22/08/2017 using Sentinel-2 (C and F) and Landsat 8 (E and G) imagery.

3.3 Image selection

There are several factors to consider when selecting imagery for glacier lake outline mapping. Ideally, the glacier lake surface should be observed at its areal maximum, with no surface snow and ice cover. The lake perimeter should ideally be snow free to avoid misrepresentation of the snow covered perimeter for water or vice versa. Cloud cover as well as cloud and terrain iduced shadowing should be minimal. As later described, it can be difficult to find an image that complies with all the aforementioned criteria.

Scrutinizing the Sentinel-2 archive for 2015-2018 revealed that, as expected, the snow and ice cover of the glacier lakes vary from season to season. Generally, the glacier lakes in Norway tended to become ice and snow free towards the end of the summer season, depending also on their altitude. However, the timing of the lake surface clearance was found to have a large spatio-temporal variability. For the Jostefonni region for example, different snow and ice conditions were found in the month of July of 2016-2019 and August 2015 (Figure 3). While the lakes and lake perimeters were not snow and ice free in August 2015, they were completely snow and ice free in July 2018 (as early as 13/07/2018). The summer of 2018 was particularly warm in Norway, whereas the summer of 2015 was cold with a late onset of summer melting. This resulted in very different lake exposure. The earlier the lake surface and its perimeter become ice and snow free, the higher the chances for useful imagery in the remaining summer season. Often, the earliest useful imagery found for lake outline mapping was from July. Usually, August and early September had useful acquisitions with minimal snow and ice cover. The previous three lake outline inventories based on Landsat imagery were compiled using exclusively imagery from August and September.

All images were visually inspected prior to selection. The image acquisitions used for the inventory were from the period 03/07/2018-08/09/2018. The images from 2018 were preferred due to early lake surface exposure, and due to the possibility of having a complete inventory using the most up-to-date imagery covering a short time window. The image selection had to be thorough as many of the 2018 acquisitions, especially in southern Norway, suffered from abundant cloud cover in late July and throughout August. Predominantly, we used Sentinel-2 imagery that was orthorectified with the Norwegian DTERRENG DEM produced at the 10m ground resolution. Imagery orthorectified with the 10m DTERRENG DEM is superior in the positional accuracy of the features to imagery orthorectified with the Planet DEM at the 90m resolution for mainland Norway or other DEMs with coarser resolution (Kääb et al., 2016). In total, ca. 11 % of the lakes were mapped using non-DTERRENG orthorectified imagery.

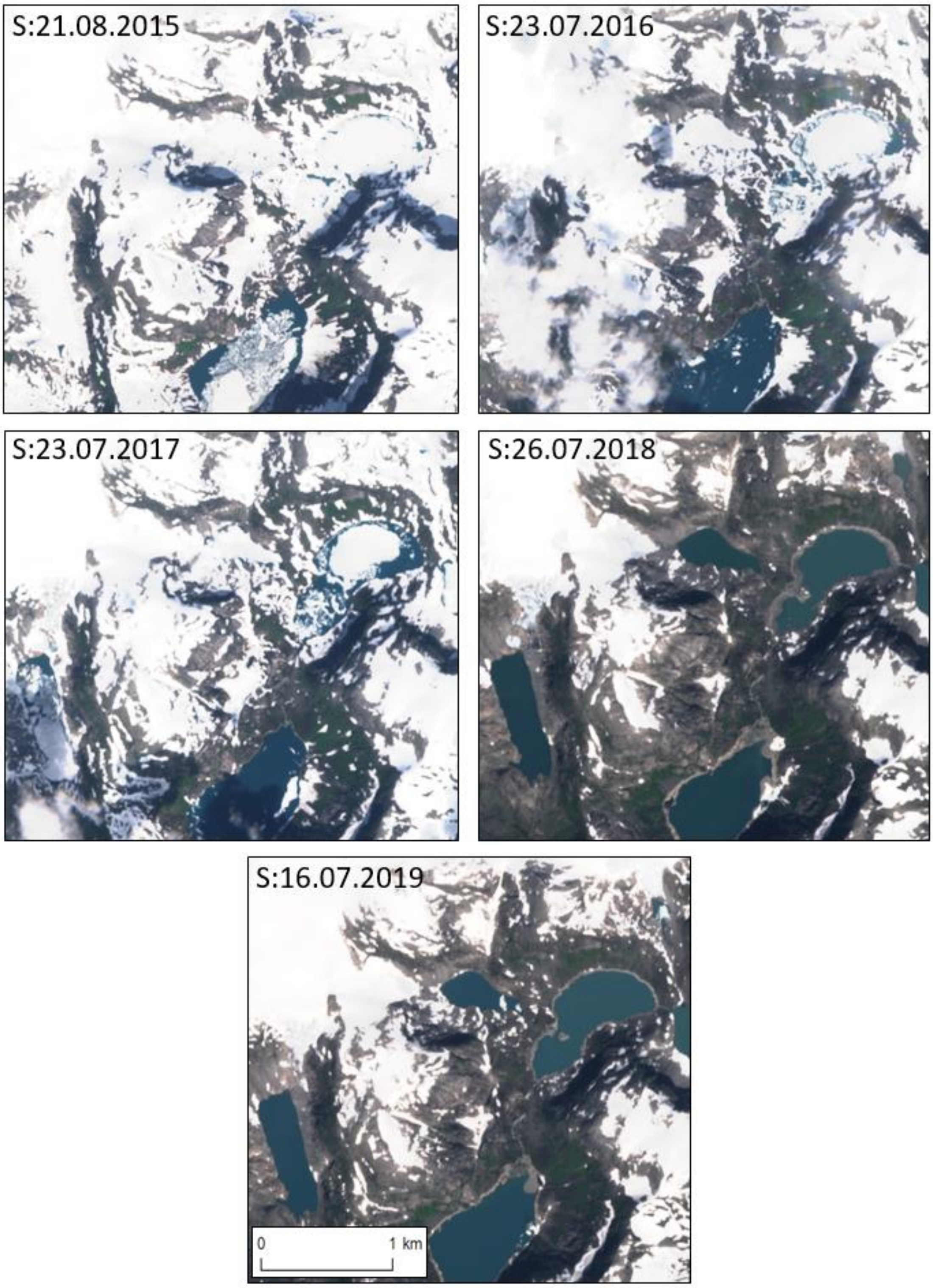

Figure 3: Sentinel-2 natural colour imagery of lake surface conditions in August 2015 and July 2016-2019 of southern part of Jostefonni glacier, test region 1. See Figure 1 for location.

The terrain induced shadowing is at its minimum during the summer solstice (~21/06) due to a high sun angle. The further the temporal distance from the summer solstice, the lower the sun angle, and the more widespread the shadowing becomes (Figure 4). This is often problematic for glacier lakes lying north of a mountain ridge or in areas of prominent topography. To minimize the effect of shadowing, imagery that was selected for the analysis was therefore often the first clear image with a full exposure of the glacier lake outlines. Figure 4 shows how shadowing develops in 25 days.

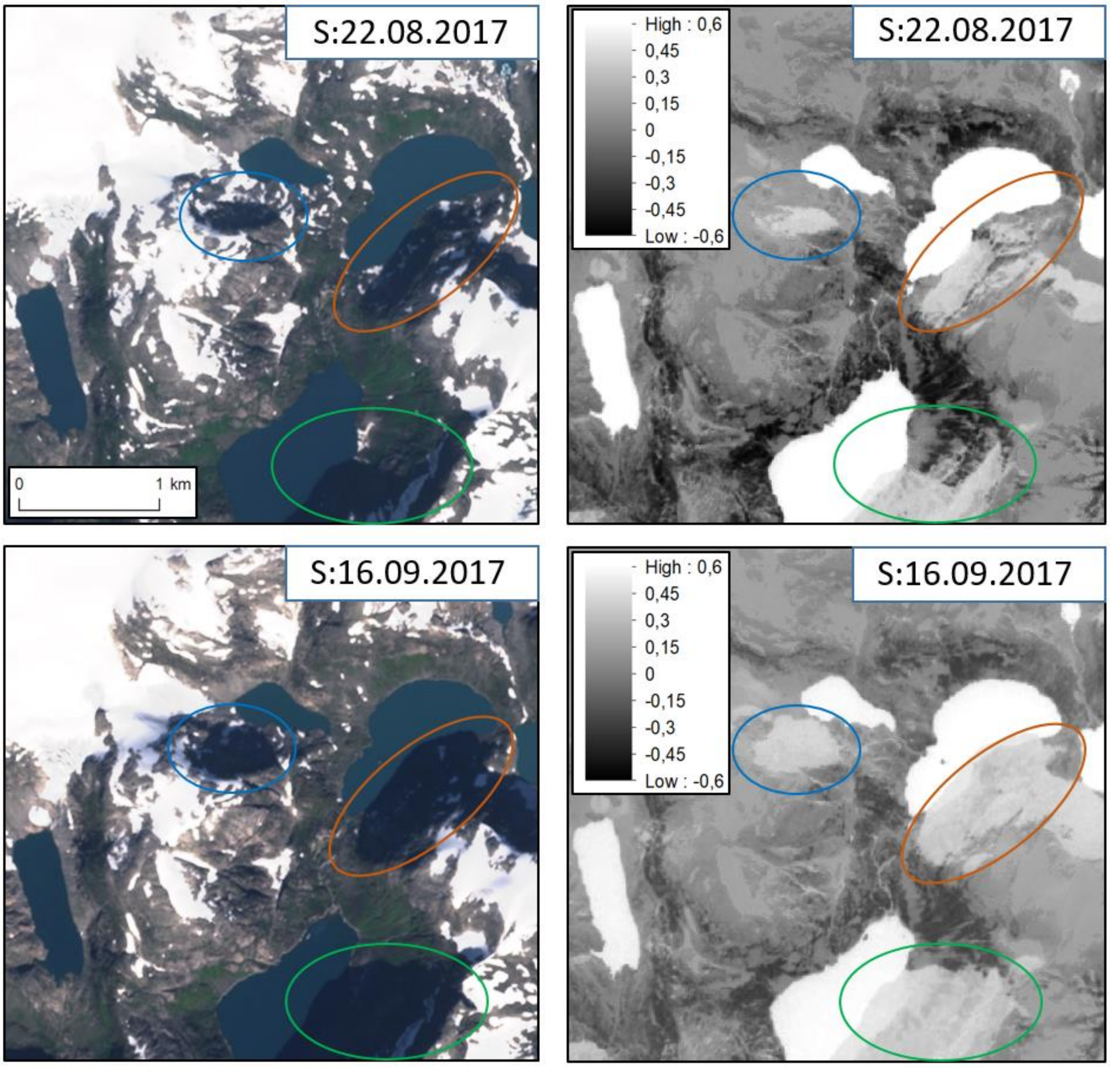

Figure 4: Sentinel-2 natural colour imagery and corresponding NDWI maps illustrating increased spatial extent of terrain induced shadowing in 25 days over southern part of Jostefonni glacier. Three lake-bordering areas influenced by shadowing are depicted in blue, orange and green. High-end positive NDWI values indicate presence of water. Shadowing over stable terrain manifests in increased NDWI values over non-water covered areas. NDWI is explained in detail in chapter 3.4.

3.3.1 Availability of Sentinel-2 imagery for glacier lake monitoring

Time series of Sentinel-2 imagery can be useful for regular monitoring of glacier lake conditions. To assess the availability of useful imagery for a selection of lakes of interest, all imagery from the melting seasons 2015, 2016, 2017 and 2018 was considered. A subset of seven lakes with a history of emptying events in the 21st century was selected: Sauanutvatnet, Nedre Demmevatnet, Marabreen lake, Tystigbreen lakes, Heiavatnet, Øvre Messingmalvatn and the Koppangsbreen lake. In the Norwegian language the terms 'sjø' and 'vatn/vannet' mean lake. This subset of seven lakes gives an opportunity to assess the image availability for a South-North transect. All the aforementioned lakes were looked at using imagery from May-November for the years 2015-2018.

The Sentinel 2 imagery was classified for the lake subset into the following categories*:

I: The lake is free of clouds, and is not covered by snow or ice.

II: The lake has residual icebergs or snow, but the full perimeter of the lake is distinguishable. Limited cloud cover may be present.

III: Part of lake is covered by clouds, snow or ice and only parts of the lake perimeter can be observed.

IV: The lake area and perimeter area are visible only in a few points due to snow, ice or clouds.

**Each category can be annotated with 's' standing for the presence of cloud or terrain induced shadowing. A lake image free of ice, snow and clouds, but with terrain induced shadowing would be classified as a Category I.s. image.*

Imagery that had 100% cloud cover over the lakes was not included or classified. In total, 375 images were classified for the seven lake sites (Figure 5). The mean of the sample was ca. 54 images per lake site. More imagery was available for the three lake sites in northern Norway. This is mainly due to denser Sentinel-2 observations. Northern Norway is often imaged from three different orbits. Southern Norway is most often imaged from two orbits, but can also be imaged from three orbits. Of 375 images (Table A1), 207 were classified in the I, I.s., II, and II.s. categories. This presents a mean of ca. 30 images per lake for the period 2015-2018, where a perimeter of the lake and its area can be distinguished. More imagery was available from 2017 and 2018 (282 images) than 2015 and 2016 (93 images). This is due to: a) doubled coverage of years 2017 and 2018 by Sentinel-2B satellite; b) Sentinel-2A sensor malfunction and irregular observations in 2015; c) difficult snow cover conditions in years 2015 and 2016. Figure 6 shows the cloud, snow and lake ice conditions over Nedre Demmevatnet in a 4 month period 29/05/2018-28-09/2018. Lake snow, ice cover and cloud cover are limiting the number of useful images for glacial lake monitoring.

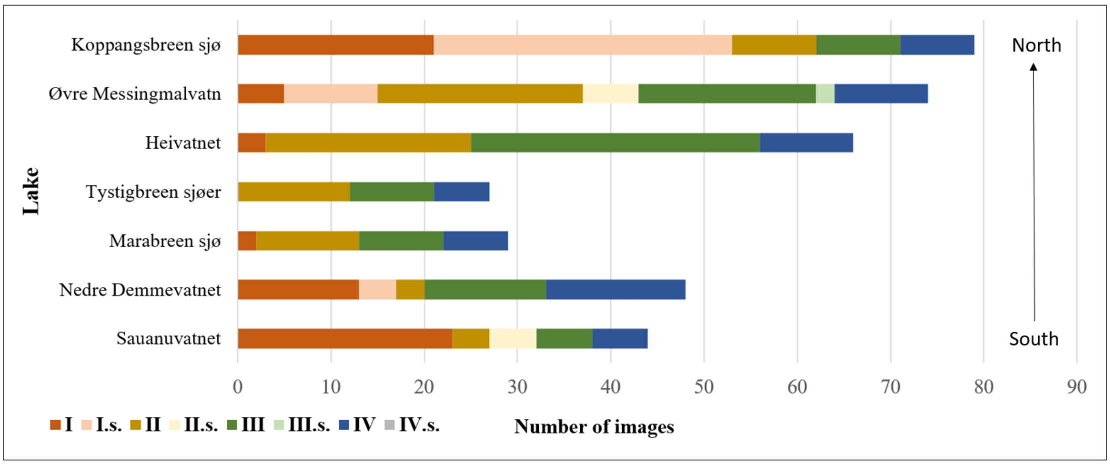

Figure 5: Categorization of Sentinel-2 imagery for the months May-November from 2015-2018 based on its usefullness for glacier lake outline mapping for a subset of seven lakes along the S-N transect. See Figure 1 for location.


28/09/2018
26/09/2018
23/09/2018
21/09/2018
18/09/2018
16/09/2018
13/09/2018
11/09/2018
08/09/2018
06/09/2018
03/09/2018
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29/08/2018
27/08/2018
24/08/2018
22/08/2018
19/08/2018
17/08/2018
14/08/2018
12/08/2018
09/08/2018
07/08/2018
04/08/2018
02/08/2018
30/07/2018

Figure 6: Natural colour Sentinel-2 imagery of Nedre Demmevatnet, glacier dammed lake with a history of jøkulhlaup events, from the period 29/05/2018-28/09/2018. For the location, see Figure 1 (test region 2). Dimensions of each of the frames are ca. 0.7 x 1.2km.

3.4 Lake outline mapping

Mapping of the lake outlines can be done using manual digitisation of colour composites or by calculating NDWI and thresholding imagery. NVE used both approaches in previous inventories. Manual mapping as used by NVE for the 1988-1997 and 2014 lake outline inventories was found time efficient, but introduces a subjective bias and also risks overlooking smaller lakes. With the enriched details of Sentinel-2, compared to Landsat 8, we decided to explore the use of NDWI mapping for our new inventory.

The NDWI as proposed by McFeeters (1996) maximizes the water body reflectance in the green band and minimizes its reflectance in the near infra-red (NIR) band:

$$NDWI = Green - NIR / Green + NIR \tag{1}$$

where Sentinel-2 band 3 (559nm) and band 8 (833nm) correspond to the green and NIR bands. As both bands are available at the 10m ground resolution, no resampling was needed and NDWI was calculated as:

$$NDWI = Band\,3 - Band\,8 / Band\,3 + Band\,8 \tag{2}$$

following other studies (Du et al., 2016; Watson et al., 2018). A semi-automatic approach was chosen as method for the lake outline generation. Thresholding of the NDWI maps has been commonly used (Miles et al., 2017; Watson et al., 2018; Williamson et al., 2018), however, the specific threshold values are dependent on the application. A threshold, is used to separate the NDWI map pixels into the water and non-water pixels. The threshold value (T) must be high enough to differentiate between ice and water, but also low enough to minimize the omission of the water pixels. Using visual inspection of the results, against the colour composites of the imagery or other validation data, the lake outlines can be manually corrected if necessary. The need to correct the outlines usually stems from the misrepresentation of ice, snow, or shadows for water. While lower threshold values can work better for the lakes surrounded by debris or snow and ice free terrain, the lower threshold values should not be used for the lakes that are in a contact with the glacier ice or snow cover due to need of extensive manual filtering of the lake outlines.

To find the suitable threshold value for the glacier lake outline delineation and to assess the uncertainty of the glacier lake outline product, we used high resolution orthophotos from norgeibilder.no with almost perfect temporal overlap with Sentinel-2 imagery in test region 1 (see Figure 1). We manually digitized the lake outlines from the orthophotos and calculated the surface area of a selected lake subset from western Jostedalsbreen, Grovabreen and Jostefonni (Figure 7). The orthophotos have a ground resolution of 0.25m and were acquired in August and September 2017.

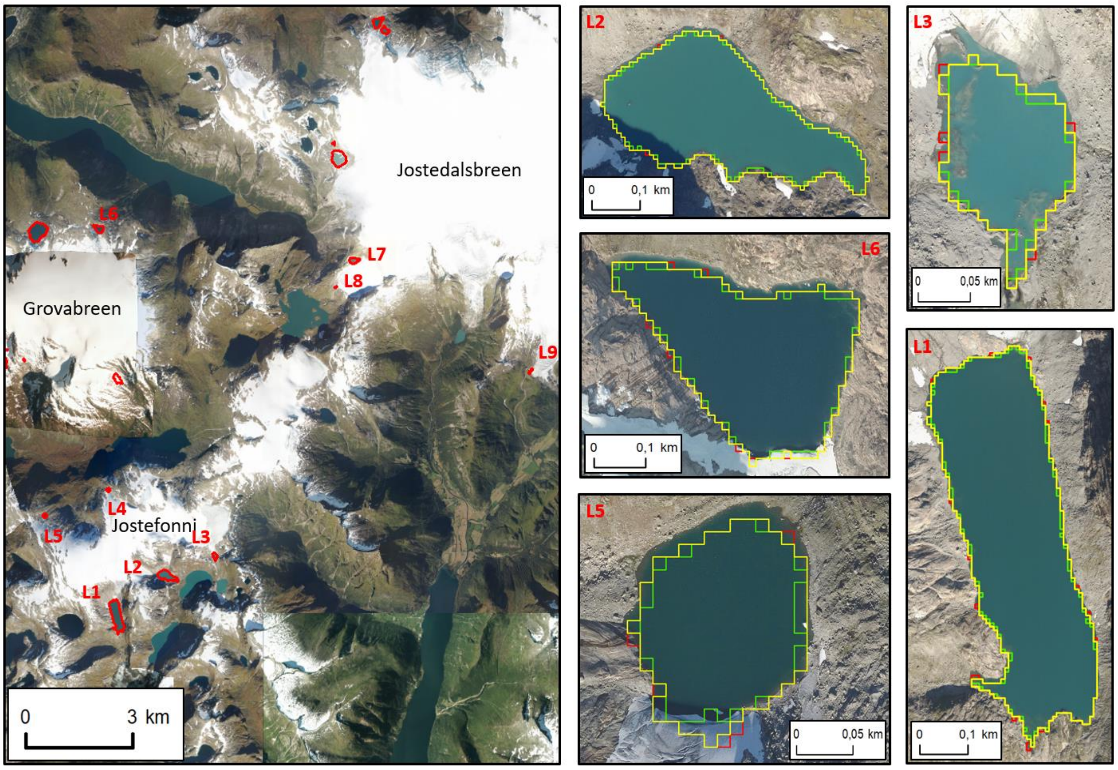

Figure 7: Map of the test region 1 (see Figure 1) showing derived lake outlines in western Jostedalsbreen, Jostefonni and Grovabreen including the location of the subset of lakes L1-L9 used for the product accuracy assessment. The lake outlines of lakes L1, L2, L3, L5 and L6 calculated using the Sentinel-2 NDWI image from 16/09/2017 are shown in detail for the thresholds: T0.23 in red; T0.25 in yellow; T0.35 in green. The background orthophotos are from 16/09/2017 and 23/09/2017 and were used to manually digitize the lake outlines.

Both the orthoimagery and Sentinel-2 acquisitions had favourable snow, lake ice and cloud conditions. The Sentinel-2 acquisition from 16/09/2017, orthorectified with the DTERRENG DEM was used to compute the NDWI map. After an initial visual assessment (Figure 8), we thresholded the NDWI map. The NDWI values determined from the test site (Figure 8) were: snow: 0.03-0.07; ice: 0.09-0.23; terrain: > -0.60 ; water: < 0.62. Three different thresholds (0.23, 0.25, 0.35) were applied to determine the subset area accuracy under different thresholding conditions.

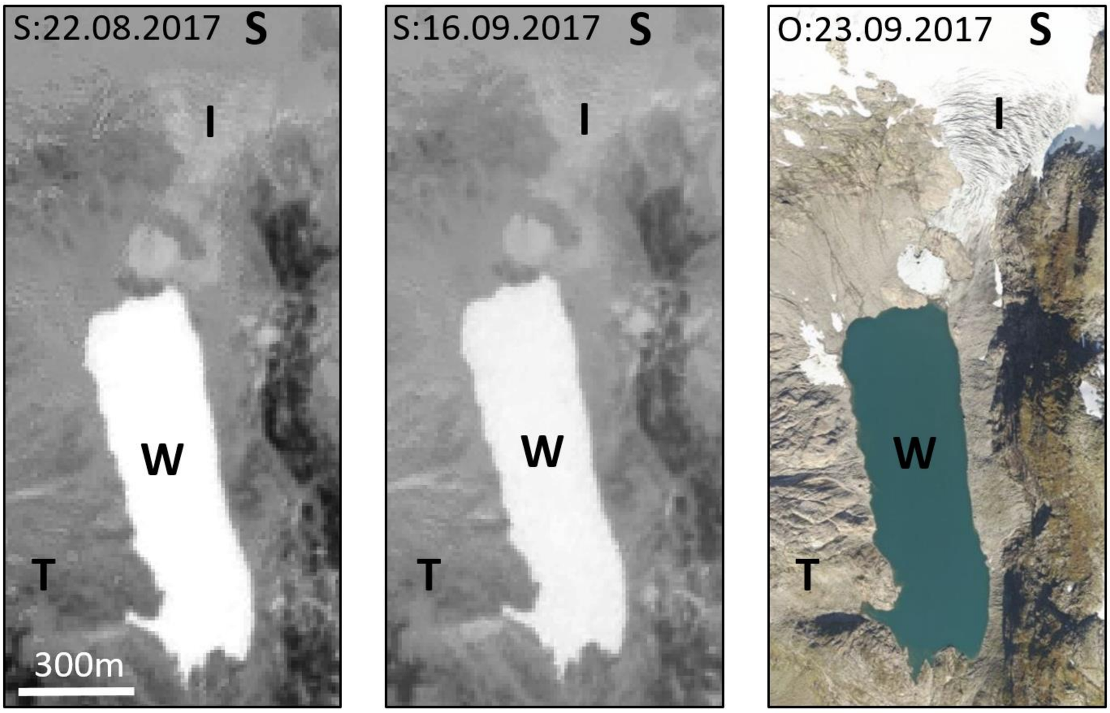

Figure 8: Comparison of the Sentinel-2 NDWI maps with a high-resolution orthoimage, depicting different representation of water (W), snow (S), ice (I) and terrain (T) for lake L1 south of the Jostefonni glacier (see Figure 7 for location).

The analysis of the subset of nine lakes (L1-L9) revealed that the overall accuracy was highest using a threshold of 0.23 (96.2%), and lowest for 0.35 (90.3%) (Table 2). The 0.23 threshold was thus chosen for the further mapping as it was found to be the best compromise that would minimize the need for the lake outline redigitization and also maximize the inclusion of the 'true' water pixels.

The accuracy assessment was carried out using imagery of 2017, whereas the glacier lake outline product used 2018 imagery. We believe that the 2017 accuracy assessment is representative also for the 2018 GLO product. Based on our findings, we estimate an uncertainty in glacier lake area of ±4%. We find that 0.23 threshold underestimated the lake area of the subset L1-L9 for each of the lakes. Therefore, a 4% increase in the lake area could be considered to correct for the underestimation assuming this is representative for the inventory. The uncertainties in the digitisation of the high resolution orthophotos used for validation itself are small as lake outlines were easy to map and are therefore not quantified.

Table 2: The estimated areal extents of the lake subset L1-L9, test region 1, derived using different values of the NDWI threshold compared with lake area digitised from orthophotos. Lake types: 1: Lake has no interface with glacier ice, but is within ca. 100m of the ice perimeter; 2: Lake has an interface with glacier ice; 3: Lake is glacier dammed; 4: Lake is moraine dammed; 5: Lake is a dam with artificial water level regulation; 6: Supraglacial lake. See Figure 7 for location of the lake subset.

Lake	**Lake type**	**Orthophoto (km^2)**	**T0.35(km^2)**	**T0.25(km^2)**	**T0.23(km^2)**
L1	2	0.1342	0.1231	0.1283	0.1286
L2	1	0.2776	0.2619	0.2706	0.2724
L3	2	0.0221	0.018	0.0198	0.0203
L4	2	0.0166	0.0121	0.0133	0.0134
L5	2	0.0188	0.0151	0.0175	0.0180
L6	2	0.0609	0.0545	0.0583	0.0588
L7	3	0.0332	0.0282	0.0300	0.0316
L8	2	0.0058	0.0030	0.0045	0.0046
L9	4	0.0080	0	0.0062	0.0074
Sum of area & estimated accuracy		0.5772	0.5159 (89.4%)	0.5485 (95.0%)	0.5551 (96.2%)

3.4.1 Lake outline correction

To obtain a glacier lake product within a minimal time period only Sentinel-2 imagery from 2018 was used. An image from 26/07/2018 was used for the lake outline mapping in the Jostefonni and western Jostedalsbreen regions and none of the lakes L1 – L9 had terrain induced shadowing. Using a relatively early acquisition results in a reduced need for manual redigitization of the lake boundaries (Figure 9). However, in some of the other regions, glacier lake outlines had to be computed using imagery from September 2018, when terrain induced shadowing is spatially more prominent than in July. Areas of terrain with shadowing have a higher NDWI (Figure 4) than the selected threshold of 0.23, ranging ca. 0.25-0.45. This can result in inclusion of the non-water terrain pixels into water polygons (Figure 9).

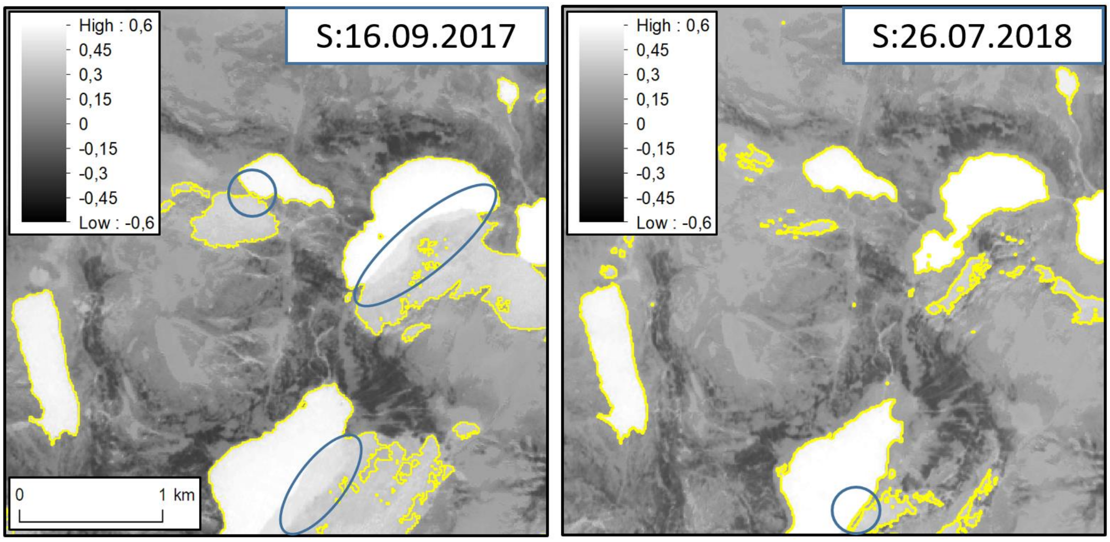

Figure 9: NDWI maps of Sentinel-2 imagery from 16/09/2017 and 26/07/2018 with polygons derived using T0.23 (in yellow) illustrating different inclusion of areas in shadow over a 50 day temporal baseline. The areas that need manual corrections of outlines are highlighted in blue.

Manual corrections of a part of the glacier lake outline was necessary for ca. 1/3 of the lakes in the entire lake inventory. This was mainly due to shadowing, glacier ice, and lake ice cover that were erroneously mapped as water pixels (Figure 10). Water outflow from the glacier lake may also need to be corrected for, if it is connected to the lake itself. Missclassified water polygons such as seen east of the Tunsbergdalsbreen lake (Figure 10) that are due to shadowing, snow, ice cover, or cloud cover were filtered out from the lake outline dataset.

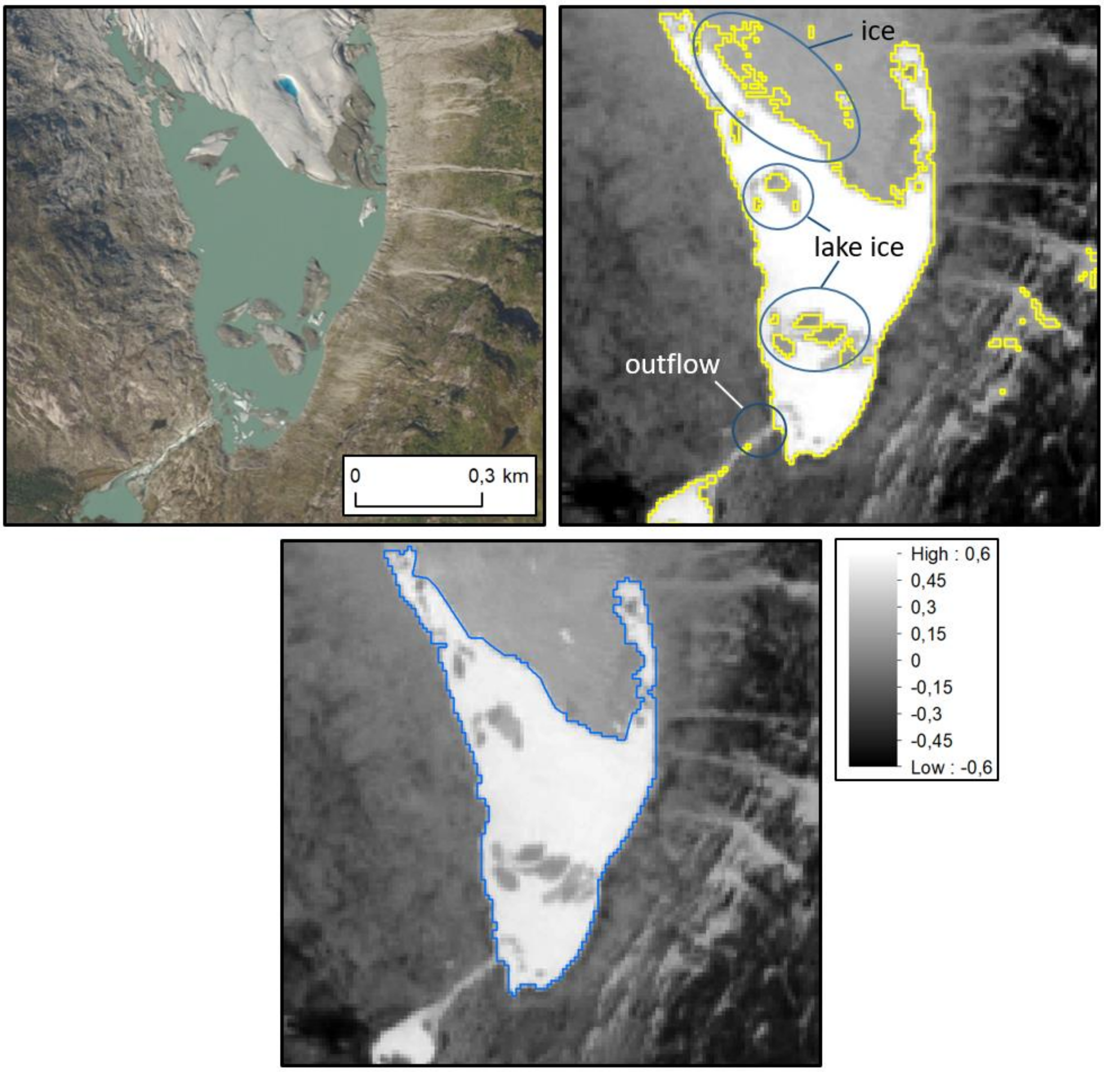

Figure 10: Orthophoto of Tunsbergdalsbreen glacier lake from 26/08/2017 and corresponding NDWI map from 26/07/2018 (with T0.23 outlines in yellow) used for the glacier lake outline mapping in the inventory. The areas where manual correction due to lake ice and glacier ice was needed are highlighted in blue. In the case of Tunsbergdalsbreen proglacial lake, no correction for the lake outflow was necessary as the river outlet was not connected to the lake polygon. Corrected lake outline is shown in blue. See Figure 1 for location.

3.4.2 Variability of NDWI

The NDWI values varied for lakes in the same region, and within the same image. This can be caused by the different depth of the water, lake sedimentation, and cloud and atmosphere conditions. Maximum NDWI values of 0.40-0.70 are common for most of the lakes throughout the inventory. Figure 11 illustrates similar NDWI values in a range of 0.55-0.63 for the same subset of the lakes from southern Jostefonni.

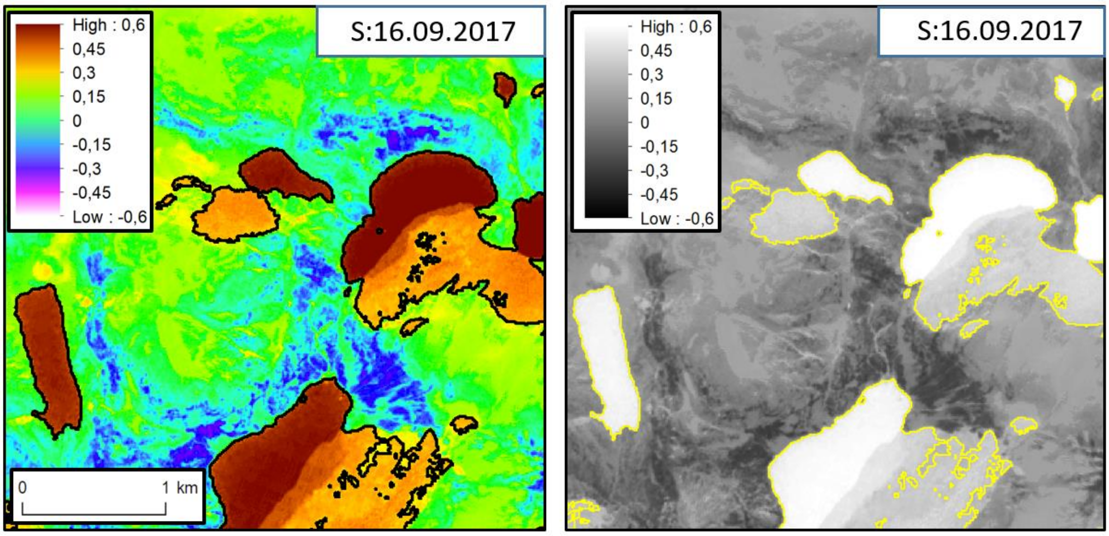

Figure 11: Colourcoded and non-colourcoded NDWI map of southern Jostefonni lake subset from 16/09/2017 illustrating relatively uniform NDWI values (dark brown) of the lake subset with a range of ca. 0.55-0.63. See Figure 7 for location.

The calculated NDWI maps revealed that values can vary within a single lake. This can be due to different water depth in the lake. The NDWI values of Lake 3 (L3) vary from ca. 0.43-0.50 in shallow areas to ca. 0.60-0.63 where there is no visible bedrock or sediment under the water surface (Figure 12).

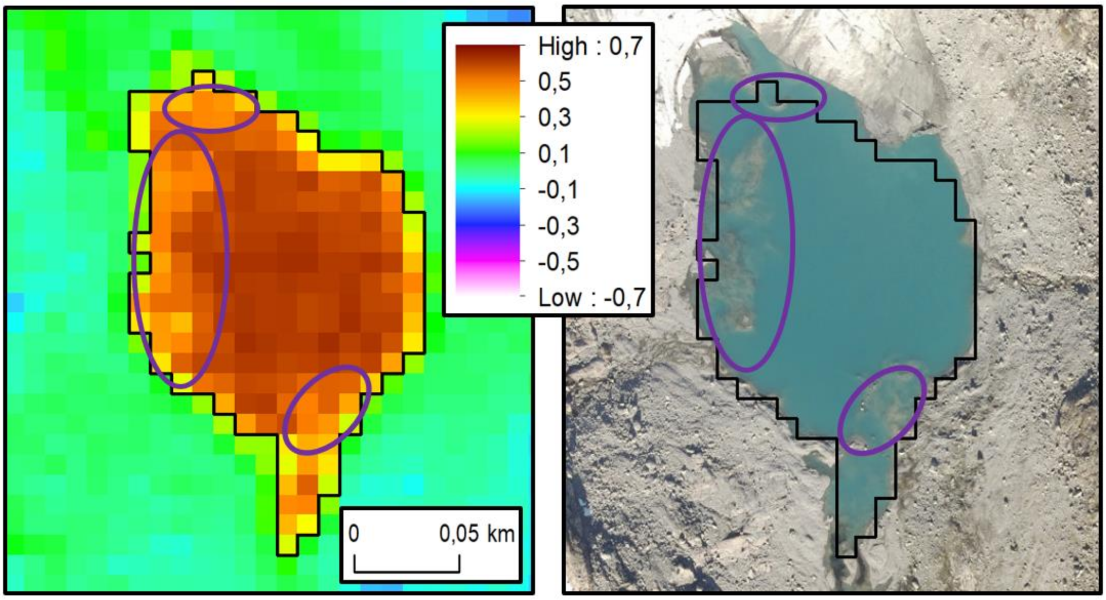

Figure 12: NDWI map from Sentinel-2 image from 16/09/2017 and orthophoto from 23/09/2017 of Lake 3 (L3) revealing contrasting NDWI values in the area of shallow water highlighted in purple elipses, with visible underlying bedrock or underlying sediment forms. Lake outline in black was calculated using T0.23. The relative positional accuracy of the orthophoto to the Sentinel-2 acquisition was ca. 5-10m. See Figure 7 for location.

In addition to spatial variations in lake NDWI, temporal variations were also found. For the Tunsbergdalsbreen proglacial lake, the NDWI fluctuated from 0.55 to 0.65 using images from 27/08/2017, 16/09/2017 and 26/07/2018 (Figure 13). The temporal variation can, similarly to the spatial variation, be caused by changed water turbidity, sediment load, water depth, and atmosphere conditions. Since most of the water bodies have NDWI values in a range 0.40-0.70, our threshold value of 0.23 used in the mapping of lakes is low enough to include the majority of the water bodies.

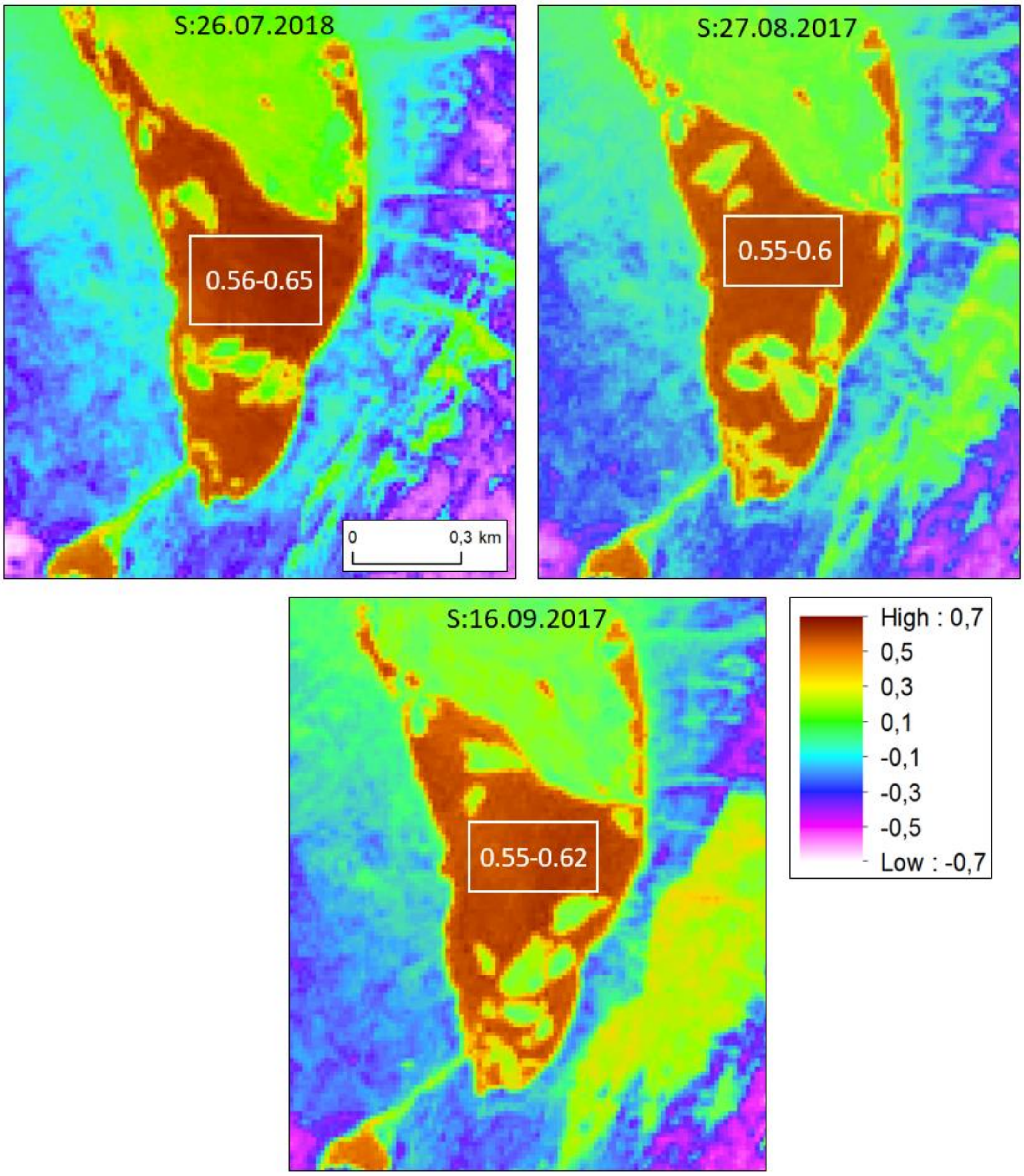

Figure 13: Three colourcoded NDWI maps of Tunsbergdalsbreen glacier lake illustrating temporal variation of the NDWI. The maximum NDWI over the water surface is shown to fluctuate by up to 0.05 points, when the index maps from 26/07/2018 and 27/08/2017 are compared. See Figure 1 for location.

To further assess suitability of threshold T0.23 for the inventory, a time series of the NDWI maps from 2018 was used. NDWI was calculated over the region west of Hardangerjøkulen ice cap, containing a lake subset (test region 2) of seven lakes (L10-L16) (Figure 14). The imagery selected for the analysis had minimal cloud, snow and lake ice cover (Figure 6). Four images in the period 13/07/2018-03/09/2018 were used. Lake area of all seven lakes was observable except for two cases. The first one being cloud coverage over part of lake L16 in 28/07/2018 acquisition and the second one being the lake L12 (Nedre Demmevatnet) that was empty in acquisition on 03/09/2018. Manual correction was needed to adjust for terrain induced shadowing affecting NDWI values in the acquisition from 03/09/2018 over lake L15 and at the ice-water interface of Nedre Demmevatnet (L12) in acquisitions from 13/07/2018 and 28/07/2018 (Figure 15). Percentual variation between the smallest and largest observed areas for each lake using a consistent threshold value ranged from 1.5 to 6.2% with an average percentual difference of 3.1% (Table 3). No trend in dates with largest observed area was detected. All but one of the lakes from 13/07/2018 were spatially smaller than the calculated areas from other three images. This is likely due to residual snow or ice cover over lakes, which marginally increased the omission of the water pixels. The images from 28/07/2018 and 03/09/2018 used for the evaluation were not available as corrected images with DTERRENGDATA resulting in positional differences of calculated lake outlines (Figure 15).

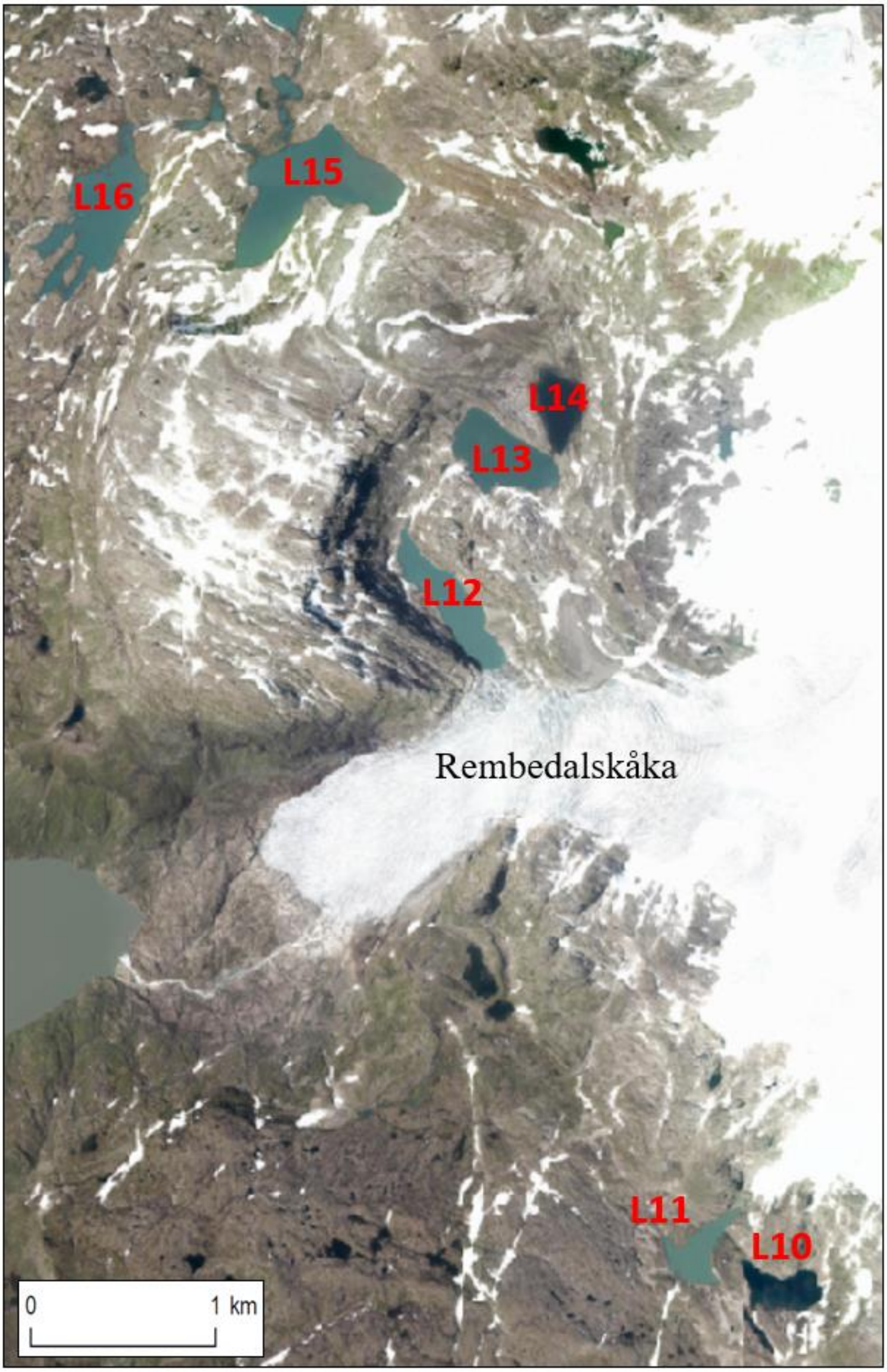

Figure 14: Orthophoto from 20/07/2013 depicting the location of lakes L10-L16 in test region 2 and the western part of the Hardangerjøkulen ice cap with Rembedalskåka glacier tongue. See Figure 1 for location.

Table 3: Calculated area of lakes L10-L16 and percentual variation of the smallest (in blue font) and largest areas (in red font) for each lake acquired by using T0.23 in a time series of NDWI maps from 2018 over the test region 2 (Figure 14). N/A stands for not applicable / no data.

Lake	% difference	03/09/18 (km^2)	28/07/18 (km^2)	20/07/18 (km^2)	13/07/18 (km^2)
L10	4.00	0.0650	0.0646	0.0635	0.0624
L11	6.18	0.0668	0.0680	0.0658	0.0638
L12	3.24	N/A	0.1428	0.1414	0.1382
L13	2.34	0.1368	0.1354	0.1342	0.1336
L14	1.72	0.0746	0.0757	0.0750	0.0744
L15	3.02	0.2949	0.2947	0.2910	0.2860
L16	1.50	0.2103	N/A	0.2135	0.2116

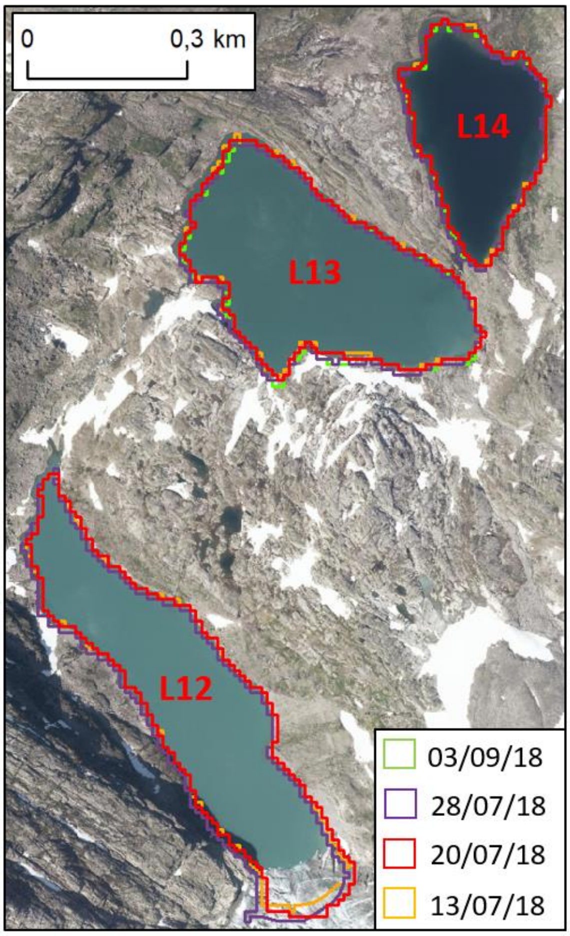

Figure 15: Variation of the glacier lake outlines L12-L14 in test region 2 acquired with threshold T0.23 over a time series of NDWI maps from 2018. Background high resolution orthoimage is from 20/07/2013. Ice-lake boundary was manually corrected for NDWI maps from 13/07/2018 and 28/07/2018. See Figure 14 for location.

3.3.3 Lake inclusion criteria

Only lakes that are coupled with, or decoupled from, glacier units larger than 0.25km^2 were included in the inventory. This is to avoid inclusion of the lakes located by small ice fields, ice patches or glacier remnants, which pose little or only theoretical danger of increasing in size and emptying. In the inventory, we included all lakes larger than 0.001km^2 (1000m^2) that are within ca. 100m of the glacier perimeter. This is to ensure that the recently decoupled lakes that are still in the proximity of the glacier were also included in the inventory to be able to compare results with previous and future lake inventories. If a smaller distance is wanted for an analysis, or only lakes that are coupled with glaciers are of interest, this is easy to reselect and filter in a GIS. Lakes that are spatially smaller than 1000m^2 (10 pixels) are difficult to reliably identify in both colour image and NDWI map of the area. However, our low size limit ensures inclusion of many small glacier lakes (Figure 16). No upper limit of lake size was used.

Figure 16: The lake in front of Storbreen is an example of a small glacier lake formed by glacier retreat. The size in 2018 as mapped from Sentinel-2 imagery was ca. 0.0015km^2 (1500m^2). The glacier retreated further 10-20m to 15/08/2019 when this photo was taken and where the distance across the lake was ca. 24m. The lake was categorized as a glacier lake in contact with the ice perimeter (cat. 2). Photo: Liss M. Andreassen.

4 Results

In total, more than 400 lakes were included in the 2018 glacier lake inventory. All lakes were visually inspected and categorized based on glacier-lake contact and nature of damming. (Table 4). Although we also mapped glacier lakes not in a direct contact with ice, our categorization allows for reselecting glacier lakes that are coupled with glaciers.

Table 4: Categorization used for assessment of glacier lake coupling and damming nature.

Category	Definition
1	Lake decoupled from glacier, but within ca. 100m of glacier perimeter
2	Lake is coupled with glacier
3	Lake is coupled with glacier and dammed by glacier ice
4	Lake is coupled with glacier and dammed by moraine
5	Lake is a regulated dam with artificial water level
6	Supraglacial lake – water body on top of the glacier

To categorize the lakes, we used: a) available orthophotos from years 2013-2018 at high 0.25-0.50m ground resolution and the DEM derived from them provided by norgeibilder.no; b) the DEM for mainland Norway; c) colour Sentinel-2 imagery from given dates; d) dataset of lakes with a previous history of GLOFs in mainland Norway (Jackson and Ragulina, 2014). Out of 414 lakes, 327 lakes (ca. 79%) were found to have an interface with the glacier ice, of which 39 lakes were found to be glacier dammed. There were also two moraine dammed lakes and one supraglacial lake mapped. There may be more supraglacial lakes, however they are often too small to be identified and mapped. The final dataset contains the area and perimeter of the lakes, lake category, as well as information on the image used and data processing. As example of how lakes were categorized, lakes L1 and L3 were classified as coupled with glacier with neither ice nor moraine damming. Lake L2 was defined as decoupled from the glacier, but lying within ca. 100m from the ice perimeter at the time of mapping (Figure 17).

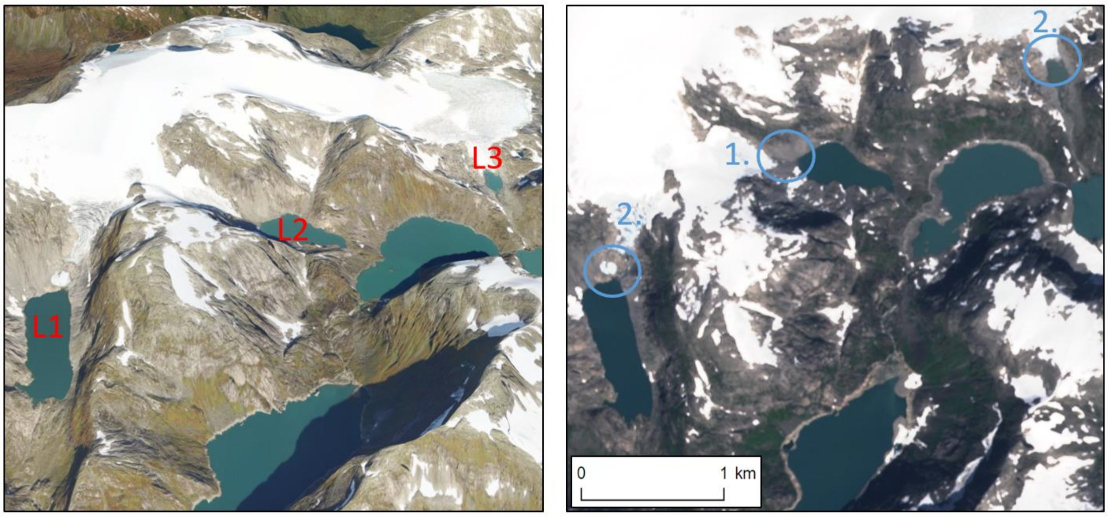

Figure 17: A 3D representation of high resolution orthoimage from 23/09/2017 over the lake subset from southern Jostefonni illustrating that the lakes L1-L3 (in red font) were neither dammed by ice nor moraine. The Sentinel-2 color image from 26/07/2018 used for the NDWI inventory calculation illustrates the coupling state of the three classified lakes in blue. The first category (decoupled) lakes are marked by 1. (in blue font) and the second category (coupled with glacier) marked by 2. (in blue font). See Figure 7 for location.

An example of a glacier dammed lake is lake L7 of Marabreen, which drains to lake L8 (Figure 18).

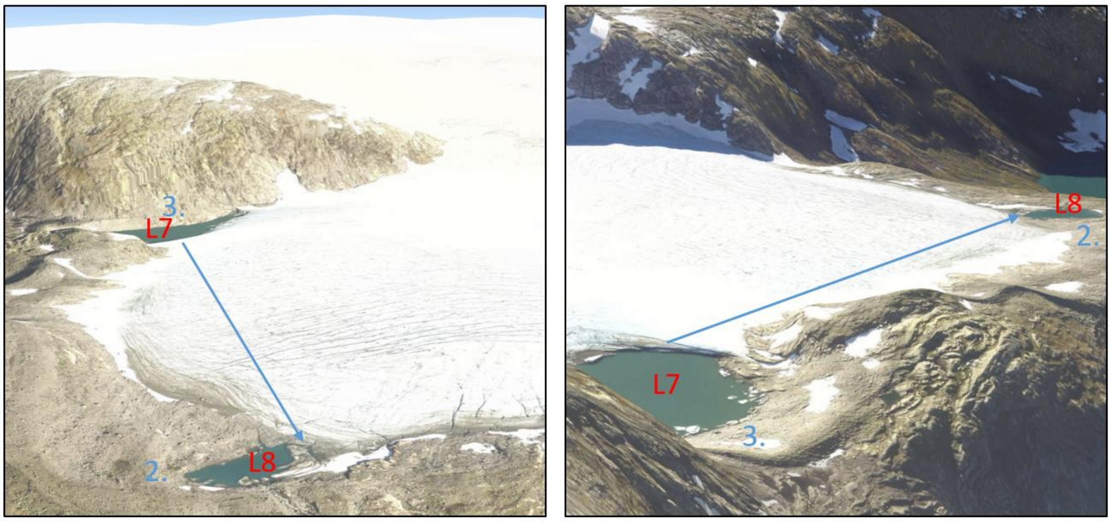

Figure 18: A 3D representation of high resolution orthophoto from 16/09/2017 showing glacier dammed lake L7, dammed by Marabreen glacier, and a likely drainage path to lake L8. Lake L7 is glacier dammed (3.) and lake L8 is a proglacial lake in contact with ice (2.). See Figure 7 for location.

4.1 Glacier and moraine dammed lakes

Lakes dammed by either moraine or ice can lead to GLOFs, which have a destructive potential. There exists a good record of the GLOF events, which has been summarized by Jackson and Ragulina (2014) with NVE updates that are available from http://glacier.nve.no/Glacier/viewer/GLOF/en/ (NVE, 2019). Analysing the Sentinel-2 satellite imagery for the period 2015-2019 and available high-resolution orthophotos revealed further events (Table 5, Figure 20). In total, eleven sites displayed evidence of emptying in the Sentinel-2 imagery (Table 5). In addition, further seven sites were identified, where no water bodies were seen on the Sentinel-2 imagery, but with a potential of filling up (Table 5).

The example lakes with a history of frequent jøkulhlaups are Nedre Demmevatnet, dammed by Rembedalskåka, an outlet of Hardangerjøkulen and Øvre Messingmalvatn, dammed by Rundvassbreen, part of Blåmannsisen. Figures 21 and 22 show pre and post-event imagery for the four events that occurred. Based on eye witness account and water level data provided by Statkraft from Rembedalsvatnet, a regulated lake downstream of Nedre Demmevatnet, the 2018 event of Nedre Demmevatnet happened on 10/08/2018. Out of 14 images taken between 28/07/2018 and 03/09/2018, none showed the complete lake perimeter due to the persistent cloud coverage throughout August (Figure 6).

The emptying of Øvre Messingmalvatn was recorded by SISO Energi and was estimated to have started on 25/08/2018. The closest pre and post event imagery with partly distinguishable lake outlines came from 14/08/2018 and 26/08/2018 respectively. Thus, glacier lake emptying can be observed from Sentinel-2 imagery, but whether there is good imagery available close to time of the event depends mainly on the cloud cover. Many GLOF events occur in late summer, when clouds are persistent, and Sentinel-2 imagery may give little or no information. Sentinel-1 imagery can be a good supplementary source that can be used to provide more information on timing of glacier lake emptying.

A glacier with a recent event was Nupsfonn (ID 3075). This glacier had an outburst flood on 24/08/2019 with a roughly estimated drainage of 8-10mill m^3 water and a ~10 m lowering of the lake (Axel Lang Jørgensen, Statkraft, personal communication, September 2019). Sentinel-2 imagery of 04/08/2019 and 27/08/2019 revealed that the two largest lakes were smaller on 27/08/2019, after the event, but had not completely emptied (Figure 19). Thus careful assessment of imagery is needed to detect events where lakes are only partially emptied.

Figure 19: Upper image: Nupsfonn glacier with its glacier dammed lakes on 27/08/2019. Photo: Axel Lang Jørgensen/Statkraft. Lower imagery: Sentinel-2 imagery of Nupsfonn prior to and after the event as viewed in NVE's expert tool xGeo. Lowering of the water level can be observed in areas highlighted in red. Lake area outlines (in blue) were calculated from 2018 imagery.

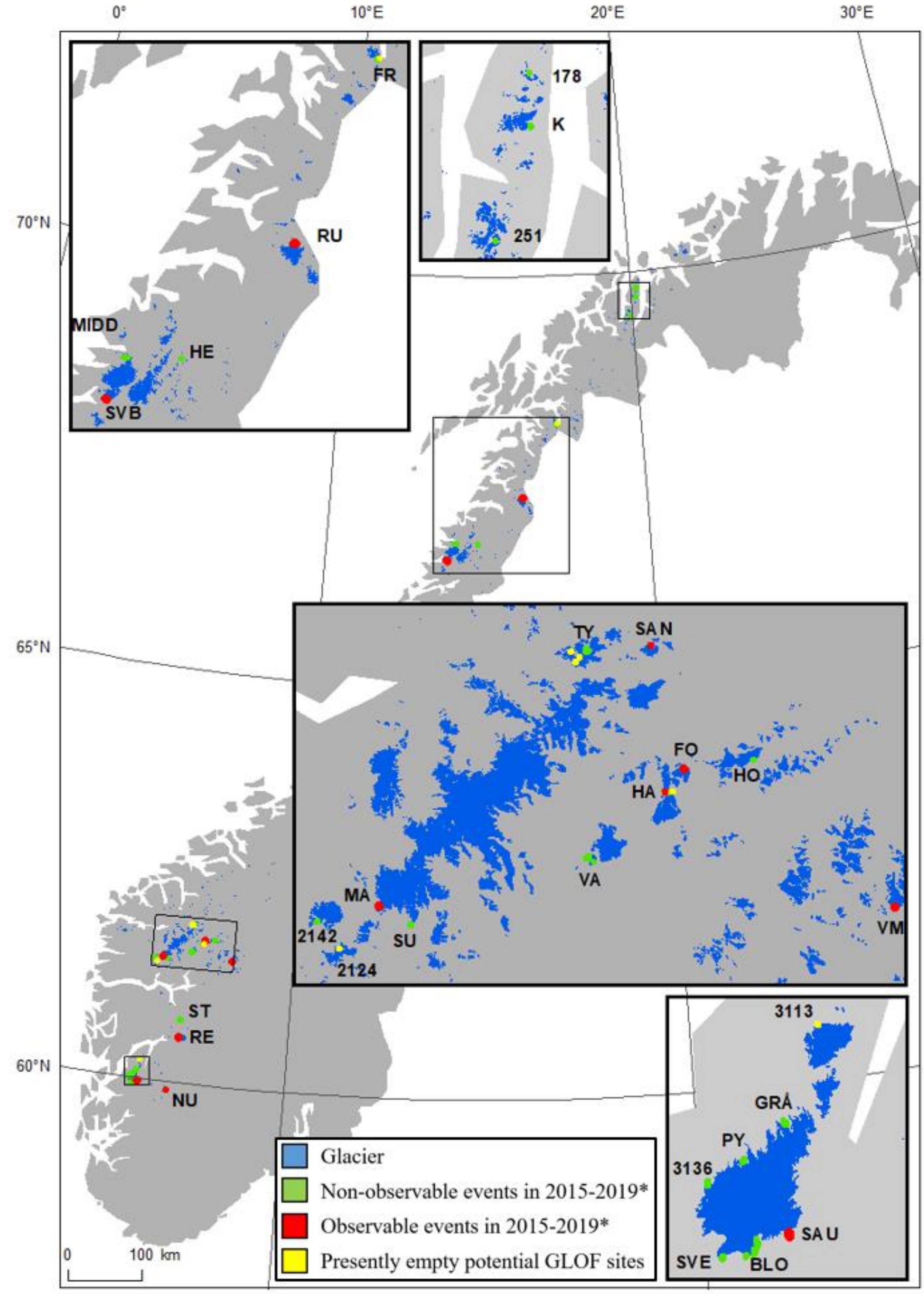

Figure 20: A map of Norway showing distribution of identified glacier and moraine dammed lakes in the present glacier lake inventory. Seven additional presently empty sites, where filling up is considered possible, are also identified. For abbreviations see Table 5. Green: No observable emptying was recorded in the period 2015-2019*. Red: At least one observable event was recorded in the period 2015-2019*. Yellow: No water body was detected but there is a potential for filling up of the space with water. *Last image of observation was 23/07/2019 (later imagery from 2019 was used for Nupsfonn, Rembedalskåka, and Rundvassbreen).

Table 5: Identified sites with glacier and moraine dammed lakes and activity assessment for the period 2015-2019 (until 23/07/2019). Later imagery (until 11/09/2019) was used to observe events at Nupsfonn, Rembedalskåka, and Rundvassbreen. The glacier ID (Andreassen et al., 2012) and site name refer to the glacier unit bordering identified lakes. 'Potential lake no.' lists areas with no observable lake but with a potential for filling up. Pre and post event image dates are the closest images, where event is observable.

ID	Glacier site	Abbre-viation	Lake no	Potential lake no.	Observa-ble event	Pre and post event imagery dates
178	V Vaggasblåisen	178	1	0		
205	Koppangsbreen	K	1	0		
251	Midtbreen	251	1	0		
752	Frostisen	FR	1	1		
941	Rundvassbreen	RU	1	0	x	15/09/2016-08/10-2016, 14/08/2018-26/08/2018, 08/09/2019-11/09/2019
1080	Middagstuvebreen	MIDD	1	0		
1135	Svartisheibreen	SVB	1	0	x	26/08/2016-28/09/2016
1260	Hengfjellbreen	HE	1	0		
2124	Jostefonni	2124	1	0		
2142	Grovabreen	2142	0	1		
2352	Supphelbreen	SU	1	0		
2364	Marabreen	MA	1	0	x	27/08/2018-01/09/2018
2434	Sandåbreen	SAN	1	0	x	23/07/2016-22/08/2016, 23/07/2017-22/08/2017, 20/07/2018-23/07/2018, 02/08/2019-05/08/2019
2435	Tystigbreen	TY	3	3	x	22/08/2017-16/09/2017
2509	Fortundalsbreen	FO	1	0	x	20/07/2017-22/08/2017, 13/06/2018-26/06/2018, 28/06/2019-10/07/2019
2514	Harbardsbreen	HA	1	1	x	21/08/2015- 10/09/2015
2532	Vanndalsbreen	VA	2	0		
2564	Holåbreen	HO	1	0		
2772	Vestre Memurubreen	VM	1	0	x	20/07/2017-22/08/2017, 13/07/2018-28/07/2018
2852	Storskaulen	ST	3	0		
2968	Rembedalskåka	RE	1	0	x	22/08/2016-08/09/2016, 18/10/2017-02/11/2017, 28/07/2018-03/09/2018, 09/08/2019-27/08/2019
3075	Nupsfonn	NU	4	0	x	04/08/2019-27/08/2019
3113	N Folgefonna	3113	0	1		
3127	Gråfjellsbrea	GRÅ	2	0		
3132	Pyttabrea	PY	2	0		
3136	3136	3136	1	0		
3137	Svelgjabreen	SVE	1	0		
3141	Blomstølskardsbreen	BLO	5	0		
3142	Sauanutbreen	SAU	2	0	x	08/09/2016-18/09/2016
Sum			42	7	11	

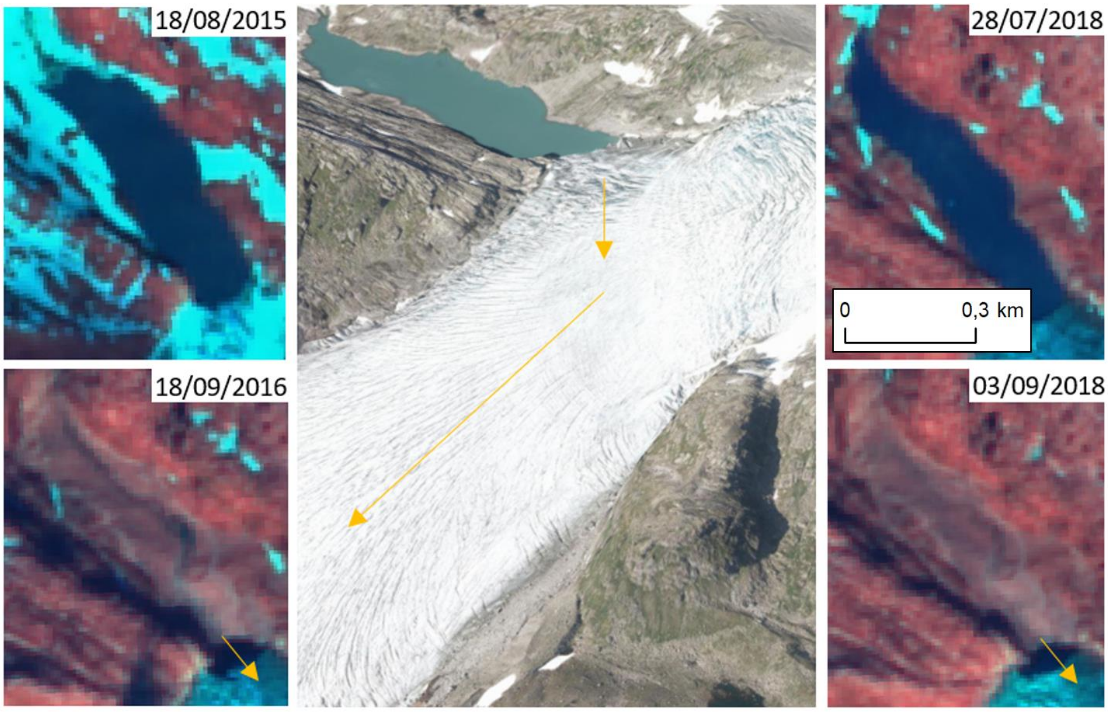

Figure 21: GLOF events (jøkulhlaups) of Nedre Demmevatnet in 2016 and 2018. A pre and post-event Sentinel-2 false colour imagery is shown together with a 3D representation of an orthophoto from 20/07/2013. Yellow arrow approximates the likely drainage path. See Figure 1 for location.

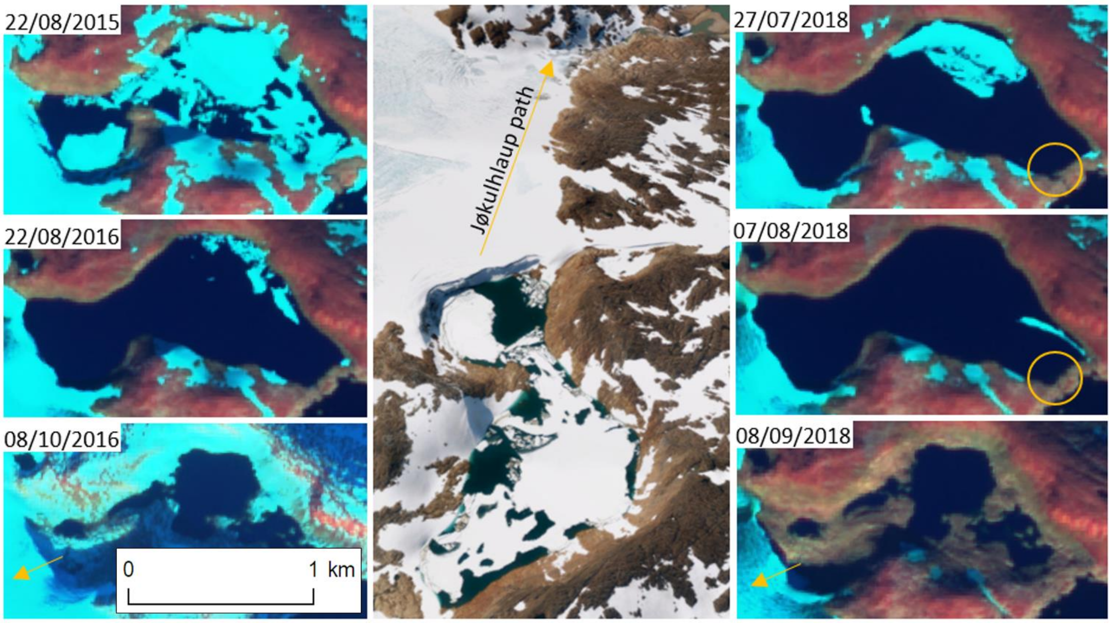

Figure 22: GLOF events (jøkulhlaups) of Øvre Messingmalvatn represented by Sentinel-2 false colour imagery and a 3D representation of an ortophoto from 16/08/2015. Yellow arrow approximates the likely drainage path. Lake filling in the 10 day period 27/07/2018-07/08/2018 is illustrated by the yellow circle. See Figure 1 for location.

To calculate the theoretical minimum lake surface fluctuation that can be observable with some degree of confidence, a median size inventory lake of 0.0185km^2 can be approximated as a circle with radius r2. Assuming a 4% inaccuracy in the inventory, the difference between the second circle with radius r1 representing a median size inventory lake with an additional error of ±4% of 0.0192km^2 area is found to be ca. 1.5m (Figure 23). Using the 1.5m horizontal distance, the minimum lake water level decrease or increase that can be observed for the lake slopes of 45, 30 and 15 degrees is 1.5, 0.87 and 0.40m respectively. Using the calculated area of Nedre Demmevatnet from 28/07/2018, and assuming the average lake sloping of 15 degrees, the minimum water filling up of ca. 57000m^3 would need to occur for the filling up to be theoretically observable. This represents ca. 3% of the maximum lake volume, based on the estimated water volume 1.85mill m^3 from the 2016 emptying event.

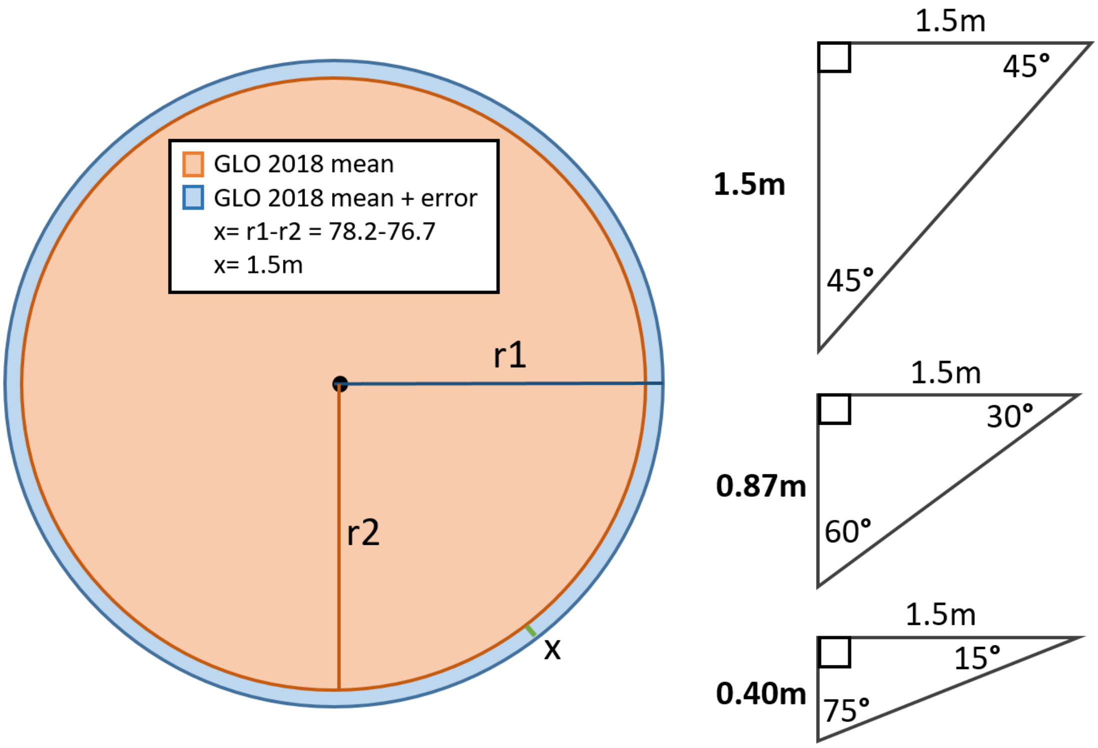

Figure 23: Theoretical approximation of a difference between a mean size inventory lake with radius r2 and a mean size inventory lake with estimated inventory inaccuracy of 4% with radius r1. Three triangles show the lake level fluctuation (in bold) for 15, 30 and 45 degree sloping lakes that cannot be observed with confidence using an inaccuracy of 4%. Figure is an approximation.

4.2 Lake change

Until 2018, three glacier lake outline inventories were produced using imagery from Landsat 5, 7 and 8 missions. The number of the lakes mapped is lower in the current inventory (414) than in the previous one (636) that was based on manual digitization of Landsat 8 imagery from 2014. This is partly due to different lake inclusion criteria in our mapping. Although we had a longer distance to glacier termini (100m) than the 2014 inventory (50m), the 2014 inventory used the glacier outlines from 1999-2006 as reference and the glacier retreat has been substantial in many regions. Thus, fewer lakes may be included when using updated glacier outlines or stricter criteria. The first two inventories were made using Landsat 5 and Landsat 7 imagery. Given a coarser ground resolution of 30m and limited availability of high resolution orthophotos, the errors in the inventories will naturally be larger than when using Sentinel-2 acquisitions at 10m resolution and an archive of high resolution orthoimagery. When using imagery of 30m resolution, it is more difficult to identify the lakes and accurately map and categorize them, leading to higher uncertainty in the products. Lakes can be left out or be erroneously included. In order to compare the results of the 1999-2006 lake outline inventory conducted by semi-automatic lake outline digitization, we used high resolution imagery from 16/09/2006 in test region 1 acquired on the same date as the Landsat 5 image used for the inventory. Lake L3 was omitted in the 1999-2006 inventory. The lake was smaller in 2006 and that could have led to its omission. The underestimation in lake areas was ca. 16% for L1 and ca. 30% for L2. For the comparison of the lake outline inventory from 2014, Google Earth high resolution imagery from 17/09/2014 was used in test region 1. The lake outlines in the inventory were calculated using the Landsat 8 image with a two day temporal difference from 15/09/2014. We found that the lake area was underestimated by 7% for L1, 18% for L2, and 20% for L6. These differences likely stem from coarser resolution of Landsat 8 imagery.

To assess changes in extent of the 414 lakes that were included in the 2018 lake inventory, the 2018 lake outlines and the most recent orthophoto (from 2013-2018) were compared to the oldest corresponding orthophoto. If orthophotos were not available or of not sufficient quality, earlier Sentinel-2 imagery from 2015-2018 was used to assess the change. The oldest orthophotos used for the lake change assessment were from 2004 and covered the region of Jotunheimen. Each glaciated region of Norway is covered by 2-5 available orthoimages. The assessment of change in glacier lake area was subjective and based on visually observable changes in the lake surface extents only (Table 6). No quantifying of the areal difference was made.

Table 6: Categorization of lakes based on observable change in lake extent.

Category	Number of lakes	Definition
1	163	Lake area has increased
2	46	Lake area appears to have stayed unchanged
3	119	Lake area change could not be determined
4	83	Lake is new, no lake could be observed previously
5	3	Lake is regulated and its area fluctuates artificially

The date of the earlier image used for the change estimation was marked in the attribute table of the final glacier lake outline product. If a lake’s change could not be determined, (category 3), e.g. due to lake ice and snow cover, the earlier image date was not provided.

In total, 163 lakes were found to have increased in size, and 46 lakes were found to have stayed unchanged (Figure 24). Further 83 new lakes were found to have formed. There were three regulated lakes mapped in our inventory, such as Styggevatnet (Figure 25). The size change of 119 lakes could not be determined, e.g. due to lake ice or snow cover (Figure 25) The glacier lakes that were classified as glacier dammed and with a history of GLOFs were also categorized as not possible to provide observable change (category 3). This is due to periodic filling and emptying of the lakes.

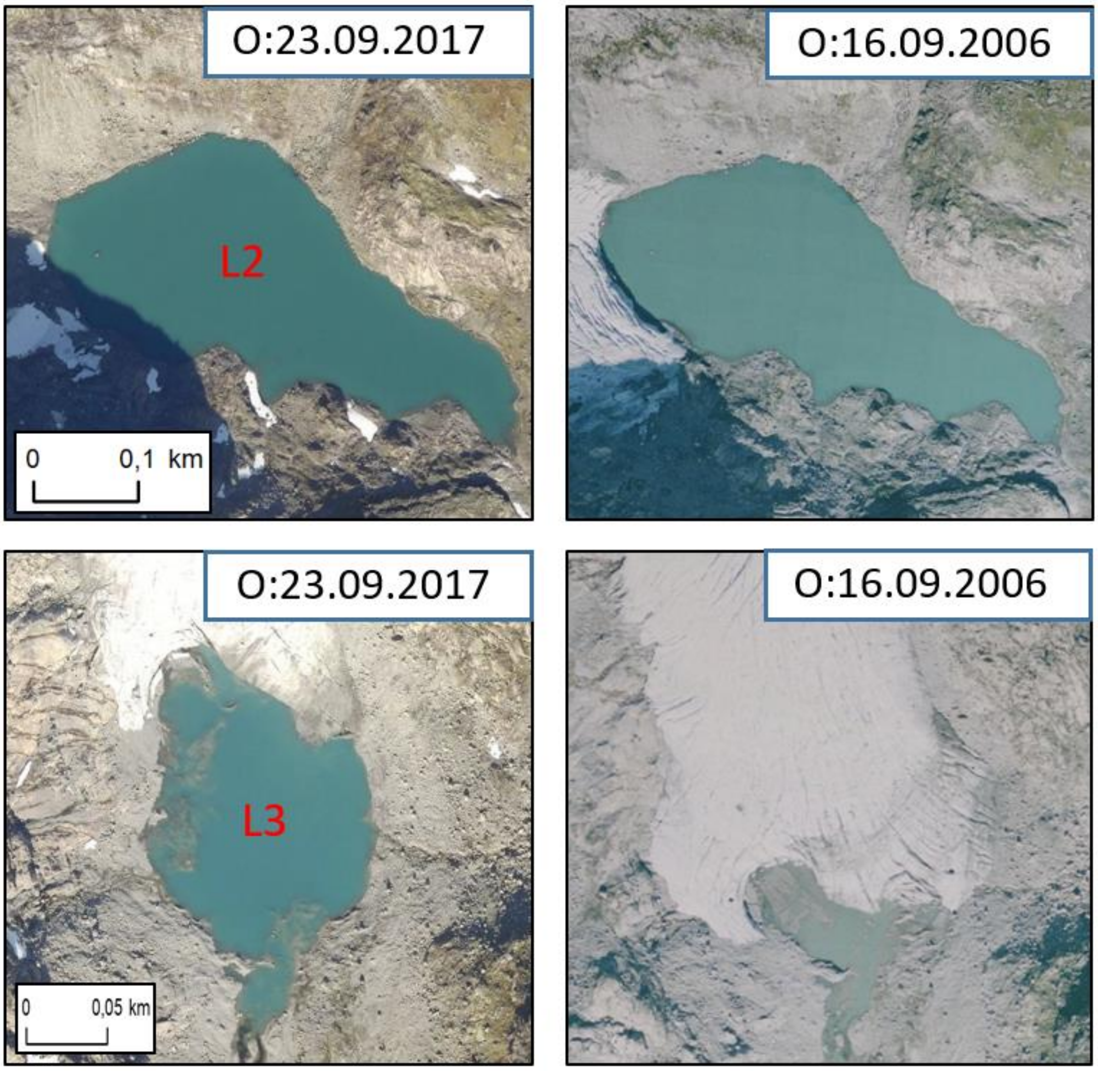

Figure 24: Illustration of lake area change categorization using high resolution orthoimagery from norgeibilder.no over the lake subset from southern Jostefonni. Upper photos show lake L2 that appears to have stayed constant despite glacier retreat and is categorized as (2): Lake area appears to have stayed unchanged. Lower photos show lake L3 has increased due to glacier retreat and was categorized as (1): Lake area has increased. See Figure 7 for location.

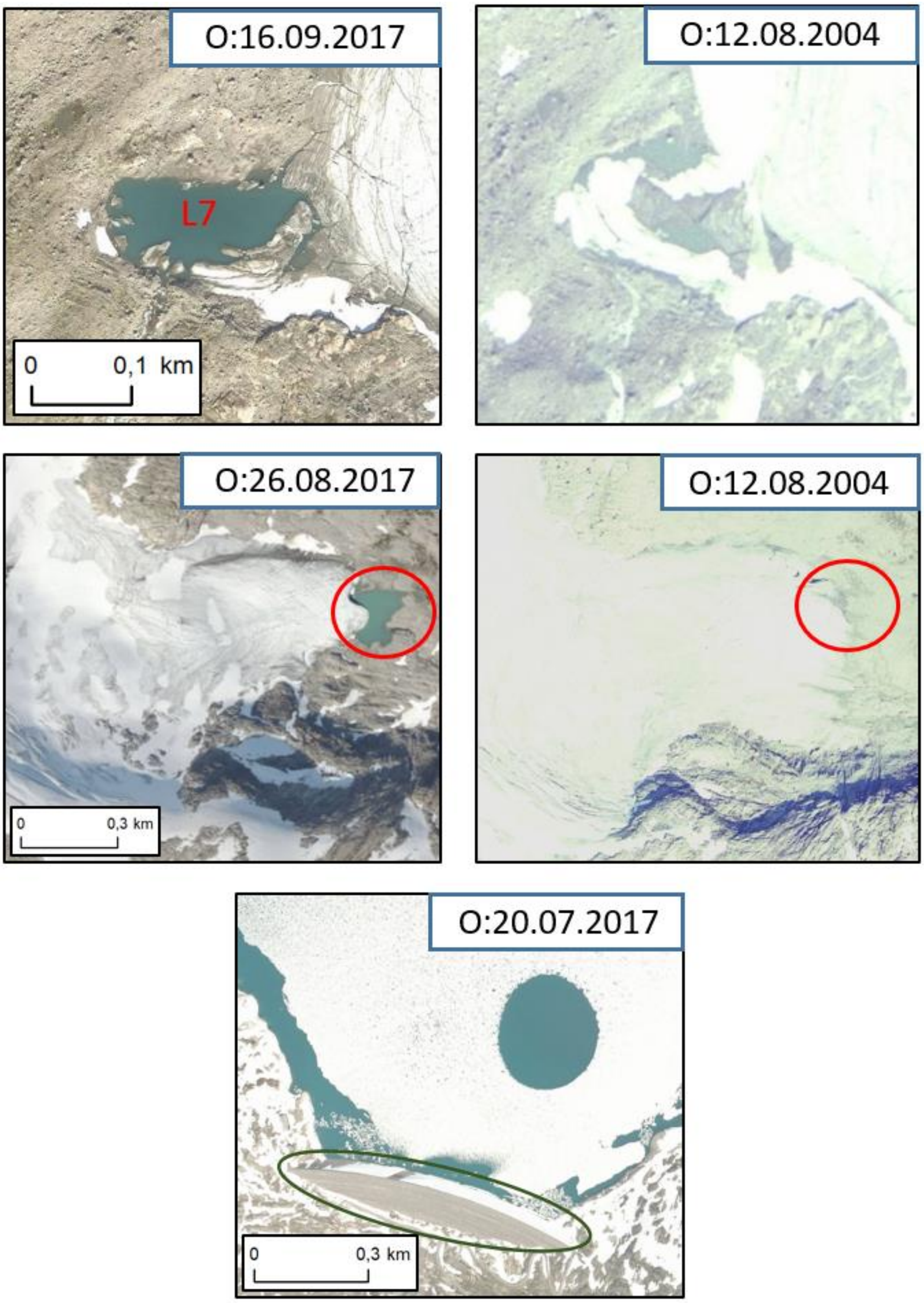

Figure 25: Illustration of lake area change categorization using high resolution orthoimagery from norgeibilder.no. Upper photos: show Lake L7 (dammed by Marabreen glacier) that was categorized as (3): Lake area change cannot be determined. Mid row photos show glacier (ID 2345) with lake in red circle that was categorized as (4): New lake, no lake observed previously. Lower photo shows Styggevatnet in front of Austdalsbreen that is an artifically regulated water body with the dam structure highlighted in green. Lake was categorized as (5): Regulated lake, fluctuates artificially. See Figure 7 and Figure 1 for location.

5 Conclusion and further work

A glacier lake outline dataset for mainland Norway has been derived using freely available Sentinel-2 satellite imagery of 10m ground resolution from 2018. In total, 414 lake outlines within ~100 m of the 2018 glacier perimeter were mapped. The lakes were subcategorized based on the proximity to the ice interface and the nature of damming. In total, 327 lakes were identified as having direct ice contact, whereof 41 lakes were glacier or moraine dammed and one was supraglacial. Emptying events were observable in Sentinel-2 imagery at eleven sites in the period 2015-2019. The frequency of the imagery and the cloud conditions determine how well each event can be observed.

The glacier lakes outlines were mapped by calculating Normalized Difference Water Index (NDWI) maps and applying a threshold. The threshold value had to be high enough to differentiate between ice and water, but also low enough to minimize the omission of the water pixels. The threshold was optimised in a test region using high resolution orthophotos from 2017 from the same date or seven days apart from the Sentinel-2 image. The lake subset for testing and validation was selected so that it contained lakes of varying sizes, varying proximity to the glacier ice, and varying damming nature. An analysis of a subset of nine lakes (L1-L9) indicated an overall uncertainty of ±4% using a threshold value of 0.23. About 1/3 of the lake outlines had to be manually corrected, mainly in areas influenced by shadow and on the water-ice interface.

The threshold value T0.23 was further assessed using a lake subset west of Hardangerjøkulen ice cap. The time series of NDWI maps from 2018 was used to observe the variation among the lake subset areas using the same threshold value 0.23 over Sentinel-2 imagery from four different dates. The percentual difference between the smallest and largest observed areas for each lake using a consistent threshold value ranged from 1.5 to 6.2%. The variation can be explained by residual snow or ice cover over lakes, possible fluctuations in water level, orthorectification errors, changes in lake colour due to varying turbidity and sedimentation, and varying cloud and atmosphere conditions.

A qualitative assessment of changes in glacier lake extents using high resolution orthophotos revealed an overall increase in lake areas and formation of new lakes. In total, 163 lakes were found to have increased in size, and 83 lakes were newly formed, where no water body was previously detected. This number could be higher as the areal change of 119 lakes could not be determined. The increase in glacier lake area and formation of new lakes is linked to the glacier retreat in the past decade, which results in exposure of terrain overdeepenings immediately by the glacier margin, where new lakes can develop or grow. Further lake area increase can be expected given that the glacier retreat continues. The number of mapped lakes in any inventory, and the total area of them, will also depend on the inclusion criteria. The lakes that were mapped for the 2018 inventory and were (in 2018) ca. 100m away from the glacier perimeter may not be included in the next inventory if the same 100m, or a smaller, zonation criterion is applied, given that the glacier retreat continues.

Sentinel-2 imagery was shown to have a good potential to be used in Norway for monitoring and mapping the glacier lakes. For seven lakes with a history of jøkulhalup events in a S-N transect, there was an average of ca. 30 usable scenes per lake for the period 2015-2018, defined as where a perimeter of the lake and its area could be distinguished. We estimate that there can be on average ca. 10 Sentinel-2 images with observable lake perimeter every year. The main improvements in using Sentinel-2 for glacier lake outline mapping compared to Landsat imagery are: improved chances of having useful imagery due to a high revisit time of 1-3 days in Norway and freely available imagery of 10m resolution for the bands used for NDWI calculation. The main challenges in using Sentinel-2 imagery in Norway are cloud, snow, lake ice cover and terrain induced shadowing.

The new 2018 glacier lake outline inventory can be used as a baseline for monitoring glacier lakes and lake changes in mainland Norway. New glacier lake outline mapping can be performed when needed, either using NDWI as used here, or by manual digitisation from Sentinel-2 imagery. New high resolution (<1m) orthoimagery from Kartverket and Pleiades satellite imagery may be used for further validation of the current and future versions of the glacier lake inventory. Monitoring of glacier and moraine dammed lakes of interest can be done regularly, e.g. on a weekly basis using NVE's expert tool xGeo.no where colour composite Sentinel-2 imagery are available and can be displayed with lake outlines from the inventory and identified GLOF sites. In addition, the lake outline dataset will be useful for glacier mapping purposes to differentiate between glacier ice and glacier lakes when mapping glacier outlines.

6 Data availability

The lake inventory dataset will be available for viewing and downloading from the following sources (see www.nve.no/glacier as direct hyperlinks below may change):

- NVEs Breatlas (NVE's digital glacier inventory) displays different GIS datasets including glacier lakes: https://gis3.nve.no/link/?link=breatlas
- xGeo (NVE's expert tool for notification and emergency) displays satellite imagery along with glacier lakes and other glacier products: http://satellitt.xgeo.no/index.html?p=bre (Figure 26).
- The Copernicus Glacier Service gives information on the project and links for data download: https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/

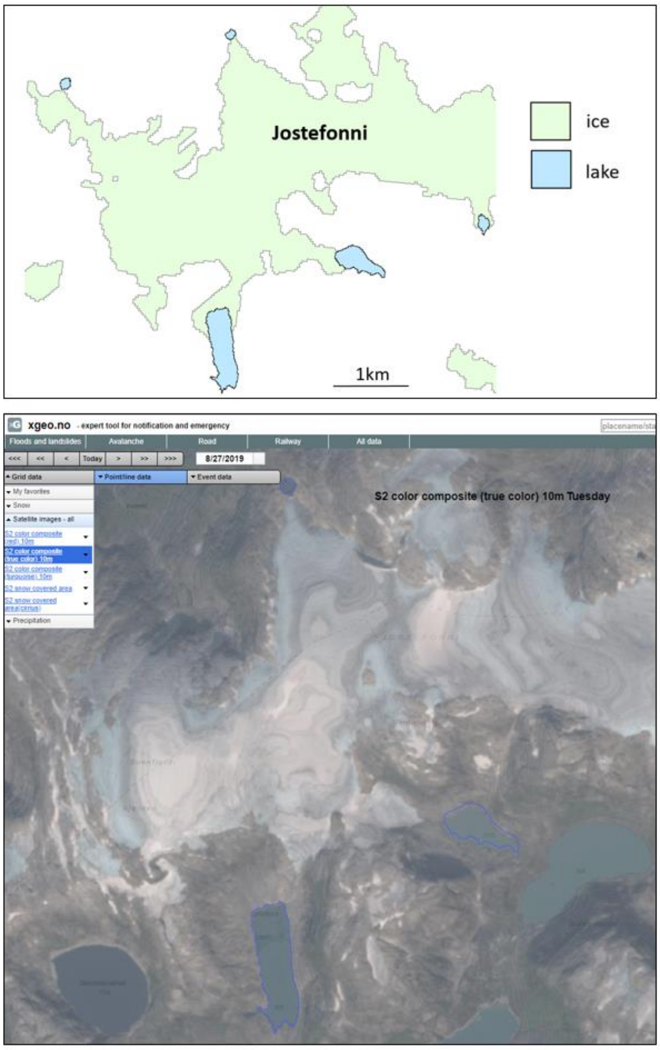

Figure 26: Upper figure shows the downloadable glacier lake outline product featuring lakes L1-L5 by Jostefonni glacier from test region 1 (See Figure 1). Glacier outline is from Andreassen et al. (2012). Lower figure shows the glacier lake outlines (in blue) displayed on a background Sentinel-2 image from 27/08/2019 as visualized in xGeo.

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Appendix A

Table A1: List of Sentinel-2 images for the period 2015-2018 over seven glacier lake sites with previous GLOFs. The imagery is categorized based on its usefullness for glacier lake monitoring and outline mapping. Refer to page 17, chapter 3.3.1. for category explanation.

	I	I.s.	II	II.s.	III	III.s.	IV	IV.s.
Koppangsbreen sjø	15.08.2015		05.08.2015		17.09.2015			
	18.08.2015							
	19.08.2015							
	23.07.2016	30.07.2016	20.07.2016		30.06.2016		27.06.2016	
	22.08.2016	19.08.2016	24.07.2016					
		21.09.2016	22.09.2016					
		15.10.2016	25.09.2016					
		18.10.2016						
		21.10.2016						
		22.10.2016						
	16.08.2017	01.09.2017	04.08.2017		25.07.2017		22.07.2017	
	19.08.2017	05.09.2017	08.08.2017		27.07.2017		23.07.2017	
		07.09.2017			28.07.2017		24.07.2017	
		08.09.2017			29.07.2017		25.07.2017	
		16.09.2017					06.08.2017	
		20.09.2017					18.10.2017	
		26.09.2017						
		27.09.2017						
		28.09.2017						
		30.09.2017						
		01.10.2017						
		05.10.2017						
		10.10.2017						
		12.10.2017						
		13.10.2017						
		20.10.2017						
	10.07.2018	28.08.2018	02.07.2018		01.08.2018		14.08.2018	
	12.07.2018	01.09.2018	05.07.2018		18.08.2018			
	13.07.2018	05.09.2018			18.09.2018			
	17.07.2018	07.09.2018						
	18.07.2018	08.09.2018						
	19.07.2018	10.09.2018						
	22.07.2018	12.09.2018						
	27.07.2018	05.10.2018						
	22.07.2018	18.10.2018						
	28.07.2018							
	29.07.2018							
	08.08.2018							
	24.08.2018							
	26.08.2018							

Øvre Messingmalvatn			22.08.2015		15.08.2015		29.07.2015	
			25.08.2015		18.08.2015			
	29.08.2016	08.10.2016	20.07.2016		13.07.2016		30.06.2016	
		15.10.2016	23.07.2016				10.07.2016	
		18.10.2016	16.08.2016					
		21.10.2016	22.08.2016					
			26.08.2016					
			15.09.2016					
		08.10.2017	08.09.2017	26.09.2017	22.07.2017	03.10.2017	30.06.2017	
		10.10.2017	20.09.2017	28.09.2017	23.07.2017	26.10.2017	20.07.2017	
		11.10.2017	23.09.2017	30.09.2017	25.07.2017		07.08.2017	
		13.10.2017	25.09.2017	01.10.2017	28.07.2017		11.09.2017	
		15.10.2017		20.10.2017	04.08.2017			
				21.10.2017	06.08.2017			
					17.08.2017			
					19.08.2017			
					06.09.2017			
	01.09.2018	18.09.2018	15.07.2018		02.07.2018		20.07.2018	
	05.09.2018		17.07.2018		05.07.2018		23.07.2018	
	03.09.2018		18.07.2018		10.07.2018		15.10.2018	
	08.09.2018		27.07.2018		12.07.2018			
			28.07.2018		13.07.2018			
			30.07.2018		26.08.2017			
			01.08.2018		28.09.2018			
			02.08.2018					
			07.08.2018					
			14.08.2018					
Heivatnet			11.09.2015		15.08.2015		29.07.2015	
					18.08.2015			
					22.08.2015			
					18.08.2015			
					25.08.2015			
			16.08.2016		20.07.2016			
			22.08.2016		30.07.2016			
			26.08.2016		12.08.2016			
			15.09.2016		19.08.2016			
			28.09.2016		08.09.2016			
					08.10.2016			
					11.10.2016			
					15.10.2016			
					21.10.2016			
			04.08.2017		20.07.2017		02.08.2017	
			22.08.2017		22.07.2017		17.08.2017	

			24.08.2017		23.07.2017		26.08.2017	
			03.09.2017		25.07.2017		20.10.2017	
			20.09.2017		27.07.2017		28.10.2017	
			25.09.2017		02.08.2017			
			26.09.2017		06.08.2017			
			28.09.2017		16.09.2017			
			30.09.2017		23.09.2017			
			01.10.2017		05.10.2017			
			10.10.2017		08.10.2017			
					21.10.2017			
					23.10.2017			
	02.08.2018		17.07.2018		10.07.2018		02.07.2018	
	05.09.2018		20.07.2018		12.07.2018		26.08.2018	
	08.09.2018		27.07.2018		13.07.2018		21.09.2018	
			28.07.2018		18.07.2018		03.10.2018	
			07.08.2018					
Tystigbreen sjøer			21.08.2015		18.08.2015			
			10.09.2015					
			05.08.2016		23.07.2016		11.09.2016	
			22.08.2016					
			22.08.2017		11.07.2017		06.07.2017	
			25.08.2017		21.07.2017		07.08.2017	
			27.08.2017		23.07.2017		01.09.2017	
			16.09.2017		19.09.2017			
			26.09.2017					
			13.07.2018		01.07.2018		26.06.2018	
			16.07.2018		03.07.2018		18.07.2018	
			26.07.2018		07.08.2018			
Marabreen sjø							18.08.2015	
							21.08.2015	
							10.09.2015	
	04.09.2016		22.08.2016		23.07.2016		13.06.2016	
			21.09.2016					
	16.09.2017		07.08.2017		23.07.2017		28.06.2017	
			22.08.2017					
			25.08.2017					
			26.09.2017					
			03.07.2018		01.06.2018		27.05.2018	
			13.07.2018		03.06.2018		29.05.2018	
			16.07.2018		06.06.2018			
			26.07.2018		08.06.2018			
			28.07.2018		26.06.2018			
					01.07.2018			
					11.07.2018			

Nedre Demmevatnet			18.08.2015					
	18.09.2016	08.10.2016	20.07.2016		23.06.2016		10.06.2016	
		11.10.2016	08.09.2016		22.08.2016		13.06.2016	
	22.08.2017	18.10.2017			30.06.2017		13.07.2017	
	27.08.2017				05.07.2017		15.07.2017	
	16.09.2017				10.07.2017		01.09.2017	
					20.07.2017		03.09.2017	
					23.07.2017			
					30.07.2017			
					13.09.2017			
					08.10.2017			
	30.06.2018	18.09.2018			05.06.2018		14.05.2018	
	03.07.2018				08.06.2018		21.05.2018	
	05.07.2018				13.06.2018		24.05.2018	
	08.07.2018						26.05.2018	
	10.07.2018						29.05.2018	
	13.07.2018						31.05.2018	
	20.07.2018						03.06.2018	
	28.07.2018						10.06.2018	
	03.09.2018						14.08.2018	
Sauanuvatnet	04.09.2016				15.08.2016		23.07.2016	
	08.09.2016						05.08.2016	
	18.09.2016							
	04.10.2016							
	08.10.2016							
	11.10.2016							
	22.08.2017				25.08.2017		20.07.2017	
	27.08.2017				06.09.2017		23.07.2017	
	16.09.2017						23.10.2017	
	23.09.2017							
	06.10.2017							
	08.10.2017							
	09.10.2017							
	18.10.2017							
	13.07.2018		10.07.2018	17.11.2018	03.07.2018		28.06.2018	
	16.07.2018		16.10.2018	18.11.2018	05.07.2018		30.06.2018	
	26.07.2018		28.10.2018	20.11.2018	06.07.2018		01.07.2018	
	14.08.2018		29.10.2018	22.11.2018	15.07.2018		08.07.2018	
	03.09.2018			27.11.2018	19.09.2018		23.07.2018	
	04.09.2018				24.09.2018		12.08.2018	
	23.09.2018							
	28.09.2018							
	11.10.2018							

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