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Tracking rapid and slow ice-dammed lake changes through optical satellites and local knowledge: a case study of Tystigbreen in Norway

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Abstract

The number of glacial lakes has grown globally concurrently with the retreat of glaciers in the last few decades, increasing the risk of potentially hazardous glacial lake outburst floods (GLOFs) and posing a threat to downstream communities. Norway has several known ice-dammed lakes that produce repeated GLOFs but as we show here, the existing GLOF database is incomplete and needs to be improved through continuous monitoring of glaciers and glacial lakes. This study examines the case of an ice cap in central Norway hosting at least four drainage-prone lakes. We reconstruct the sequence of lake drainage events through a combination of remote sensing, ground-truthing and citizen science while scrutinising the applicability of the PlanetScope imagery vs Sentinel-2 and Landsat-8 OLI products. As opposed to the Landsat imagery that often fails to resolve even the largest glacial lakes of Tystigbreen, both PlanetScope and Sentinel-2 are helpful in identifying previously unrecognised glacial lakes and undocumented drainage events. Our analysis suggests that a fusion of the two satellite products may be beneficial for automated tracking of glacial lake changes. We also demonstrate that local knowledge and systematic involvement of citizens in data collection have a potential to enrich GLOF databases.

1. Introduction

Rapid glacier retreat in the last few decades has led to major changes in glacier dynamics and arguably induced an increase in glacier hazards like glacial lake outburst floods (GLOFs), rapid glacier surges and glacier collapses/avalanches, among others (Huggel and others, 2002; Moore and others, 2009; Wang and others, 2015; Wang and others, 2020; Kääb and others, 2021). In particular, the number and sizes of glacial lakes and related hazards have continued increasing globally at least since the 1990s (Clague and others, 2012; Carrivick and Quincey, 2014; Haeberli and others, 2016; Nie and others, 2017; Shugar and others, 2020) which is also the case in Norway (Nagy and Andreassen, 2019; Andreassen and others, 2022). Glacial lakes are some of the most dynamic and potentially hazardous glacial features that can be prone to sudden and unpredictable drainages (GLOFs) because of dam failures (Emmer and others, 2022a). As opposed to GLOFs from moraine- or landslide-dammed glacial lakes that usually occur only once, ice-dammed lakes often follow cycles of repeated filling and drainage (Iturrizaga, 2011) and can drain through different mechanisms (Tweed and Russell, 1999; Carrivick and others, 2017).

The current state of knowledge on ice-dammed lake drainage mechanisms suggests that GLOFs are mostly induced by either lifting of the glacier at high pressures or melting of ice walls, resulting in a subglacial drainage (Nye, 1976; Clarke, 1982; Björnsson, 2010a). Other mechanisms include overspill, breaching of ice dams, syphoning and changes in the subglacial cavity drainage systems (Tweed and Russell, 1999; Carrivick and others, 2017). Depending on the drainage mode, GLOFs reach their peak discharge within several hours to 2 d, while non-hazardous drainages can last for a period of up to 3 weeks (Björnsson, 1992, 2010a, 2010b). The underlying mechanisms for the initiation of GLOFs have been subjects of numerous studies (Liestøl, 1956; Nye, 1976; Clarke, 1982; Björnsson, 1992, 2010a, 2010b; Walder and Costa, 1996; Huss and others, 2007; Carrivick and others, 2017) including their relation to glacier dynamics and climate variability (Tweed and Russell, 1999) but we are still lacking understanding of external indicators for the timing and magnitudes of drainages (Ng and others, 2007; Ng and Liu, 2009; Kingslake and Ng, 2013; Liu and others, 2014; Yan and others, 2017). These knowledge gaps inhibit our ability to predict hazardous GLOFs and develop early warning systems to mitigate life loss and damage (Ng and Liu, 2009; Mergili and others, 2011; Wang and others, 2022).

In situ monitoring of glacial lakes is expensive, time consuming and logistically challenging due to their remote locations (Yang and others, 2013). In contrast, changes in these environments can be continuously monitored through remote sensing using optical, multispectral or synthetic aperture radar (SAR) satellite imagery (Racoviteanu and others, 2008; Chen and others, 2021). Compared to the other two types of satellite data, SAR imagery has an advantage that the data quality is not impaired by clouds (Zhang and others, 2020). Over recent decades, remote sensing of surface water has increasingly utilised automated mapping with band ratio calculations and machine-learning algorithms (Jain and others, 2012; Li and Sheng, 2012; Bhardwaj and others, 2015; Cooley and others, 2017; Barbieux and others, 2018; Zhang and others, 2018; Qayyum and others, 2020; Wangchuk and Bolch, 2020; Chen and others, 2021; Nazakat and others, 2021), although these studies have mostly focused on large glacial lakes (>0.01 km^2) (Wangchuk and Bolch, 2020), which are a minority among GLOF-prone lakes in Norway (Andreassen and others, 2022). For Norway, digital glacier and glacial lake inventories have been produced for three time periods – 1988–97, 1999–2006 and 2018–19 – using Landsat imagery for the first two and Sentinel-2 imagery for the most recent dataset (Andreassen and others, 2012, 2022). The latest inventory documents a total of 455 ice-contact lakes of variable sizes between 0.00042 and 38.5 km^2.

Previous glacier-related hazards in Norway, including GLOFs, are documented by Liestøl (1956), Jackson and Ragulina (2014) and the GLOF database of the Norwegian Water Resources and Energy Directorate (NVE). The latter is based on the events registered from the literature, in situ observations and remote sensing (Kjollmoen and others, 2022). While GLOF research is overwhelmingly dominated by physical science, there is a need to complement remote-sensed, model-based and in situ studies with qualitative methods due to the direct relevance of this research for local communities. Indeed, according to Emmer and others (2022b), over 95% of GLOF-centred publications from 2017 to 2021 were associated with the physical sciences domain, suggesting a research gap between the social and physical sciences. However, qualitative research can provide relevant information to help fill gaps in natural hazard risk management through combining interviews and informal conversations with relevant actors (Ahmed and Kelman, 2018). In addition to qualitative methods, citizen science can complement quantitative data by involving members of the public in the production of scientific knowledge (Strasser and others, 2019).

Given the above knowledge gaps, this study has aimed to combine remote sensing with local knowledge and citizen data collection to identify and fill data gaps in the current national GLOF inventories. The main goals of this research are (1) to evaluate whether non-commercial satellite products are fit to consistently track sub-seasonal changes in small ice-dammed glacial lakes in Norway, including de-icing, lake filling and drainage processes; (2) to test the potential of this new workflow to bridge gaps in the temporal resolution of open-access satellite products through accounts of local people in touristic areas where an installation of expensive real-time monitoring systems is currently unjustified and (3) to present a proof-of-concept using an example of an individual ice cap with four drainage-prone ice-dammed glacial lakes in western-central Norway.

2. Study area

Tystigbreen is a glacier complex located at Strynefjellet northeast of the largest ice mass in mainland Norway, Jostedalsbreen (7.21° E/61.55° N) (Fig. 1). It covers an area of 16.4 km^2 within an elevation range between 1288 and 1835 m a.s.l. (Andreassen and

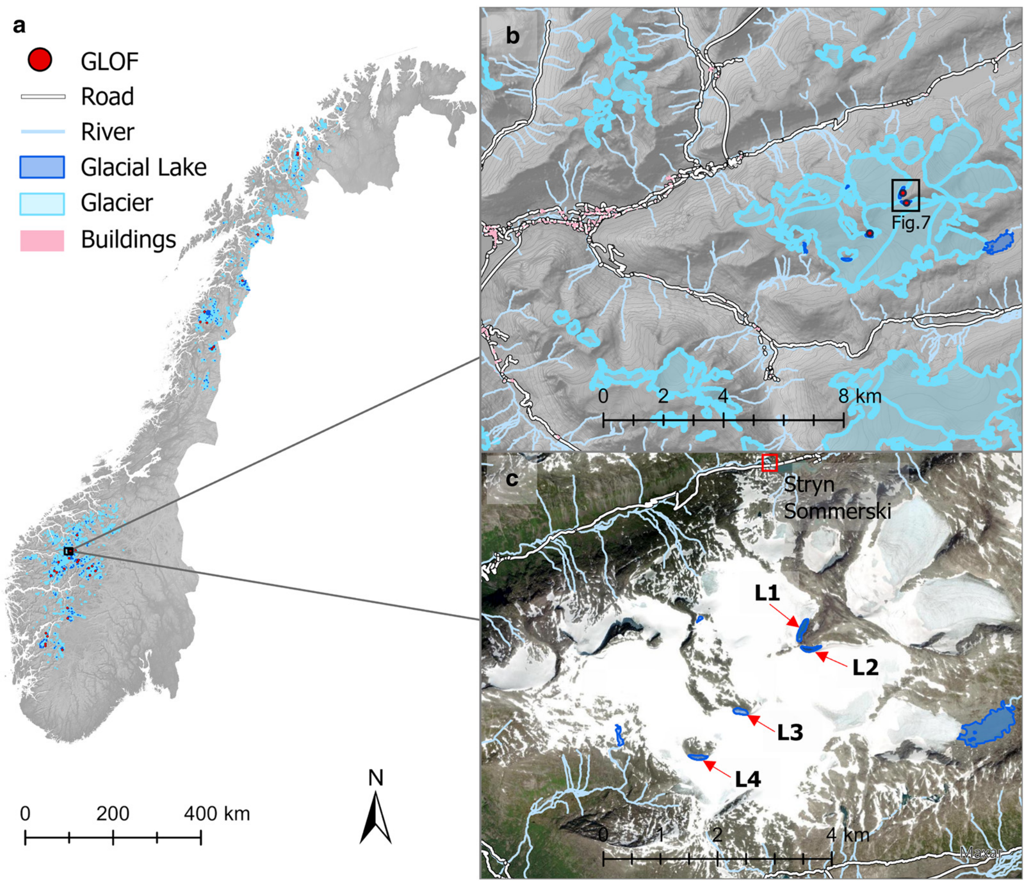

Figure 1. Map of the study area showing (a) the distribution of glaciers and glacial lakes in Norway, (b) map of the study area of Tystigbreen and downstream areas with previously documented GLOF-generating glacial lakes and (c) Worldview-2 satellite image of Tystigbreen (30 July 2021) with the confirmed and newly identified drainage-prone ice-dammed lakes (lakes 1–4 marked as L1–L4) and the location of the Stryn Summer Ski centre testing a citizen-based data collection for this project. *Sources*: NVE's glacier and glacial lake outlines 2018–19 (Andreassen and others, 2022) (a, b) with manual adjustments (c), Kartverket (a–c), Esri (2022) (c).

others, 2022). The climate at Tystigbreen is highly dynamic due to its location on top of a mountain that acts as a divide between maritime fjord areas and continental inland regions, coinciding with an area of strong gradient in annual precipitation sums (Andreassen and others, 2012). Precipitation sums per hydrological year vary between 1583 and 3879 mm during the reference period of 1991–2022 (Lussana and others, 2019; Fig. 2). Annual local mean temperatures fluctuate ∼−1.6 ± 0.9 °C, with the warmest temperatures for summer months ranging between 6.2 and 12.6 °C and the coldest winter temperatures between −16 and −6.1 °C (Lussana and others, 2019; Fig. 2). Typically, January and February are the coldest months of the year, while the warmest temperatures are experienced in July or August.

Tystigbreen has six ice-marginal lakes, four of which are prone to frequent drainages (Fig. 1c). Lakes 1 and 2 (Fig. 1c) have average areas of 0.035 and 0.019 km^2 and are located at elevations of 1621 and 1616 m a.s.l., respectively (Andreassen and others, 2022). Lakes 3 and 4 are not registered in the national glacial lake database but according to our analysis, lake 3 has an area of 0.021 km^2 and is located at an altitude of 1478 m a.s.l., while lake 4 has a lake extent of 0.020 km^2 and an elevation of 1412 m a.s.l. A country-scale inventory based on satellite images may miss lakes that are empty at the time of image acquisition, or they may not yet have reached their maximum extents. Based on our sub-seasonal analysis, lake 2 has a larger area than lakes 3 and 4 as opposed to the lake extents listed above. Therefore, several images from different dates should be used to map all glacial lakes with their maximum extents (Andreassen and others, 2022). Until now, the glacier complex and its glacial lakes have not been monitored by scientific studies, except for the above country-scale inventories. This is at odds with the fact that the glacier complex is easily accessible due to pre-existing infrastructure including roads, ski lifts and the Stryn heliport. So far, no truly damaging impacts have been documented by the downstream communities due to glacial lake drainages from the Tystigbreen lakes. Regardless of this fact, the hazard exposure may change in the future, and investments into studies of this site are well justified, because it is an ideal study area for testing remotely sensed monitoring approaches in combination with in situ monitoring and witness accounts due to the large number of glacial lakes with different drainage behaviours.

3. Data and methods

3.1 Non-commercial optical satellite imagery

Landsat satellites have provided consistent imagery of the Earth surface since 1972 (USGS, 2012), representing a unique uninterrupted archive over five decades. Currently operational Landsat satellites 7–9 record in spectral bands within the visible (VIS), near-infrared (NIR), shortwave infrared (SWIR) and thermal infrared (TIR) spectra. The spatial resolution of the imagery ranges from 15 m for the panchromatic bands to 100 m for the TIR bands, while all the other bands have a resolution of 30 m. This study uses Landsat-8 OLI/TIRS L1T (Operational Lands Imager/Thermal Infrared Sensor Level 1 Tier) products for mapping, complemented by Landsat-7 ETM+ images for visual suitability assessment. Both are corrected for geometric distortion and atmospheric conditions. Landsat-8 OLI L1T images reach a geolocation accuracy of 12 m (Storey and others, 2014).

Sentinel-2 was launched in 2015 as part of the EU Copernicus programme (ESA, 2015). Sentinel-2 satellites acquire data in 13 spectral bands in VIS, NIR and SWIR spectra. Their spatial resolution ranges from 10 to 20 m for most bands (ESA, 2015). The Sentinel-2 mission is based on a constellation of two satellites positioned at a 180° distance with a repeat cycle of 5 d. Orthorectified and atmospherically corrected L2A (level 2A) as well as Top-Of-Atmosphere corrected L1C (level 1C) scenes were used in this study. The geometric corrections ensure a geolocation accuracy of 12.5 m (Dechoz and others, 2015).

The PlanetScope mission started in June 2016 and reached daily global coverage with 130 CubeSat satellites between February and July 2017 (PlanetLabs, 2020). PlanetScope imagery has a spatial resolution of 3.7–4.1 m and is recorded in four bands (eight bands since March 2021) in VIS and NIR spectra (Qayyum and others, 2020) (see Table S1 in the Supplementary material for detailed specifications of the utilised satellite products). This study uses PlanetScope orthoscenes that are geometrically corrected and scaled to surface-reflectance radiance with a reported geolocation accuracy of 10 m. Free access to the PlanetScope satellite data is limited to 5000 km^2 per month and is currently only possible through the education and research programme of Planet Labs (PlanetTeam, 2017). Pros and cons of the different satellite missions are listed in Table 1.

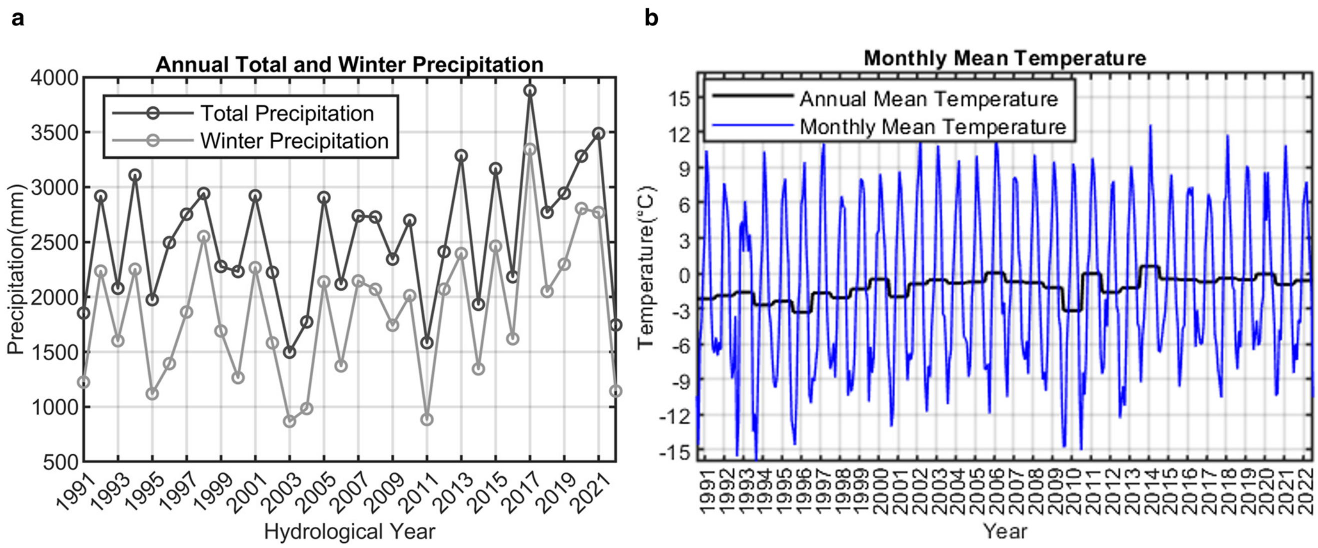

Figure 2. Multi-decadal evolution of the annual and winter precipitation (a), and annual and monthly mean temperature (b) at Tystigbreen for the period of 1991–2022 derived from the national gridded dataset seNorge (Lussana and others, 2019). The hydrological year is defined as the period from 1 September to 31 August (NVE, 1993). Here, 'winter precipitation' refers to the accumulation season between 1 October and 30 April.

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Table 1. Pros and cons of Landsat 7–8, Sentinel-2 and PlanetScope satellite products

	Pros	Cons
Landsat 7–8	• Long record (since 1999–2013, potential to track back to 1972 if images from all Landsat missions could be used) • High spectral resolution (has SWIR and TIR bands) • Lower processing time • High relative geolocation accuracy • Consistent image quality • Consistent orbit • Freely available for download	• Lower spatial resolution (15-30-60 m) • Lower temporal resolution (16 d) • Gaps in Landsat-7 imagery since 2003 due to failure of the Scan Line Corrector
Sentinel-2	• Higher spatial resolution (10 and 20 m) • Higher temporal resolution (5 d) • Intermediate spectral resolution (has SWIR bands) • Consistent image quality • Consistent orbit • Freely available for download	• Shorter record (since 2015) • Lower relative geolocation accuracy • Does not have TIR bands
PlanetScope	• Highest spatial resolution (3–4 m) • Highest temporal resolution (daily imagery)	• Shortest record (since 2016) • Lowest spectral resolution (4–8 bands, no SWIR or TIR bands) • Lowest relative geolocation accuracy • Satellites travelling in different orbits • Inconsistent image quality • Limited access (subscription required)

3.2 Selection of satellite images

When selecting images for outlining glacial lakes, several criteria must be specified, such as the ablation season, the maximum cloud cover for suitable images and the image quality to minimise cases of misclassification (Racoviteanu and others, 2009). Although images acquired around the summer solstice contain fewer cast shadows, Norwegian glaciers during this time are often still covered by snow, and lakes are likely to have ice cover (Nagy and Andreassen, 2019). The latter is an issue for this study since ice-covered lakes are hard to distinguish from ice bodies and snow (Wangchuk and Bolch, 2020; Chen and others, 2021). Here we have defined the ablation season as 1 June to 31 October and have pre-selected all images in which the area around the ice-dammed lakes was not cloud-covered and then assessed whether quality was high enough to visually detect the existence or absence of a waterbody.

3.3 Sub-seasonal glacial lake mapping and GLOF detection

We manually mapped the two largest ice-dammed lakes of Tystigbreen using all pre-selected Sentinel-2 and PlanetScope images (Fig. 3) throughout the ablation seasons between 2016 and 2022 to analyse their filling and drainage behaviours. In addition, we tested a threshold-based indexing method against manual mapping. To automatically extract water from non-water surfaces we used the normalised difference water index (NDWI) (McFeeters, 1996), which is one of the most widely used indices to classify water in satellite imagery (Hui and others, 2008; Huang and others, 2018). The NDWI is calculated as follows:

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

Typically, low-threshold values close to 0 are used for the waterbody extraction in ice-free terrain using the NDWI (McFeeters, 1996; Xu, 2006). However, the use of higher threshold values is recommended for the mapping of ice-contact lakes (Nagy and Andreassen, 2019). Here we have adopted a threshold of 0.23 used by Nagy and Andreassen (2019) when working with the Sentinel-2 imagery. In contrast, visual inspection of the NDWI when using PlanetScope imagery has revealed a need for a different threshold value even though the PlanetScope and Sentinel-2 datasets are radiometrically harmonised. To reconcile this difference, we have calibrated the NDWI method for PlanetScope and found a threshold of 0.1 as most suitable for a binary raster calculation in the target area. To test its skill against manual mapping, we have performed a NDWI classification on all pre-selected PlanetScope and Sentinel-2 images from the ablation season of 2021, since the number of available cloud-free images for this year is some of the largest within the studied period.

3.4 Local knowledge and citizen science

To verify the drainage timing of the glacial lakes, we conducted semi-structured interviews in the community of Hjelledalen, the main impact area of Tystigbreen, during the field campaign in September 2021. During the participant selection process, we utilised a combination of convenience sampling, including criterion and snowball. Our first interviewee was selected through criterion sampling, a purposeful selection method used to identify participants based on pre-defined criteria (Stratford and Bradshaw, 2016). Following the initial interview, we located additional interviewees through snowball sampling, a method involving the recommendation of other potential informants by current participants (Stratford and Bradshaw, 2016).

As it was important to include different intersections of the population in Hjelledalen, we interviewed a variety of actors who lived or worked in the area. Specifically, we conducted the interviews with participants who varied in occupation, age and gender. To ensure participants were asked questions that generated relevant information, we created an interview guide with open-ended questions that had the purpose to gather qualitative data on participant's knowledge, awareness and perception of glacial lakes and GLOFs. In addition, we carried out informal conversations with local actors, including employees of hotels and staff of camping sites, to complement the data collected during the interviewing process. In total, we conducted six interviews, as well as seven informal conversations (Table 2). The sample size of collected interviews has been adversely impacted by the low number of permanent inhabitants in Hjelledalen. Moreover,

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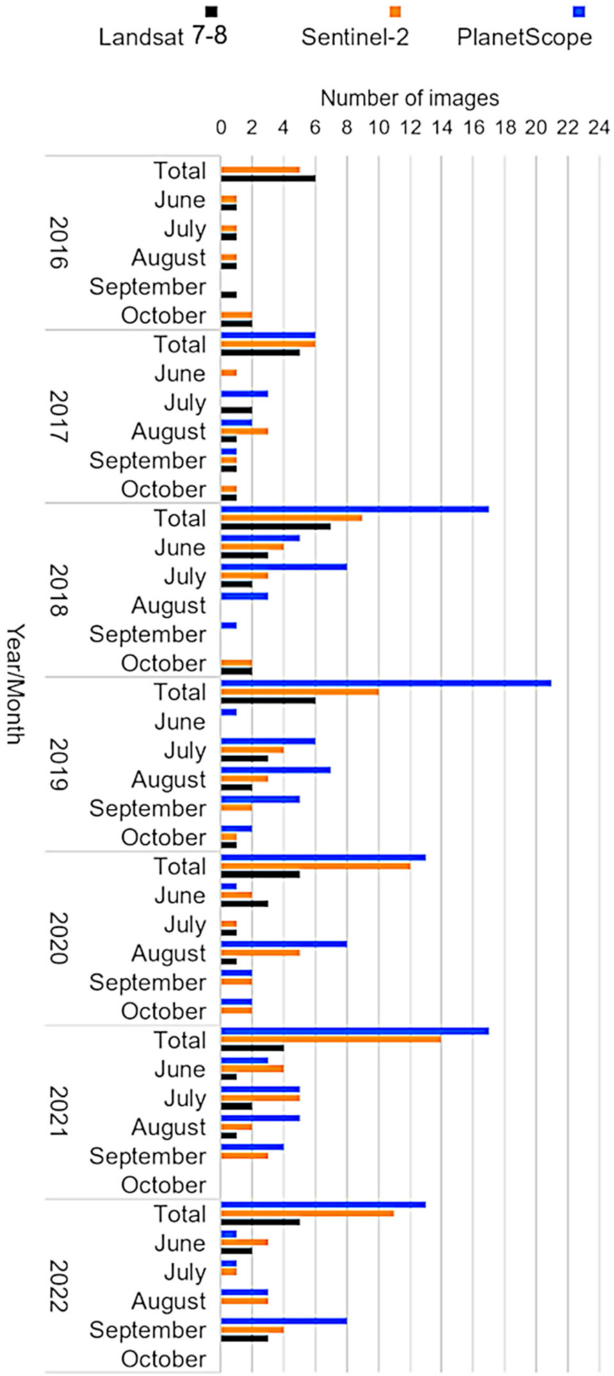

Figure 3. Number of suitable images from Tystigbreen during the ablation season (June–October) for the period of 2016–22. All the images from October, except for 2017, are snow covered and thus unfit for a reliable mapping.

some of the potential interview subjects we approached were unable to aid our research since they were lacking knowledge about the glacial lakes of Tystigbreen. Following transcription and review of the qualitative data, we categorised the responses by theme. Relevant information provided by the participants included knowledge on lake drainage, such as time, water levels, sediment transport and velocity.

Through the collaboration with the Stryn Summer Ski centre since spring 2021, we have received access to multi-annual data collected in the field and regular reports and photographic evidence documenting glacial lake levels and drainage events. Using these data, we have tested and refined strategies for the acquisition of photos, starting from a relatively unstructured and occasional sampling and moving towards a more regular documentation from nearly fixed positions at the margin of lake 1 (see Fig. 9).

4. Results

4.1 Mapping of glacial lakes with different satellite products

Our selection of imagery has revealed significant heterogeneities in the availability of high-quality images from different satellite missions across the years (Fig. 3). Prior to July 2017, the PlanetScope mission did not cover the area of Tystigbreen, while starting from 2018, it has consistently offered the largest number of high-quality images during the ablation season due to its close-to-daily coverage of the Earth surface. The only instance when Sentinel-2 and/or Landsat generated more suitable images was in June of 2020–22.

We have estimated the maximum temporal gap between two high-quality PlanetScope images as 36 d (25 June–1 August 2020). This is in contrast to 76 d for Sentinel-2 (26 July–11 October 2018) and 102 d for Landsat (16 July–27 October 2018) (see Table S2 in the Supplementary material). However, regardless of the satellite product, it is challenging to recognise and map the lakes with certainty at the beginning and the end of the ablation season due to early snowfall before mid-October and persistent lake ice and snow cover in June. These limitations impose large uncertainties in our lake reconstructions in the first half of June. Similarly, in all October images but one (9 October 2017), it has been difficult to identify and map those glacial lakes that were not empty at the time of the image acquisition. These difficulties mainly arise from either too extensive snow cover or too low resolution of the images (i.e. Landsat in October 2020). The above issues are further exacerbated by an illumination issue that adversely impacts the quality of the PlanetScope imagery when the surface is snow covered. Thus, its higher image output does not help during the initial and terminal stages of the ablation season.

As demonstrated in two examples in Figure 4, the Landsat-8 imagery is clearly not up to par when it comes to tracking sub-seasonal glacial lake changes or constraining the timing of their drainages. While the two larger lakes (lakes 1 and 2) can be at least identified, the two smaller lakes (lakes 3 and 4; Fig. 4) are unrecognisable in the Landsat-8 images due to their coarse spatial resolution. The temporal resolution of the Landsat-8 imagery is also suboptimal for the studies of the sub-seasonal variations in glacial lakes, especially those that are as small and rapidly changing as the ones at Tystigbreen (Fig. 4). Following these observations, we omitted the Landsat imagery from further analyses.

4.2 Tracking the evolution and drainage of glacial lakes

Using pre-selected PlanetScope and Sentinel-2 images, we manually mapped the extents of lakes 1 and 2 and calculated their respective areas throughout the ablation seasons of 2016–22 (Fig. 5). The small sizes of lakes 3 and 4 and considerable ice cover on all available images where the waterbodies are detectable, hindered their accurate and reliable mapping. To avoid biased results, we therefore excluded them from this analysis. Our results demonstrate that the temporal resolution of the sub-seasonal lake area development can be increased through a combination of the PlanetScope and Sentinel-2 imagery (Figs 5c and f) compared to the mapping based on one satellite product only (Figs 5a and d, b and e). On the one hand, the PlanetScope imagery has made it possible to detect events that would have been missed by the Sentinel-2 image analysis, e.g. lake 1 in 2018 (Fig. 5b, orange). On the other, the identified shortcomings of the PlanetScope images during the early and late stages of the ablation season

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Table 2. Local citizens interviewed during field campaigns in September 2021 in Hjelledalen, Stryn, Norway

Participants	Subject occupation	Sampling method	Purpose of interview	Date
No. 1	Ski business owner	Cumulative	The purpose of this interview was to learn about how glacier change was affecting the ski and tourist industry.	11 Sep 2021
No. 2	Retired national park employee	Snowball	The purpose of this interview was to learn about how glacier melt, recession and hazards were directly impacting local citizens.	11 Sep 2021
No. 3	Farmer	Snowball	The purpose of this interview was to learn about how glacier melt, recession and hazards were directly impacting farmers.	10 Sep 2021
No. 4	School principal	Cumulative	The purpose of this interview was to gain insight into how local actors perceive glacial melt and hazards.	10 Sep 2021
No. 5	Teacher	Snowball	The purpose of this interview was to gain insight into how local actors perceive glacial melt and hazards.	10 Sep 2021
No. 6	Geologist	Cumulative	The purpose of this interview was to learn about how glacier melt was impacting the region.	11 Sep 2021

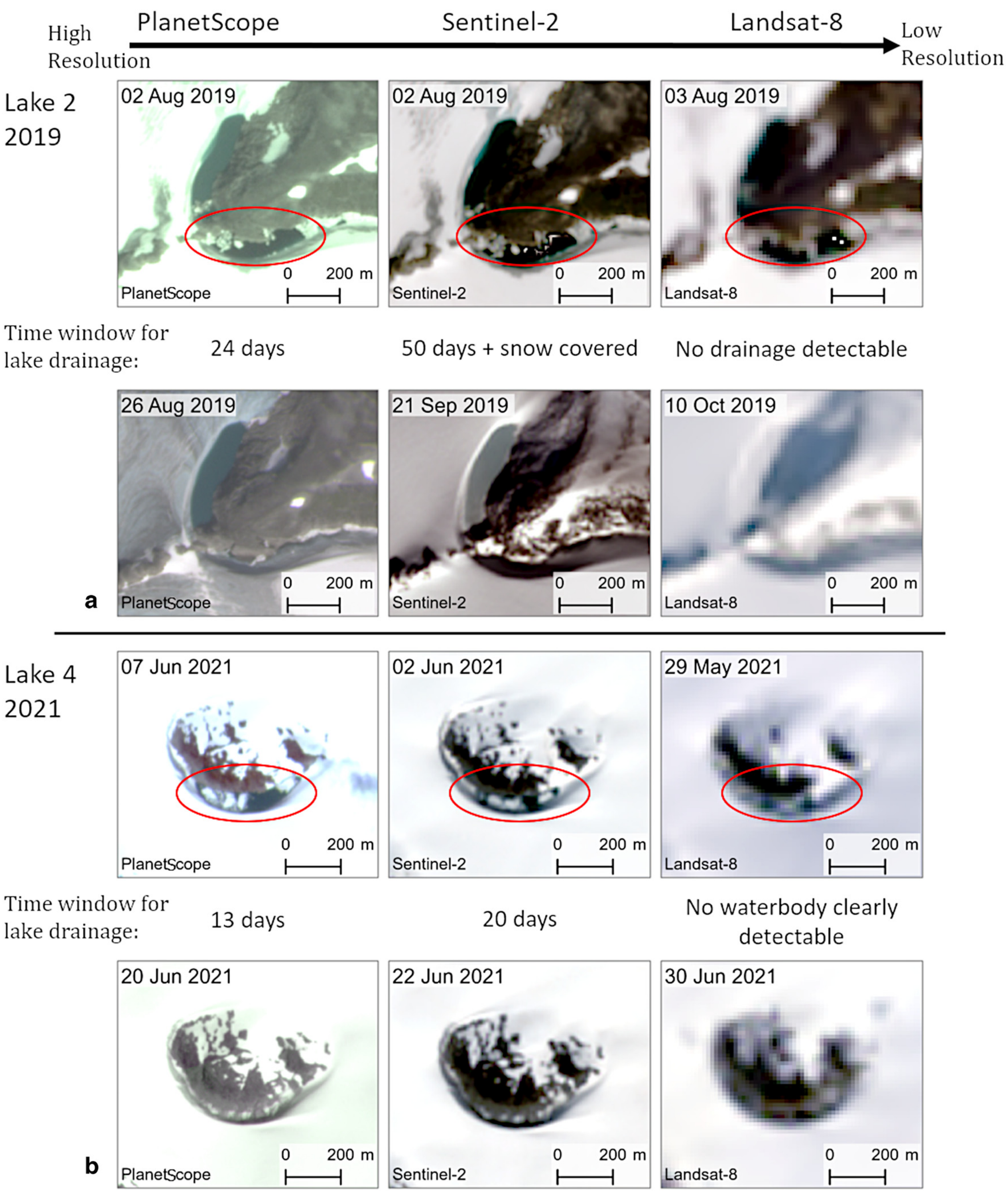

Figure 4. Detectability of Tystigbreen's glacial lakes in the PlanetScope (left), Sentinel-2 (middle) or Landsat-8 (right) imagery, including the time window constraining the glacial lake drainages for each satellite product. The upper two panels (a) show an example of the drainage event from lake 2 in 2019. The lower two panels (b) depict the drainage of lake 4 in 2021. Projection: WGS1984 UTM Zone 32N.

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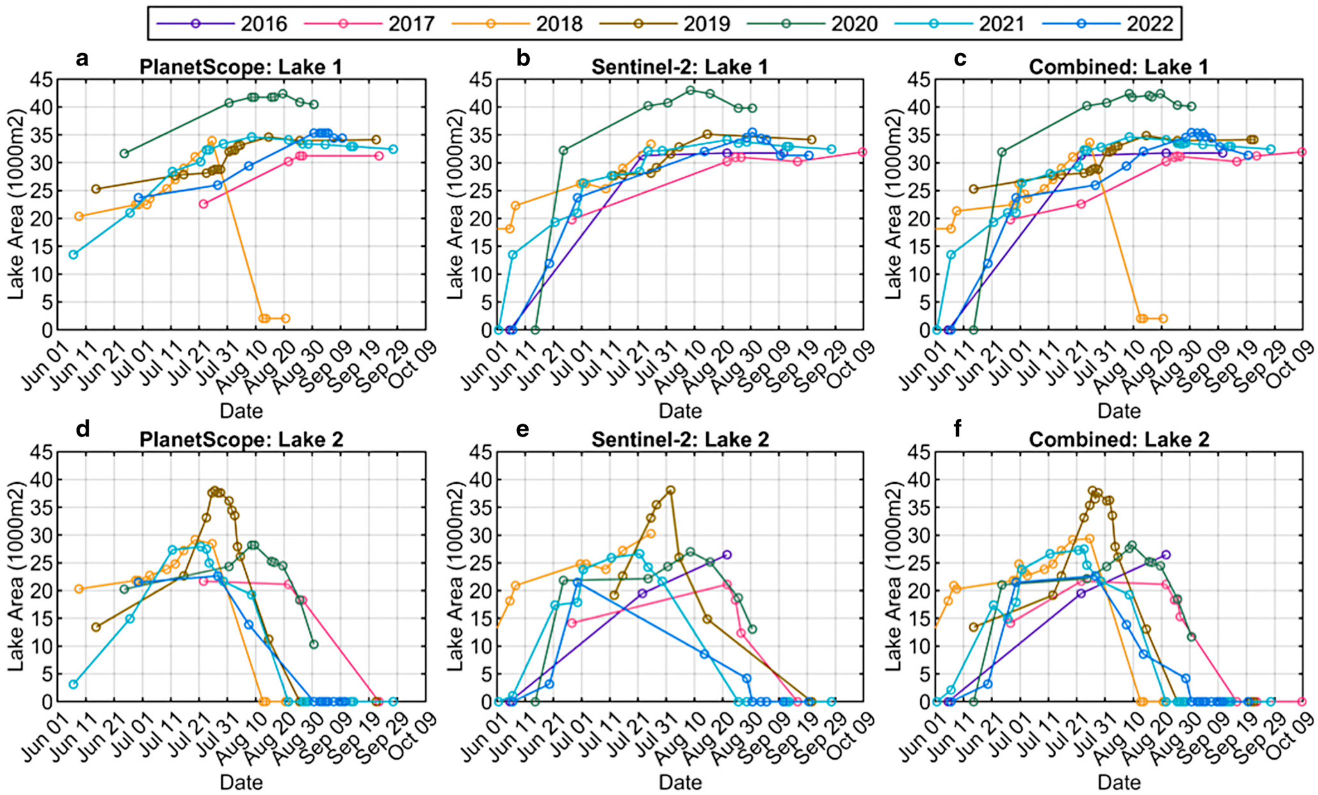

Figure 5. Development of the areas of lakes 1 and 2 at Tystigbreen throughout the ablation seasons of 2016–22. The two plots on the left (a, d) show the results based on maps derived from the PlanetScope imagery, the two plots in the middle (b, e) show lake areas derived from the Sentinel-2 imagery, and the plots on the right (c, f) show the combined results of PlanetScope- and Sentinel-2-derived lake areas.

can be partly compensated through the inclusion of the high-quality Sentinel-2 images (Figs 5a vs b, d vs e).

The mapping accuracy for the lake areas is adversely impacted by the large variability in the lake surface exposure throughout the years, complicating the comparison between them. For example, the mapped size of lake 1 is abnormally large in 2020 (41 746 m^2), which is ~25% larger than average sizes during other years (33 425 ± 1578 m^2; Fig. 5). In contrast, the estimated size of lake 2 in 2020 is average but is ~45% larger in 2019 compared to other years (37 614 m^2 vs an average of 25 941 ± 2800 m^2 during other years). While we cannot obviate the possibility of significant natural fluctuations in the maximum lake filling rate, the above outliers may also mark the mapping uncertainty. Due to geolocation errors of up to 12 m between the PlanetScope and Sentinel-2 images, we could not automatise change detection without pre-processing the imagery. Thus, we have focused our analysis on the changes in absolute lake areas.

Available satellite imagery records only one drainage event for lake 1 that occurred in 2018. In contrast, we have reconstructed complete drainages of lake 2 during all years but 2016 and 2020. The year 2018 is particularly interesting because both lakes appear to have drained within the same time window, which is constrained to a period between 26 July and 13 August (Fig. 5). The lack of data points between these two dates makes it impossible to derive the exact drainage timing and drainage mode (fast vs slow) for each lake, but it is a first indication that simultaneous drainages of the two lakes may be possible in the future.

4.3 Automated vs manual mapping

To quantify the performance of the conventional automated mapping methods such as NDWI on local scales, we compared manually digitised and NDWI-based glacial lake outlines from lakes 1 and 2 throughout the ablation season of 2021. While the manually digitised lake outlines smoothly follow the lake filling process between June and July and capture the drainage of lake 2 in August both with PlanetScope and Sentinel-2 images (Fig. 6), the NDWI-based lake outlines do not correspond to the visual assessment and are thus useless for tracking sub-seasonal lake development (Fig. 7). The NDWI maps fail to reproduce the observed filling and drainage cycle, and our results reveal that the PlanetScope-based mapping is even less consistent with the reality than that based on Sentinel-2 (Figs 6, 7). The NDWI method applied to the PlanetScope imagery introduces noise and misclassified pixels. When applied on Sentinel-2, it tends to exclude floating ice from the lake area (Fig. 7) and classify dark ice (e.g. 12 and 30 July) or shadows as water (e.g. lake 2, 29 August).

We used the Sentinel-2 imagery from 30 July to quantify contributions of different sources of misclassification in the NDWI mapping. The lake areas from the manual vs NDWI mapping differ by 5888 m^2. Of this difference, 31% originates from the exclusion of the floating ice, and 33.6 and 30.8 are due to misclassification of the dark ice and shadow as water, respectively. The remaining 4.6% of the disagreement between the maps can be presumably attributed to the mapping uncertainty including the impacts of resolution and quality of the images as well as the subjective interpretation of the mapper.

4.4 Results from the interviews and citizen science

During the interviews, five out of six participants admitted that they were aware of potential GLOFs from Tystigbreen but did not think that this phenomenon posed any danger to their community. Four participants remembered changes in the local rivers or glacial lakes during and after the drainage events. For instance, several participants believed that lake 4 drained on 9 June 2021 by

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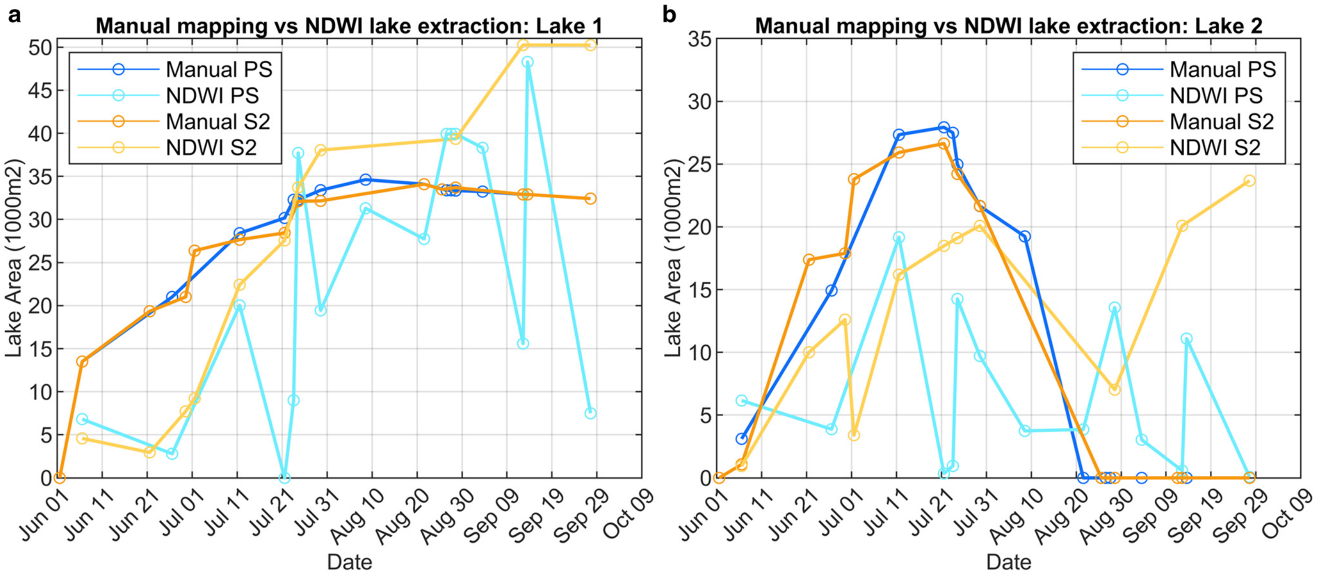

Figure 6. Sub-seasonal development of the areas of lakes 1 (a) and 2 (b) using manual vs band-ratio (NDWI) mapping on the PlanetScope (PS) and Sentinel-2 (S2) images. Note the difference in the scales of the *y*-axis in the plots.

observing abrupt changes to both the Tverrelva and Sunndøla rivers during the same period that were not related to a rainfall event. Participant nos. 2, 3 and 5 (Table 2) mentioned changes to the water levels, quality and colour of the river in June 2021. Although the river did not flood, participant nos. 3 and 5 remembered a significant increase of 'brown' water in the Tverrelva River that was accompanied by 'a lot of mud'.

Two participants suggested that lake 1 drained in both 2016 and 2018, but they disagreed on the timing of the 2016 event stating that it either occurred during the summer or the autumn. When comparing the silty water from the drainage in 2021 to the event in 2016, participant no. 3 recalled the water quality of the river as follows:

> 'The flood (in 2021) brought in a lot of loose material into the river. However, I find it very interesting that usually when the lakes on the eastern side (Lakes 2–4) drain into Tverrelva, the stream coming out of the glacier is usually very muddy. But the water (in the Videdøla river) coming out under the glacier on the western side of Tystigbreen during this event (Lake 1 in 2016) was not muddy'.

Although participant no. 3 noted that the water draining from the glacier was rather clear, it was also suggested that this was unusual.

In addition to the interviews, participant no. 1 recorded details and provided images of lakes 1 and 2 throughout the seasons of 2021 and 2022. This more frequent monitoring of the sub-seasonal lake changes has made it possible to confirm the drainage of lake 2 in 2021 (Figs 8a and b), constrain the onset of drainage of lake 2 in 2022 (Fig. 8c) and follow the filling of lake 1 in 2022 (Fig. 9). Also, this participant reported hearing cracking noises from lake 1 in October 2021 as a potential sign for a late drainage event of lake 1.

4.5 Chronologies of lake drainages and their impacts

Through the analysis of Sentinel-2 and PlanetScope imagery, we were able to detect ten certain and one probable (event 8) drainage events from four ice-dammed lakes of Tystigbreen (Table 3). Two additional events have been reported by local citizens (events 3 and 5), which could not be detected on the satellite imagery. In addition, three events outside the operational periods of Sentinel-2 and PlanetScope are registered in NVE's GLOF database (events 1, 2 and 6) (NVE, 2022). Using interviews with local people and our own analyses presented in this study, we could validate several of the detected drainage events (events 4, 15 and 16) and constrain them to a shorter time window compared to the outcomes of the remote sensing alone. In addition, we could further narrow down the possible time window for lake drainages through a combination of the PlanetScope and Sentinel-2 imagery when compared to the outcomes from a single satellite product (events 11 and 12). Lake 2 has drained every year since 2017 except for 2020 when we could not detect any lake drainages at Tystigbreen. All documented drainages from lake 2 initiated between 20 July and 22 August, corresponding to a mean onset timing on 31 July ± 14 d. Following the drainages, lake 2 was detected as empty (fully drained) between 14 August and 16 September, with a corresponding mean of 28 August ± 11 d. The statistics can also be translated into an average drainage duration of 28 ± 3 d, corresponding to a slow drainage that does not cause floods downstream. Lakes 1, 3 and 4 are assumed to drain at a faster rate as we could identify an exact drainage date (events 2 and 15) and constrain the drainage time window to a maximum of 5 d (events 14 and 16) at least once for each of the lakes.

5. Discussion

5.1 Suitability of optical satellite products for mapping drainage-prone glacial lakes in Norway

Given the focus of this study on sub-seasonal changes in relatively small ice-dammed glacial lakes, we deem both the spatial and temporal resolution of Landsat-8 images insufficient for such tasks (Watson and others, 2016). Especially, their lower spatial resolution impedes the detection of smaller glacial lakes such as we find at Tystigbreen (<0.042 km^2; Fig. 4), and it is generally problematic for Norway where the majority of glacial lakes are small, with only six of them covering areas larger than 0.2 km^2 (Andreassen and others, 2022). Also, the low-temporal resolution of Landsat is restrictive towards frequent mapping of drainage-prone glacial lakes of any size, since there are oftentimes only five or fewer cloud-free Landsat-8 images available per season for a given location, with gaps of several months in between (2018, 2019, 2022) (Fig. 3). This is a pity since the Landsat archive

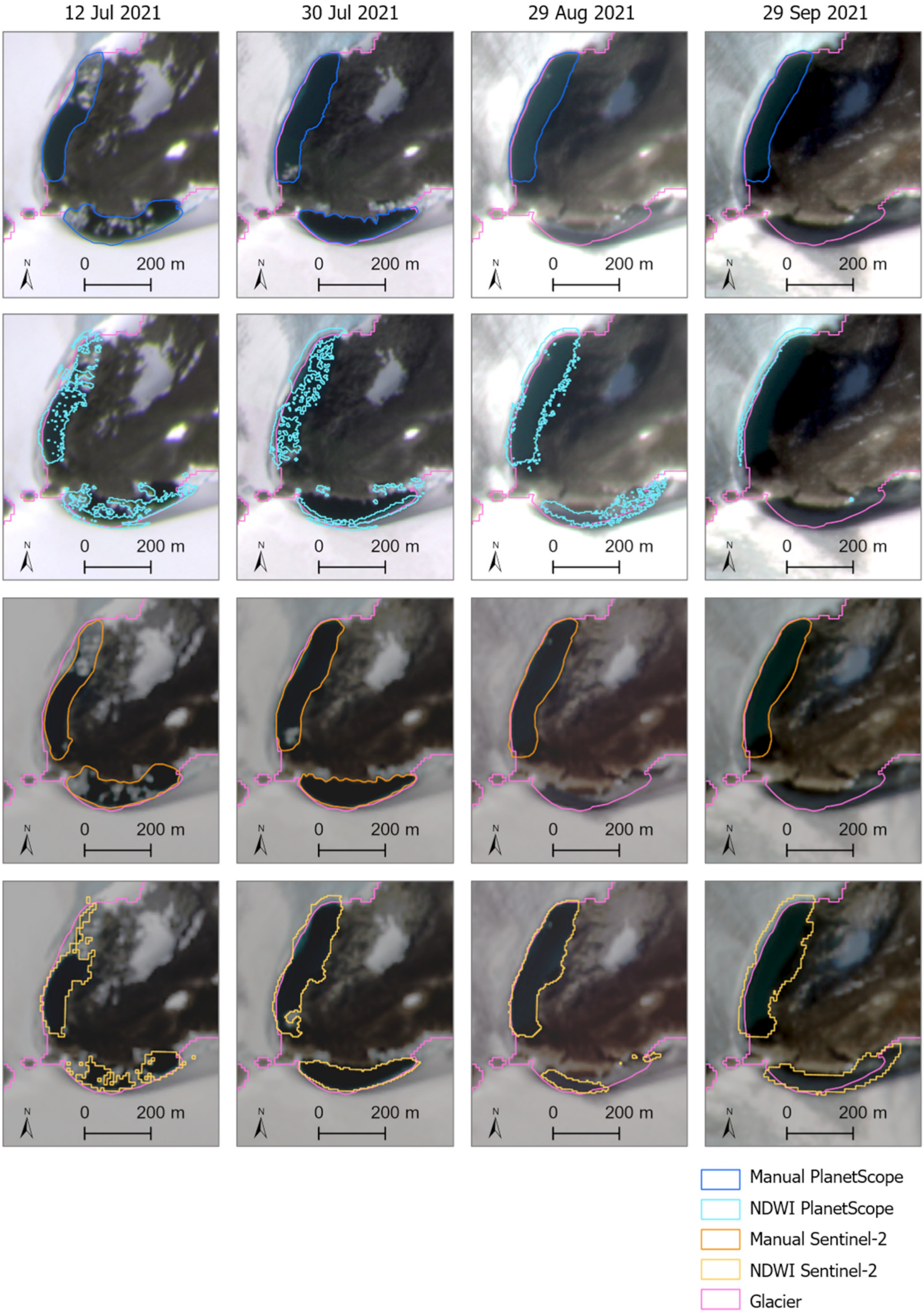

Figure 7. Sub-seasonal development of lakes 1 and 2 based on the manual vs NDWI mapping on the PlanetScope and Sentinel-2 imagery. From top to bottom: manual PlanetScope, NDWI PlanetScope, manual Sentinel-2 and NDWI Sentinel-2. *Sources*: PlanetScope imagery (rows 1–2) and Sentinel-2 imagery (rows 3–4) from respective dates, NVE glacier outlines are from August 2019 (Andreassen and others, 2022).

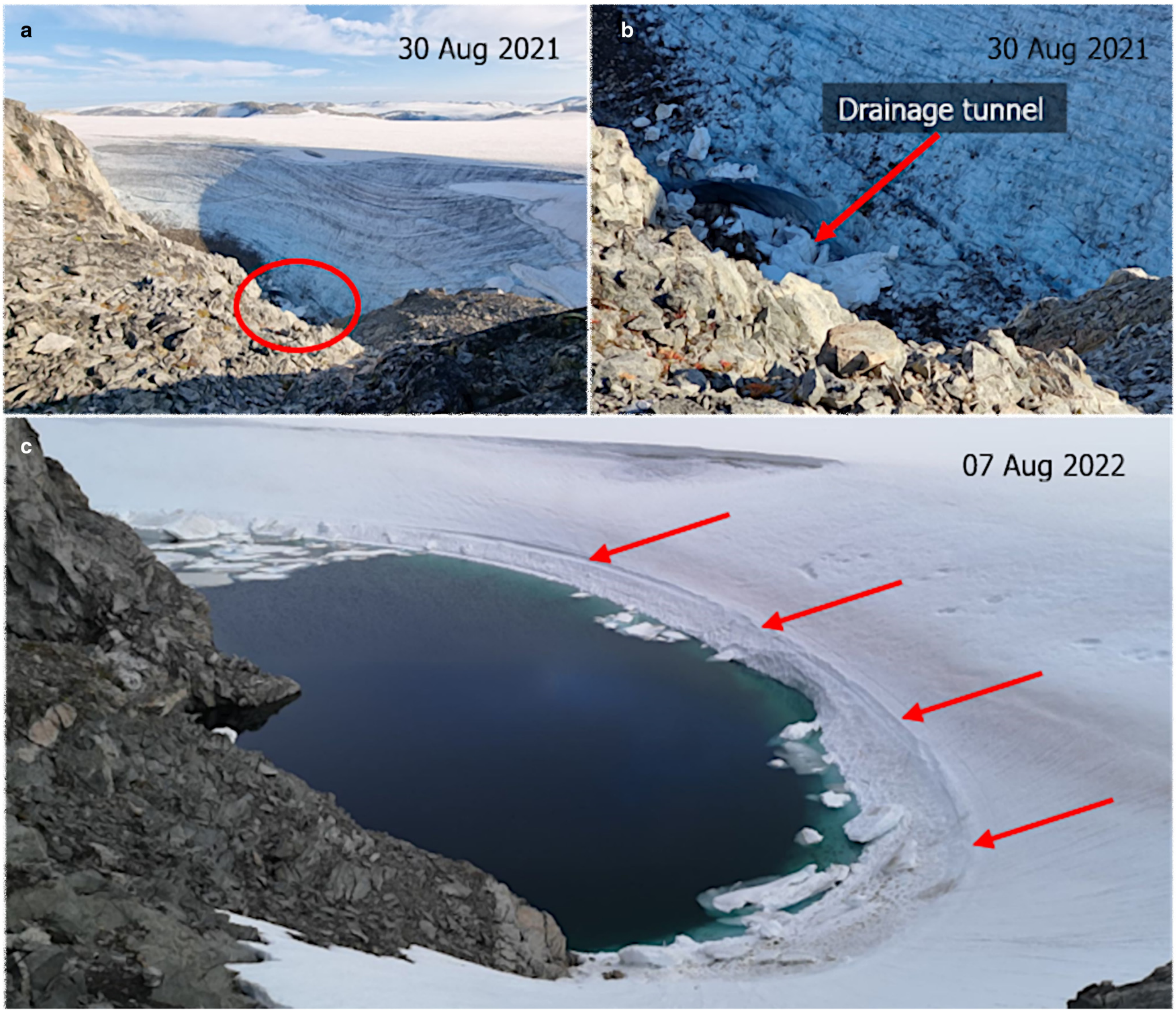

Figure 8. Detected drainage of lake 2 in August 2021 (a and b). The location of the drainage tunnel in (b) is indicated with a red circle (a). (c) The onset of drainage of lake 2 in August 2022. The arrows indicate the maximum water level. Photos: Stryn Summer Ski.

Figure 9. Photographic documentation of the filling of lake 1 in 2022. Photos: Stryn Summer Ski.

goes back to 1972, offering an advantage of mapping surface changes over incomparably longer timescales than Sentinel-2 and PlanetScope. However, the lower spatial resolution of Landsat 1–3 of ∼79 m would make mapping small glacier lakes such as those of Tystigbreen even more challenging.

At the other end of the scale, the launch of the PlanetScope mission made it possible to assess small-scale changes (with a spatial resolution of 3–4 m) with a very high-temporal resolution (close to a daily coverage). As shown in Table 3, in many cases it allowed us to constrain the lake drainage timing to the shortest

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Table 3. Drainage events and the timing of drainages of the Tystigbreen lakes detected using the PlanetScope (PS) and Sentinel-2 (S2) imagery, witness accounts (WA) and registered events in the NVE GLOF database

									Detected by			
Lake No.	ID	Year	Planet-Scope (PS)	Sentinel-2 (S2)	Planet-Scope and Sentinel-2	Witness accounts (WA)	NVE's database (NVE)	Combined	PS	S2	WA	NVE
L1	1	2010	–	–	–	–	Aug	Aug (31 d)				x
	2	2014	–	–	–	–	Aug 16	16 Aug				x
	3	2016	No imagery available	No drainage detectable	–	Aug to Sep (reported by interviewees)	–	Aug to Sep (61 d)			x	
	4	2018	26 Jul–13 Aug (18 d)	No drainage detectable	26 Jul–13 Aug (18 d)	Aug (reported by interviewees)	–	1 Aug–13 Aug (13 d)	x		x	
	5	2021	–	–	–	1 Oct–Oct 15 (reported by collaborators)	–	1 Oct–15 Oct (15 d)			x	
L2	6	2010	–	–	–	–	Aug	Aug (31 d)				x
	7	2017	23 Aug–23 Sep (31 d)	23 Aug–16 Sep (24 d)	23 Aug–16 Sep (24 d)	–	–	23 Aug–16 Sep (24 d)	x	x		
	8	2018	26 Jul–13 Aug (18 d)	No drainage detectable	26 Jul–13 Aug (18 d)	–	–	26 Jul–13 Aug (18 d)	x			
	9	2019	2 Aug–26 Aug (24 d)	2 Aug–21 Sep (50 d)	2 Aug–26 Aug (24 d)	–	–	2 Aug–26 Aug (24 d)	x	x		
	10	2021	25 Jul–21 Aug (27 d)	25 Jul–26 Aug (32 d)	25 Jul–21 Jul (27 d)		–	25 Jul–21 Jul (27 d)	x	x		
	11	2022	28 Jul–30 Aug (33 d)	22 Jul–29 Aug (38 d)	28 Jul–29 Aug (32 d)	Onset of drainage before 7 Aug (reported by collaborators)	–	28 Jul–29 Aug (32 d)	x	x	x	
L3	12	2018	12 Jun–30 Jun (18 d)	8 Jun–26 Jun (18 d)	12 Jun–26 Jun (14 d)	–	Before 26 Jun	12 Jun–25 Jun (13 d)	x	x		x
	13	2019	24 Jun–10 Jul (16 d)	11 Jun–11 Jul (30 d)	24 Jun–10 Jul (16 d)	–	–	24 Jun–10 Jul (16 d)	x	x		
	14	2021	22 Jun–27 Jun (5 d)	22 Jun–27 Jun (5 d)	22 Jun–27 Jun (5 d)	–	–	22 Jun–27 Jun (5 d)	x	x		
L4	15	2021	7 Jun–20 Jun (13 d)	7 Jun–22 Jun (15 d)	7 Jun–20 Jun (13 d)	9 Jun (reported by interviewees)	–	9 Jun	x	x	x	
	16	2022	9 Jun–30 Jun (21 d)	4 Jun–20 Jun (16 d)	9 Jun–20 Jun (11 d)	15 Jun full (fieldwork)	–	15 Jun–20 Jun (5 d)	x	x	x	

ID stands for event ID. The lake drainages are categorised as certain if they could be detected using two or more sources of information or if they are registered in NVE's database (NVE, 2022).

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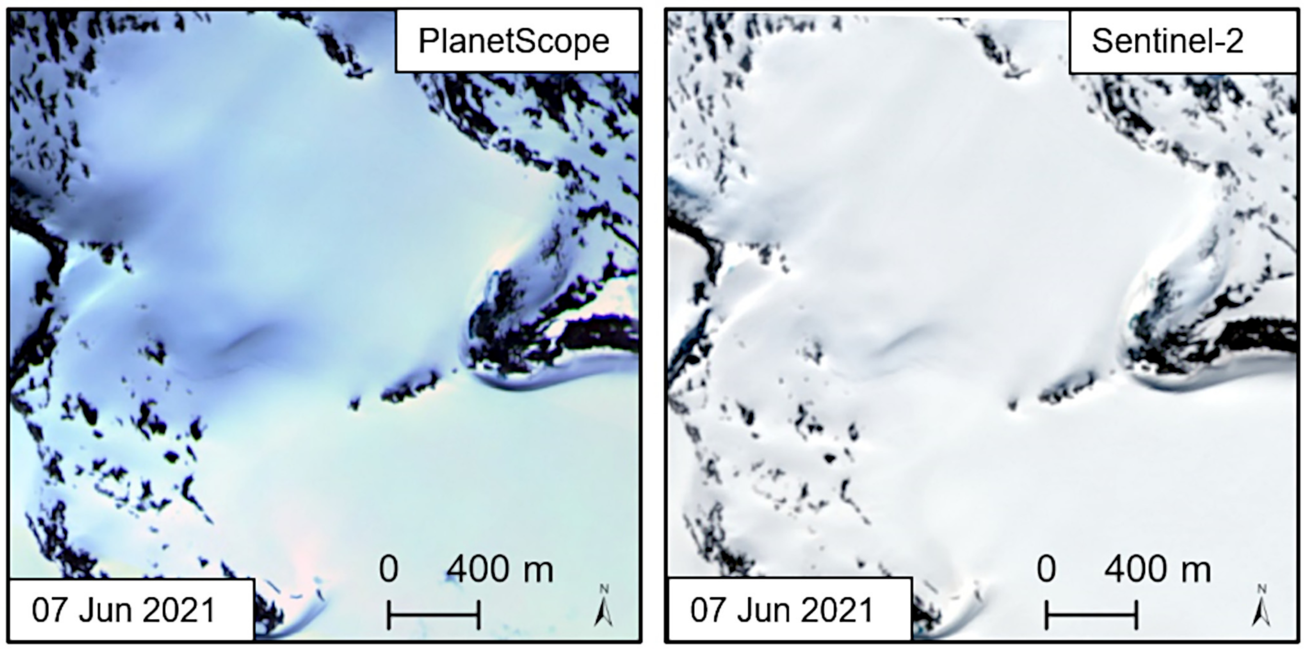

Figure 10. Comparison of the PlanetScope and Sentinel-2 image quality during the early ablation season. The maps show that the PlanetScope image suffers from illumination disturbances due to the snow cover, while the quality of the Sentinel-2 image is more consistent.

time window (events 4, 8–10, 13 and 15). Yet, it has a lower spectral resolution, with only four bands for most satellites and eight bands for the newest satellites, compared to 11 and 13 bands for Landsat-8 and Sentinel-2, respectively. Furthermore, the PlanetScope imagery is acquired from numerous small CubeSats travelling in different orbits. This causes a weaker spatio-spectral calibration and significant illumination disturbances of the raw images (Houborg and McCabe, 2018; Leach and others, 2019), especially when the surface is snow covered (Fig. 10). If one aims at an automated image analysis, such technical issues would necessitate pre-processing steps such as radiance adjustments, mosaicking and resampling (Latte and Lejeune, 2020). In addition, free access to the PlanetScope imagery is currently limited due to requirements of an admission to the education and research programme (PlanetTeam, 2017) and restricted data volume per month. It is therefore difficult to benefit from the full potential of PlanetScope imagery, especially for large-scale mapping exercises.

With a 5 d repeat cycle, Sentinel-2 images have only minor shortcomings relative to the PlanetScope imagery but also have a clear advantage such as a stable image quality (Fig. 10). As a result, Sentinel-2 outperforms PlanetScope in the early spring and late autumn when snow cover obstructs the image quality of the latter. Although the PlanetScope imagery was essential for constraining the drainage time periods at the Tystigbreen lakes (Table 3, Fig. 4), it was often assisted by the Sentinel-2 imagery (events 7, 11, 12 and 16). By combining Sentinel-2 and PlanetScope images, we were able to track glacial lake development and detect drainage events with a higher temporal resolution than would be possible with data from only one satellite mission. With the choice of currently available non-commercial imagery, a combination of the Sentinel-2 and PlanetScope products might be therefore the best option for the detection of GLOF events and the associated lake filling and drainage patterns. Especially for the smaller lakes, comparison of the images from both missions would increase the chances of arriving at the right conclusions. However, such combined applications are currently restricted by the limited non-commercial availability of PlanetScope for the public use.

While we show that the combination of the two satellite datasets allows us to track the de-icing, filling and drainage patterns for lakes 1 and 2 throughout individual seasons (Fig. 5), it is unclear why mapped areas of lakes 1 and 2 are considerably larger in one of the analysed seasons (lake 1 in 2020, and lake 2 in 2019). These two instances stand out, since the maximum mapped lake areas are consistent during other years, suggesting that the two outliers may have absorbed the misinterpreted shadowed slopes or lake ice. Due to lack of ground-truthing data and aerial photographs, the time series of lake areas presented here should be considered as rough estimates.

5.2 Validation of automated mapping of sub-seasonal glacial lake changes on local scales

The example of Tystigbreen's glacial lakes demonstrates that automated threshold-based mapping techniques are not effective on local scales, especially for frequent sub-seasonal classification of small ice-dammed lakes (Fig. 7). For larger lakes surrounded by gentler, less shadow-prone slopes, it might be possible to conduct automated sub-seasonal time-series analyses. The uncertainties in the mapping accuracy are higher for smaller lakes, because of a larger significance of single pixels for the total estimated area (Shukla and others, 2018). Our results using NDWI for glacial lake extraction and tracking have revealed common misclassification of shadowed slopes and blue ice as water and exclusion of lake ice from the lake outlines. As we show on the example of lake 1 on 30 July, 95.4% of the deviation of the Sentinel-2-based NDWI from the manually derived outline could be accounted for the above-mentioned issues. This is a common problem for the NDWI method as diverse surface objects have similar spectral values as opposed to snow and water which have highly distinct values (Huang and others, 2018; Nagy and Andreassen, 2019).

To obtain correct threshold calculations for different surface types, one needs to ensure a consistent image quality with high

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spectral and radiometric accuracy, which is critical for the successful application of band-ratio mapping (Goswami and others, 2022). This is however where PlanetScope falls short, with large fluctuations in spectral values of lake surfaces and snow cover obstructing the quality of images between different dates and scenes due to illumination issues (see Section 5.1). It is therefore unsurprising that the results of automated mapping on the Sentinel-2 imagery are superior to those on the PlanetScope images (Figs 6, 7). However, even for Sentinel-2, the results of the band-ratio classification do not pass the quality control against manual mapping (Fig. 6). The method remains sensitive to the external conditions that largely determine the robustness of the mapping outcomes. Under optimal illumination conditions with no shadow or lake ice, the NDWI performs relatively well, while the mapping accuracy drastically drops when some of the typical issues discussed above are present. Although similar issues impact manual mapping too, it is easier to identify and correct for the impacts of floating ice, shadowed slopes and ice cover during manual digitisation of lake outlines.

Even though automated mapping may spare manual labour, it is dubious that the required compromises in mapping accuracy are justified by the reduction of workload, when it comes to local scales of individual ice caps and their ice marginal lakes. Specifically, for studies of GLOF-prone ice-dammed lakes in Norway, which are mostly small, frequent manual mapping is not such an unreasonable task and may be less labour-intensive than manual corrections of erroneous glacial lake outlines inferred from automated mapping (Andreassen and others, 2022). This assumption is also supported by larger-scale glacial lake inventories conducted in Uttarakhand, India, that demonstrated superiority of manual mapping based on high-resolution images over a semi-automated mapping tested by Bhambri and others (2015).

5.3 Linking diverse sources to fill gaps in the glacial lake drainage database

Through mapping and visual inspection of the Sentinel-2 and PlanetScope satellite imagery during ablation seasons of 2016–22, we were able to detect ten fairly certain drainage events originating from four active ice-dammed lakes at Tystigbreen (see Table 3). Four of these events were validated through fieldwork and supported by informal interviews with local citizens and collaborators (events 4, 11, 15 and 16). Additional evidence from the fieldwork on 15 June 2022 has allowed us to constrain the timing of the drainage event 16 (Table 3) to a time window of 5 d compared to 11 d based on remote sensing alone (Fig. 11).

The integration of interviews and photographic documentation into our analysis helped validate our results in two important ways. First, interviews with local people provided us with valuable information regarding past GLOFs, in some cases including their precise timing and duration (event 15) and their diverse signatures in the rivers depending on the likely origin of the flood (events 4 and 15). Local knowledge helped us detect a previously unknown GLOF-generating lake (lake 4; Fig. 11), the drainage of which we were able to capture during our fieldwork in 2022. Second, regular witness reports, including photographic documentation of the lake status (Fig. 9), helped us develop, test and refine methods for future lake monitoring.

As a result, we were able to identify two additional drainage events from lake 1 in October 2021 (event 5) and in 2016 (event 3), which could not be detected through optical remote sensing using the data sources in the present study. While not detectable in the satellite images, our collaborators reported significant noise in the vicinity of the lake due to cracking of the lake ice in October 2021 (event 10), which indicates a drainage of lake 1. The reported loud cracking of the lake ice also anticipates that the event was likely associated with a rapid water discharge leading to high water levels in the downstream hydrological system. This is consistent with the residents' assumptions for other drainage events from this lake. This new information about the nature of drainage events from lake 1 has led us to a hypothesis that drainages may have been induced by high pressures leading to a glacier lift (Nye, 1976; Clarke, 1982; Björnsson, 2010a). However, further research and monitoring is necessary to confirm this hypothesis. While community-based reporting of lake drainage events and their signatures is clearly useful for validating the results of remote sensing, there are also risks of misreporting. This has been exemplified by one case in our study (event 3), where participants suggested a different timing for the occurrence of the event. Regardless of the possible inconsistent reporting, we conclude that the fusion of citizen science with quantitative methods is an invaluable source of information that sometimes cannot be captured by optical remote sensing alone.

The national GLOF database includes only three GLOF events from the lakes at Tystigbreen, two of which are dated back to 2010 and 2014 (NVE, 2022). Only one of the ten certain drainage events detected by our sub-seasonal glacial lake analysis within the period of 2016–22 is registered in the national database (event 12) (NVE, 2022). However, most of the detected drainage events (five events where event 8 is uncertain as it was only

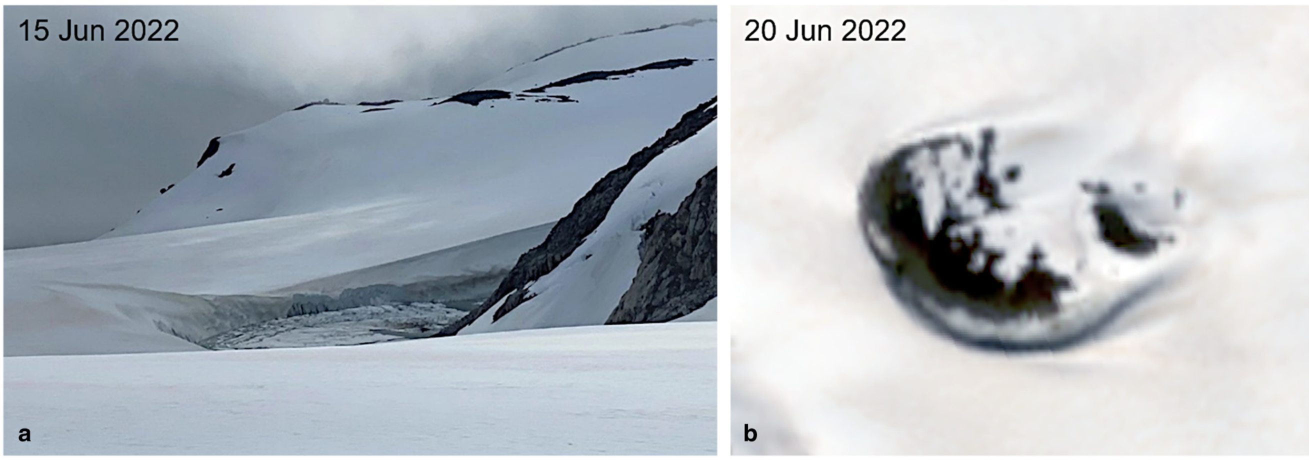

Figure 11. Documentation of the drainage of lake 4 between 15 June and 20 June 2022 (5 d). (a) The evidence of the filled lake 4 on 15 June 2022, photographed during the fieldwork. Photo: Ursula Enzenhofer. (b) A PlanetScope satellite image from 20 June 2022, where the lake is empty.

detected on the PlanetScope imagery) originate from lake 2, which according to our analysis, drains slowly over a period of 1–4 weeks. This slow drainage pattern indicates that drainage of lake 2 is likely induced by melting of ice walls and/or changes in the subglacial cavity drainage system rather than lifting of the glacier (Björnsson, 1992, 2010a, 2010b; Tweed and Russel, 1999; Carrivick and others, 2017). Such slow and non-hazardous events are typically defined as lake drainages rather than GLOFs. Nevertheless, the lake drainage behaviour may change with time following further retreat and thinning of the glacier wing that dams lake 2, as has been observed in other cases in Norway such as Demmevatnet (Elvehoy and others, 2002) and Koppangsbreen (Jackson and Ragulina, 2014).

Furthermore, we found that the two largest lakes at Tystigbreen have the potential to drain more or less simultaneously as was the case in 2018 (Fig. 5). While this dual event might have been the result of an unprecedentedly hot summer in south-western Norway (Skaland and others, 2019), such extreme summers will likely become more frequent in the future (Pachauri and others, 2014; Skaland and others, 2019). The identified potential for simultaneous drainage events from several lakes provides a strong motivation for their monitoring through the ablation season that also happens to coincide with the high season for tourism in the area. However, as demonstrated here, this task is not trivial thanks to the limitations of the current open-access satellite products. Currently, the installation of lake-monitoring systems is not a priority because of the non-hazardous nature of the documented lake drainages and the small permanent population of the downstream areas. Hence, the systematic observations by local citizens can serve as sources of validation for remote sensing and information about potential switches between slow and rapid lake drainage styles.

6. Conclusions

Our study combines remote sensing, qualitative methods and citizen science to highlight advantages and limitations of different satellite products and quantify the added value of local knowledge for the monitoring of sub-seasonal ice-dammed lake changes and glacial lake drainage events. Using the case of four ice-dammed lakes of the Tystigbreen glacier, the resolution of the Landsat-8 imagery is deemed insufficient for such analyses. Based on a combination of PlanetScope and Sentinel-2 images, we were able to detect ten glacial lake drainage events and constrain their timing with a precision of 5–32 d. While the high spatial and temporal resolution of PlanetScope is useful for detecting glacial lakes and tracking lake changes on small scales, automatising their mapping with this satellite product is still challenging due to inconsistent image quality. We suggest that further research should focus on fusing the two satellite products to overcome the above issues of PlanetScope and profit from the more consistent image quality and higher spectral resolution of Sentinel-2.

Here we demonstrate that satellite data analyses can capture most of the reported drainage events from the two largest ice-dammed lakes in our study area, albeit with a relatively low-temporal resolution. The latter is mainly due to frequent cloud cover that limits the number of available images with a clear sight of the lakes. These issues may be overcome combining multispectral images with SAR data in the future. For drainage events outside the main ablation season, we have identified further limitations related to extensive lake ice and snow cover in the early and late stages of the season. Also, our preliminary assessment of the added value of the citizen-based lake monitoring and witness accounts confirms that such data can significantly increase the precision of the remote-sensing analyses and in difficult cases, mitigate the aforementioned shortcomings. Our collaboration with the Stryn Summer Ski centre exemplifies the value of citizen science for obtaining direct constraints on the sub-seasonal glacial lake development. Information collected through interviews with local citizens has helped us identify unrecognised GLOF events and verify the occurrence and timing of previously known events. However, we recognise that the precision and quality of the reported information must be improved if it is to be used for systematic monitoring of glacial lakes and GLOFs.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2024.13.

Author contributions. J. M. A. selected, downloaded and prepared the satellite images and conducted the remote-sensing analyses and mapping. I. R. supervised the study design. K. K. B. prepared the interview guide. K. K. B. and J. M. A. conducted and analysed the interviews. J. M. A. and I. R. wrote the manuscript draft with contributions from K. K. B., R. L. and L. M. A. All authors read and commented on the manuscript.

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Data. The satellite data used in the study were accessed through the following portal sites (last accessed 23 January 2023): https://earthexplorer.usgs.gov/ (Landsat 7–8), https://scihub.copernicus.eu/ (Sentinel-2) and https://developers.planet.com/explorer/ (PlanetScope). Tystigbreen's glacial lake outlines for lakes 1 and 2 for the seasons 2016–22 are available as dataset from Nasjonalt Vitenarkiv (NVA) at: https://doi.org/10.58059/zbz8-bg39.

References

Ahmed B and Kelman I (2018) Measuring community vulnerability to environmental hazards: a method for combining quantitative and qualitative data. *Natural Hazards Review* **19**(3), 04018008. doi: 10.1061/(asce)nh.1527-6996.0000290

Andreassen LM, Winsvold SH, Paul F and Hausberg JE (2012) Inventory of Norwegian Glaciers. NVE Rapport 38-2012. Norwegian Water Resources and Energy Directorate, Oslo, Norway.

Andreassen LM, Nagy T, Kjøllmoen B and Leigh JR (2022) An inventory of Norway's glaciers and ice-marginal lakes from 2018–19 Sentinel-2 data. *Journal of Glaciology* **68**(272), 1–22. doi: 10.1017/jog.2022.20

Barbieux K, Charitsi A and Merminod B (2018) Icy lakes extraction and water-ice classification using Landsat-8 OLI multispectral data. *International Journal of Remote Sensing* **39**(11), 3646–3678. doi: 10.1080/01431161.2018.1447165

Bhambri R, Mehta M, Dobhal DP and Gupta AK (2015) *Glacier Lake Inventory of Uttarakhand*. Dehradun, India: Wadia Institute of Himalayan Geology, p. 78.

Bhardwaj A and 7 others (2015) A lake detection algorithm (LDA) using Landsat-8 data: a comparative approach in glacial environment. *International Journal of Applied Earth Observation and Geoinformation* **38**, 150–163. doi: 10.1016/j.jag.2015.01.004

Björnsson H (1992) Jökulhlaups in Iceland: prediction, characteristics and simulation. *Annals of Glaciology* **16**, 95–106. doi: 10.3189/1992AoG16-1-95-106

Björnsson H (2010a) Jökulhlaups in Iceland: sources, release and drainage. In *Megaflooding on Earth and Mars*. Cambridge University Press, pp. 50–64. doi: 10.1017/CBO9780511635632.004

Björnsson H (2010b) Understanding Jökulhlaups: from tale to theory. *Journal of Glaciology* **56**(200), 1002–1010. doi: 10.3189/002214311796406086

Carrivick JL and Quincey DJ (2014) Progressive increase in number and volume of ice-marginal lakes on the western margin of the Greenland ice sheet.

Global and Planetary Change **116**, 156–163. doi: 10.1016/j.gloplacha.2014.02.009
Carrivick JL and 9 others (2017). Ice-dammed lake drainage evolution at Russell Glacier, West Greenland. *Frontiers in Earth Science* **5**, 100 doi: 10.3389/feart.2017.00100
Chen F and 6 others (2021). Annual 30 m resolution dataset for glacial lakes in High Mountain Asia from 2008 to 2017. *Earth System Science Data* **13** (2), 741–766. doi: 10.5194/essd-13-741-2021
Clague JJ, Huggel C, Korup O and MCguire B (2012) Climate change and hazardous processes in high mountains. *Revista de la Asociación Geológica Argentina* **69**(3), 328–338. doi: 10.5167/uzh-77920
Clarke GK (1982) Glacier outburst floods from 'Hazard Lake', Yukon Territory, and the problem of flood magnitude prediction. *Journal of Glaciology* **28**(98), 3–21.
Cooley SW, Smith LC, Stepan L and Mascaro J (2017) Tracking dynamic northern surface water changes with high-frequency planet CubeSat imagery. *Remote Sensing* **9**(12), 1306. doi: 10.3390/rs9121306
Dechoz C and 9 others (2015) Sentinel 2 global reference image. Image and signal processing for remote sensing XXI, SPIE, 94-107.
Elvehoy H and 5 others (2002) Assessment of possible Jökulhlaups from Lake Demmevatnet in Norway. IAHS Publications. No. 271: 31–36.
Emmer A and 26 others (2022a) 160 glacial lake outburst floods (GLOFs) across the Tropical Andes since the Little Ice Age. *Global and Planetary Change* **208**, 103722. doi: 10.1016/j.gloplacha.2021.103722
Emmer A and 36 others (2022b) Progress and challenges in glacial lake outburst flood research (2017–2021): a research community perspective. *Natural Hazards and Earth System Sciences* **22**(9), 3041–3061. doi: 10.5194/nhess-22-3041-2022
ESA (2015) *Sentinel-2 user handbook*. ESA Standard Document, Issue 1 Rev 2.1.2, 1–64.
Esri (2022) World Imagery, https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer [accessed 2023-06-27].
Goswami A and 8 others (2022) Change detection in remote sensing image data comparing algebraic and machine learning methods. *Electronics* **11** (3), 431. doi: 10.3390/electronics11030431
Haeberli W and 5 others (2016) New lakes in deglaciating high-mountain regions – opportunities and risks. *Climatic Change* **139**(2), 201–214. doi: 10.1007/s10584-016-1771-5
Houborg R and McCabe MF (2018) A CubeSat enabled spatio-temporal enhancement method (CESTEM) utilizing Planet, Landsat and MODIS data. *Remote Sensing of Environment* **209**, 211–226. doi: 10.1016/j.rse.2018.02.067
Huang C, Chen Y, Zhang S and Wu J (2018) Detecting, extracting, and monitoring surface water from space using optical sensors: a review. *Reviews of Geophysics* **56**(2), 333–360. doi: 10.1029/2018rg000598
Huggel C, Kääb A, Haeberli W, Teysseire P and Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal* **39**(2), 316–330. doi: 10.1139/t01-099
Hui F, Xu B, Huang H, Yu Q and Gong P (2008) Modelling spatial-temporal change of Poyang Lake using multitemporal Landsat imagery. *International Journal of Remote Sensing* **29**(20), 5767–5784. doi: 10.1080/01431160802060912
Huss M, Bauder A, Werder M, Funk M and Hock R (2007) Glacier-dammed lake outburst events of Gornersee, Switzerland. *Journal of Glaciology* **53** (181), 189–200. doi: 10.3189/172756507782202784
Iturrizaga L (2011) Glacier lake outburst floods. In Singh VP, Singh P and Haritashya UK (eds), *Encyclopedia of Snow, Ice and Glaciers*. Dordrecht, Netherlands: Springer, pp. 381–399. doi: 10.1007/978-90-481-2642-2_196
Jackson M and Ragulina G (2014) Inventory of glacier-related hazardous events in Norway. NVE Rapport 83-2014. Norwegian Water Resources and Energy Directorate, Oslo, Norway.
Jain SK, Lohani AK, Singh RD, Chaudhary A and Thakural LN (2012) Glacial lakes and glacial lake outburst flood in a Himalayan basin using remote sensing and GIS. *Natural Hazards* **62**(3), 887–899. doi: 10.1007/s11069-012-0120-x
Kääb A and 14 others (2021) Sudden large-volume detachments of low-angle mountain glaciers – more frequent than thought? *The Cryosphere* **15**(4), 1751–1785. doi: 10.5194/tc-15-1751-2021
Kingslake J and Ng F (2013) Quantifying the predictability of the timing of Jökulhlaups from Merzbacher Lake, Kyrgyzstan. *Journal of Glaciology* **59** (217), 805–818. doi: 10.3189/2013JoG12J156
Kjollmoen B, Andreassen LM, Elvehoy H and Storheil S (2022) Glaciological investigations in Norway. NVE Rapport 27-2022. Norwegian Water Resources and Energy Directorate.
Latte N and Lejeune P (2020) PlanetScope radiometric normalization and Sentinel-2 super-resolution (2.5 m): a straightforward spectral-spatial fusion of multi-satellite multi-sensor images using residual convolutional neural networks. *Remote Sensing* **12**(15), 2366. doi: 10.3390/rs12152366
Leach N, Coops NC and Obrknezev N (2019) Normalization method for multi-sensor high spatial and temporal resolution satellite imagery with radiometric inconsistencies. *Computers and Electronics in Agriculture* **164**, 10489. doi: 10.1016/j.compag.2019.10489
Li J and Sheng Y (2012) An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. *International Journal of Remote Sensing* **33**(16), 5194–5213. doi: 10.1080/01431161.2012.657370
Liestøl O (1956) Glacier dammed lakes in Norway. *Norsk Geografisk Tidsskrift* **15**, 122–149.
Liu JJ, Cheng ZL and Su PC (2014) The relationship between air temperature fluctuation and glacial lake outburst floods in Tibet, China. *Quaternary International* **321**, 78–87. doi: 10.1016/j.quaint.2013.11.023
Lussana C, Tveito OE, Dobler A and Tunheim K (2019) seNorge_2018, daily precipitation, and temperature datasets over Norway. *Earth System Science Data* **11**(4), 1531–1551. doi: 10.5194/essd-11-1531-2019
McFeeters SK (1996) The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing* **17**(7), 1425–1432.
Mergili M, Schneider D, Worni R and Schneider JF (2011) Glacial lake outburst floods in the Pamir of Tajikistan: challenges in prediction and modelling. *Italian Journal of Engineering Geology and Environment*, in: Special issue: V Conference Debris Flow, Padua, Italy, 973–982. doi: 10.4408/IJEGE.2011-03.B-106
Moore RD and 7 others (2009) Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes* **23**(1), 42–61. doi: 10.1002/hyp.7162
Nagy T and Andreassen LM (2019) Glacier lake mapping with Sentinel-2 imagery in Norway. NVE Rapport 40-2019. Norwegian Water Resources and Energy Directorate, Oslo, Norway.
Nazakat H and 5 others (2021) Machine Learning Algorithms for Extraction of Glacial Lakes Using Ground Range Detected (GRD) Data: A Case Study from Hunza River Basin, Pakistan. Research Square Platform LLC. doi: 10.21203/rs.3.rs-590990/v1
Ng F and Liu S (2009) Temporal dynamics of a Jökulhlaups system. *Journal of Glaciology* **55**(192), 651–665. doi: 10.3189/002214309789470897
Ng F, Liu S, Mavlyudov B and Wang Y (2007) Climatic control on the peak discharge of glacier outburst floods. *Geophysical Research Letters* **34**(21), L21503. doi: 10.1029/2007gl031426
Nie Y and 6 others (2017) A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sensing of Environment* **189**, 1–13. doi: 10.1016/j.rse.2016.11.008
NVE (1993) Ferskvannstesaurus. Hydrologisk avdeling. Publikasjon 18.18.
NVE (2022) *Glacier Lake Outburst Floods*. Oslo, Norway: Norwegian Water Resources and Energy Directorate (NVE), http://glacier.nve.no/Glacier/viewer/GLOF/en. Downloaded 2022.10.22.
Nye JF (1976) Water flow in glaciers: Jökulhlaups, tunnels and veins. *Journal of Glaciology* **17**(76), 181–207.
Pachauri RK and 9 others (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC.
PlanetLabs (2020) Planet Imagery Product Specifications. Inc: San Francisco, CA, USA, June 2020.
PlanetTeam (2017) *Planet Application Program Interface: In Space for Life on Earth*. San Francisco, CA, **2017**, 40. https://api.planet.com
Qayyum N, Ghuffar S, Ahmad HM, Yousaf A and Shahid I (2020) Glacial lakes mapping using multi satellite PlanetScope imagery and deep learning. *ISPRS International Journal of Geo-Information* **9**(10), 560. doi: 10.3390/ijgi9100560
Racoviteanu AE, Williams MW and Barry RG (2008) Optical remote sensing of glacier characteristics: a review with focus on the Himalaya. *Sensors* **8**(5), 3355–3383. doi: 10.3390/s8053355
Racoviteanu AE, Paul F, Raup B, Khalsa SJS and Armstrong R (2009) Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space

(GLIMS) workshop, Boulder, Colorado, USA. *Annals of Glaciology* **50**(53), 53–69. doi: 10.3189/172756410790595804

Shugar DH and 9 others (2020) Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change* **10**(10), 939–945. doi: 10.1038/s41558-020-0855-4

Shukla A, Garg PK and Srivastava S (2018) Evolution of glacial and high-altitude lakes in the Sikkim, Eastern Himalaya over the past four decades (1975–2017). *Frontiers in Environmental Science* **6**, 81. doi: 10.3389/fenvs.2018.00081

Skaland RG and 12 others (2019) *Tørkesommeren 2018*. Oslo, Norway: Meteorologisk Institutt.

Storey J, Choate M and Lee K (2014) Landsat-8 operational land imager on-orbit geometric calibration and performance. *Remote Sensing* **6**(11), 11127–11152. doi: 10.3390/rs61111127

Strasser BJ, Baudry J, Mahr D, Sanchez G and Tancoigne E (2019) Citizen science? Rethinking science and public participation. *Science & Technology Studies* **32**(2), 52–76. doi: 10.23987/sts.60425

Stratford E and Bradshaw M (2016) *Qualitative Research and Rigour*. In I. Hay (Ed.). 4th edn. Ontario: Oxford University Press, pp. 117–129.

Tweed FS and Russell AJ (1999) Controls on the formation and sudden drainage of glacier-impounded lakes: implications for Jökulhlaups characteristics. *Progress in Physical Geography: Earth and Environment* **23**(1), 79–110.

USGS (2012) Landsat: A global land-imaging mission. Report 2012-3072.

Walder JS and Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. *Earth Surface Processes and Landforms* **21**(8), 701–723.

Wang X, Liu Q, Liu SY and He GL (2020) Manifestations and mechanisms of mountain glacier-related hazards. *Sciences in Cold and Arid Regions* **12**(6), 436–446. doi: 10.3724/SP.J.1226.2020.00436

Wang W, Xiang Y, Gao Y, Lu A and Yao T (2015) Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas. *Hydrological Processes* **29**(6), 859–874. doi: 10.1002/hyp.10199

Wang W, Zhang T, Yao T and An B (2022) Monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas. *International Journal of Disaster Risk Reduction* **73**, 102914. doi: 10.1016/j.ijdrr.2022.102914

Wangchuk S and Bolch T (2020) Mapping of glacial lakes using Sentinel-1 and Sentinel-2 data and a random forest classifier: strengths and challenges. *Science of Remote Sensing* **2**, 100008. doi: 10.1016/j.srs.2020.100008

Watson CS, Quincey DJ, Carrivick JL and Smith MV (2016) The dynamics of supraglacial ponds in the Everest region, central Himalaya. *Global and Planetary Change* **142**, 14–27. doi: 10.1016/j.gloplacha.2016.04.008

Xu H (2006) Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing* **27**(14), 3025–3033. doi: 10.1080/01431160600589179

Yan W, Liu J, Zhang M, Hu L and Chen J (2017) Outburst flood forecasting by monitoring glacier-dammed lake using satellite images of Karakoram Mountains, China. *Quaternary International* **453**, 24–36. doi: 10.1016/j.quaint.2017.03.019

Yang J and 8 others (2013) The role of satellite remote sensing in climate change studies. *Nature Climate Change* **3**, 875–883. doi: 10.1038/nclimate2033

Zhang MM, Chen F and Tian BS (2018) An automated method for glacial lake mapping in High Mountain Asia using Landsat-8 imagery. *Journal of Mountain Science* **15**(1), 13–24. doi: 10.1007/s11629-017-4518-5

Zhang MM, Chen F, Tian BS, Liang D and Yang A (2020) High-frequency glacial lake mapping using time series of Sentinel-1A/1B SAR imagers: an assessment for the southeastern Tibetan Plateau. *International Journal of Environmental Research and Public Health* **17**(3), 1072. doi: 10.3390/ijerph17031072