Glacier Extents of the Greater Caucasus mountain range derived from manual interpretation and digital classification of Landsat satellite data

The long debris covered tongue of the Adishi glacier, named after the nearby village of Adishi, winds its way down the southern slopes of the Greater Caucasus (Tielidze, 2012)

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Abstract

Glaciers are important indicators of climate change and an accurate and up to date inventory is needed in order to assess these changes over time. Satellite imagery allows areas which were previously understudied to be analysed in depth; the Caucasus is one region with an incomplete inventory. This study aims to analyse different methodologies for glacier delineation and use comparative qualitative and quantitative measures to assess which can produce the most accurate glacier outlines. Landsat 8 imagery was analysed using a variety of band ratio methods, a semi automatic method which uses buffers to identify debris area, and manual outlines of the Caucasus region. The efficacy of different methods is highly dependent on the environment and topography of the area and each method offers a trade off between accuracy and speed. The methodology used should therefore be chosen according to the region and tested on smaller areas to assess accuracy.

Technische Universität Dresden

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Statement of Authorship

Herewith I declare that I am the sole author of the thesis named:

"Glacier Extents of the Greater Caucasus mountain range derived from manual interpretation and digital classification of Landsat satellite data"

which has been submitted to the study commission of geosciences today. I have fully referenced the ideas and work of others, whether published or un-published. Literal or analogous citations are clearly marked as such.

KATE DOYLE

Dresden 25/09/17

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1. Introduction

Glaciers are important climate indicators that can provide an indication of current and past climate changes. With global temperatures expected to increase by up to 6°C by the end of the century (NASA, n.d), glaciers will continue to become increasingly important indicators of climate change for as long as they continue to be present. In order to gain an accurate understanding of how these glacier fluctuations are indicative of changing global temperatures it is important to have accurate delineations of glaciers in multiple environments. Monitoring and mapping these glaciers can help further climate research as well as understand climatic forcing on glaciers.

However, in many areas glacier inventories are limited and more research is required in order to better understand how local climate may be affecting growth and retreat (Vaughan, et al., 2013). Creating these inventories is integral in analyzing changes over time as well as predicting how future changes will impact other variables such as sea level rise, local water supplies and debris flows (Tielidze & Wheate, 2017; Tielidze, 2016). The World Glacier Inventory (WGI) collates a database of global glaciers, including data on the length, location and morphological glacier types. In order to improve the amount of glacier coverage recorded using satellite sensors, WGI launched the Global Land Ice Measurements from Space (GLIMS) in 1995, but in 2010 only ~30% of the world's total glacier area were accurately recorded and inventoried (Radić & Hock, 2010). Areas may not have been inventoried for a number of reasons, but largely due to inaccessibility issues (e.g. difficult terrain, political instability.) However, remote sensing has revolutionized the collection of glacier data – making areas that were previously difficult and dangerous to enter, easily accessible as well as improving the capabilities to measure volume, area and length compared to traditional methods. Accuracy of measurements have also improved since the advent of remote sensing, both temporally and spatially (Figure 1) and when combined with historical maps the inventories provide a clear depiction of glacier change.

Despite developments in satellite technology since the 1960s, some glaciated areas are under and mis-sampled. One such incomplete inventory is that of the Caucasus region. The inventory has been discontinuous as a result of political instability in the 1990s, and inaccurate spatial references in earlier records (Solomina, et al., 2016). Initial area assessments from 1911 also contain some visualization mistakes in area and number of glaciers (Tielidze, et al., 2015). Therefore, an accurate inventory for this area was invaluable as one of the major mountain ranges in Eurasia, Caucasus glaciers are an important water source for the region and the Caspian Sea, and with warming temperatures could have anthropological impacts from hazards such as mud flows and glacial lake outbursts (Shahgedanova, et al., 2009). In order to provide the most detailed data to cope with

Parameter	Method	Technique	Typical Accuracy	Number of Glaciers	Repeat Interval	Earliest Data
Length change	Various	Reconstruction	10 m	Dozens	Decadal – centuries	Holocene
	Field	*In situ* measurement	1 m	Hundreds	Annual	19th century
	Remote sensing	Photogrammetric survey	Two image pixels (depending on resolution)	Hundreds	Annual	20th century
Area change	Maps	Cartographic	5% of the area	Hundreds	Decadal	19th century
	Remote sensing	Image processing	5% of the area	Thousands	Sub-decadal	20th century
Volume change	Remote sensing	Laser and radar profiling	0.1 m	Hundreds	Annual	21st century
	Remote sensing	DEM differencing	0.5 m	Thousands	Decadal	20th century
Mass change	Field	Direct mass balance measurement	0.2 m	Hundreds	Seasonal	20th century
	Remote sensing	Gravimetry (GRACE)	Dependent on the region	Global	Seasonal	21st century

Figure 1: Methods to determine glacier length, area and volume showing the importance of remote sensing in glacier estimation (Vaughan, et al., 2013)

ramifications and better understand glacier dynamics, a thorough and complete analysis of glacier delineation methods should be undertaken.

Improved research on Caucasus glaciers and the effect of climate on glacier dynamics is an important topic which is currently understudied. This report therefore aims to further understanding of how to best digitize these glaciers to improve inventories such as the WGI. Current literature is limited on the topic of Caucasus glaciers (a search in Web of Science for the key words “Caucasus glacier” produces 85 results compared to 1,054 for “Himalaya glacier” and 356 for “Alps glacier”) and therefore more research in this region could assist in furthering scientific understanding.

Current literature focuses on three main themes: the geography of the Caucasus, digitization methods and dealing with debris cover in semi automatic classifications. Each of these topics will be discussed in turn.

1.1 Geography and geology of the Caucasus

The Caucasus Mountain range is situated at 42-44°E,40-49°N and lies on the borders between Russia, Georgia, Armenia and Azerbaijan (Figure 2). The Caucasus can be split into two mountain ranges, with the Greater Caucasus spanning the largest area and the Lesser Caucasus, situated principally in lower Georgia and Azerbaijan. The largest proportion of glaciers is in the Greater Caucasus, which includes 98% of Georgian glaciers (Solomina, et al., 2016). Therefore, this will be the main study area for this research (from hereon the Greater Caucasus will be referred to as the Caucasus).

The geology is principally composed of metamorphosed rocks such as schist, gneiss and granite in the western Caucasus while clayey schist and sandstone is more widespread in eastern regions (Encyclopaedia Britannica, 2017).

Climate and topography within the Caucasus is varied, with ecosystems ranging from semi-arid to humid and water resources fluctuating across the mountain range (Shahgedanova, et al., 2009).

Figure 2: The Caucasus region, with the Greater Caucasus forming the border between Azerbaijan, Georgia and Russia (University of Texas Library, 1994)

One reason for these disparities in water availability is that an eastward trajectory along the mountain range is accompanied by decrease of one third to one quarter in annual precipitation, largely as a result of the Siberian and Azores high blocking systems from the north – with precipitation originating in the Black Sea moving east. The topography of both the Greater and Lesser Caucasus create an 'orthographic barrier' which blocks storm systems from the Black Sea, resulting in ~2m/y precipitation (Forte, et al., 2016). This precipitation lends itself to glacier formation, with a larger percentage of glaciers found in the western part of the Caucasus. The Caucasus can be further divided into west, central and east; with the central region containing the largest number of alpine glaciers with an area of >100km^2 (Elizbarashvili, et al., 2009) In the western Caucasus, there are many wide glacial cirques and narrows passes, while in the centre there is a large amount of fragmentation as a result of glacial erosion – the central area also has the highest elevation compared to east and west regions (Tielidze, 2017). The majority of cirques in the central Caucasus contain glaciers as a result of this higher elevation, whereas in the lower western and eastern areas glaciers only appear in cirques with a favourable orientation (Solomina, et al., 2016). As a result of the lack of rainfall in the eastern Caucasus there are few glaciers. The relief of the mountains, in turn, affects glacier formation with parameters such as air temperature, precipitation and wind having an influence upon the amount of glaciation. Snow cover is also an important influence, and decreases with an eastward trajectory; on average at 2500m altitude the west receives 250 days of snow, the centre 160 and the east 100 (Lur'e & Panov, 2014). The number of glaciers is therefore a function of the orogenous relief and climatic systems.

As a result of warming temperatures, glaciers in the region are becoming more numerous through fragmentation (Lur'e & Panov, 2014). Many people rely on the Caucasus for water resources and as a consequence of warming temperatures, water sources which are crucial in both Georgia and Russia will become threatened (Lambrecht, et al., 2011).

1.2 Methods of Glacier Digitization

Creating an accurate glacier inventory is important for assessments of glacier dynamics and effects of climatic change; therefore, finding the most accurate method of glacier delineation is of paramount importance.

There are two methods which can be used to digitize glaciers. The first is manual delineation, which is perceived as the most accurate when compared to other (automated) methods of digitization (Tiwari, et al., 2016). In general, areas derived manually are smaller and more precise than those derived from semi automatic processing of Landsat Thematic Mapper (TM) data (Paul, 2002). While the manual method may be preferable for areas with a few glaciers, or individual glacier delineation, when digitization is needed on a bigger scale manually tracing the outlines can be laborious and time-consuming (Paul, 2009; Paul, 2000). In addition to this, digitizing by hand also requires a degree of 'local-knowledge' (Williams, et al., 1997) in order to precisely delineate the glacier margin.

Problems may also arise in manual delineation, as rock outcrop interpretation can be difficult (Paul, 2002). Although Raup & Khalsa (2007) suggest that when digitizing for GLIMS these outcrops could be classed as nunatuks, manual digitizing often raises the question of what constitutes a glacier (Raup, et al., 2014) and where glacier extents should be drawn.

In general, the manual method for finding glacier extents is more accurate than a comparable semi automatic method, but is also considerably more arduous. In the case of areas of extensive ice cover, Bolch et al. (2010) found that with an acceptable error of ±3-4%, a semi automatic process would be far superior as a result of the relative speed of delineation.

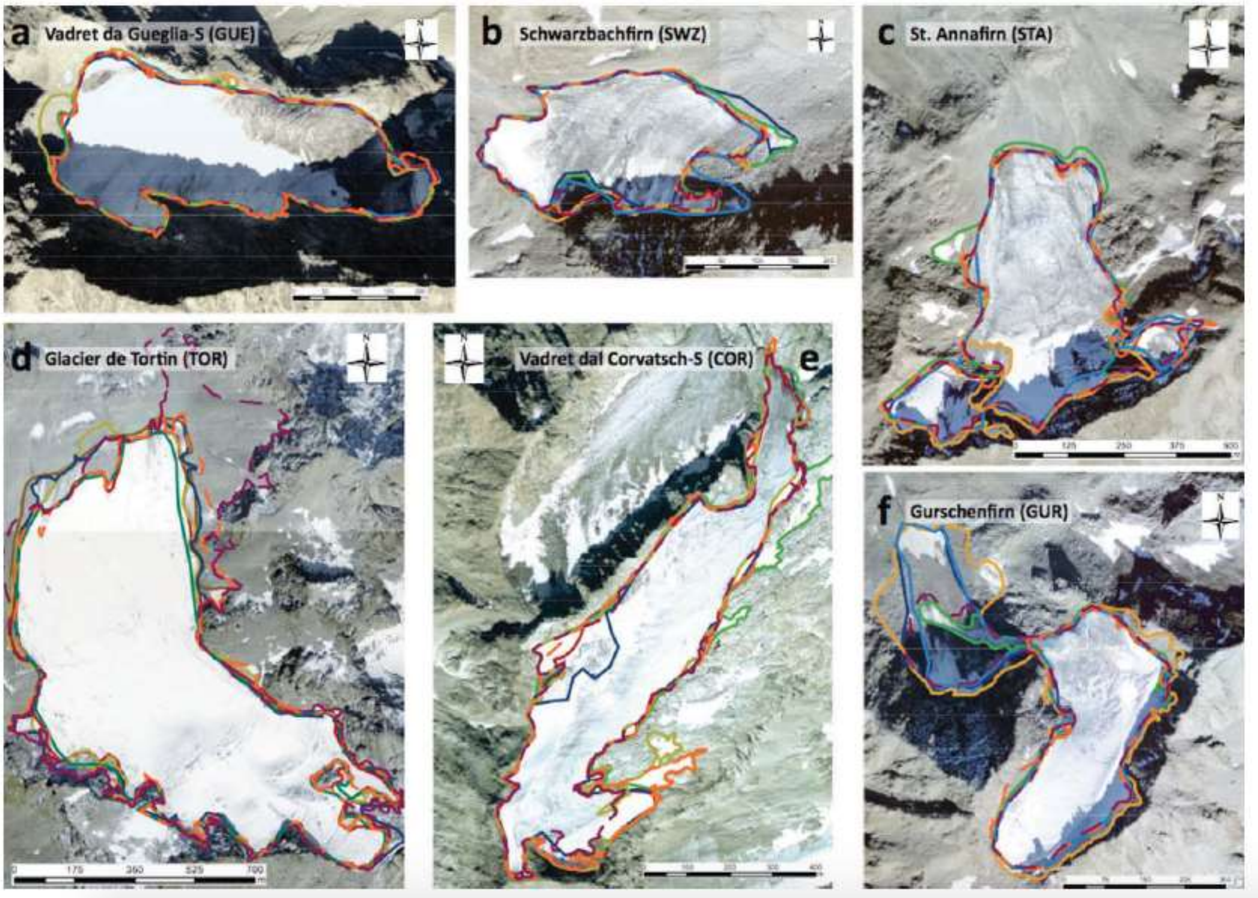


Figure 3: Glacial extents for six Swiss glaciers as drawn by seven experts, showing the subjectivity in manual delineation (Fischer, et al., 2014)

Other problems with manual delineation using satellite images may include, the lack of a 3D perspective of satellite scenes, spectral similarities between supraglacial morainic debris and the terminal moraine and marginal snow pack (Williams, et al., 1997).

The subjectivity of both methods must also be taken into account. Manual delineations are subjective with regard to where the extents are drawn even if all interpreters have local or expert knowledge (Figure 3), and semi automatic delineations could be said to be subjective due to the choice of satellite scene and subsequent threshold value (Winsvold, et al., 2016). For semi automatic methodology, perhaps the most widely used is a simple band ratio, dividing the Red or Near Infrared (NIR) by the Shortwave Infrared band (SWIR) (Sidjak & Wheate, 1999). This is effective in finding areas of clean ice, and for regions with many glaciers provides a robust, fast and often more accurate estimate of glacier area than other, more complex, methods (Paul, et al., 2016). Other research has considered combining different bands e.g. integrating the blue band to find shadowed ice, using the panchromatic band to create a more accurate delineation (Paul, et al., 2016) or combining bands to find a greater area of debris-cover (Alifu, et al., 2016). However, it is widely acknowledged that the principal problem with a simple band-ratio is the recognition of debris cover which is often not classified as glacier due to its spectral signature (see section 1.3). Therefore, many semi automatic methods now explore how to improve the accuracy of band ratios through techniques which include other layers such as digital elevation models (DEM) and texture parameters. Choosing between a manual or semi automatic method is a trade off; if a manual method is chosen it is more accurate but considerably more time-consuming, while a semi automatic method is faster but may be less precise (especially when concerned with debris covered glaciers). Tiwari et al. (2016) indicate the speed of semi automatic methods on a test area in the Himalayas (two glaciers with differing debris covers) using a DEM to calculate geomorphometric parameters (slope and curvature). The average processing time for the semi automatic method was 3-4 hours compared to the manual method, which could take between 5-20 hours depending on knowledge and experience. Although a semi automatic method will need manual corrections, the processing time can be a quarter of manual delineation.

1.3 Dealing with Debris cover

Using a semi automatic method to delineate glaciers can be problematic in areas which are not ‘clean ice’. This may be as a result of debris cover (Figure 4), shadow or other water bodies being counted as glacier. Some of these problems are rectifiable by changing the threshold, or using different bands when creating a ratio image (see section 2.3). For example, by using the NIR band and setting an appropriate threshold, water bodies can be removed while still including clean ice (Ke, et al., 2016). However, identifying debris cover in semi automatic methods still continues to be the biggest problem in creating an accurate glacier inventory. The large amounts of debris cover are principally a result of receding and down-wasting glacier margins (Williams, et al., 1997) and will become an increasingly common sight with ongoing climate change. In fact, many glaciers in the Caucasus region have debris covered termini (Stokes, et al., 2006).

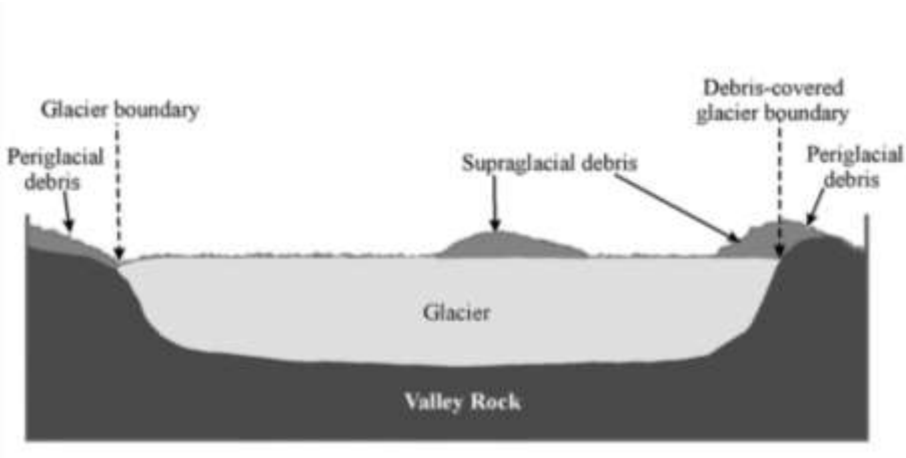


Figure 4: Cross-section a debris covered glacier, showing different types of debris cover and where they occur (Shukla, et al., 2010)

To create a more precise estimation of glacier area using semi automatic methodology a variety of techniques have been employed, but none so far have been found to be a perfect solution. One method is to integrate a DEM to assess slope, aspect profile and plan curvature. A high resolution DEM is needed due to the complex topography of mountain regions (Paul, et al., 2016), and a coarser spatial resolution, particularly on glacier margins, can be problematic – however, using a DEM can help to improve delineation of glaciers with debris cover overall (Buchroithner & Bolch, 2007).

Another method being explored is using the thermal band to assess areas covered by debris (which would be cooler than the surrounding bedrock). Although this methodology seems promising, it is difficult to distinguish between stagnant and active glacier ice and visual interpretation is needed to correct the outlines (Bolch, et al., 2007); exclusively using the thermal band is not enough for glaciers with a large amount of debris.

A more recent method of glacier debris identification is to use texture parameters to find debris covered glacier texture measures such as coarseness/smoothness, roughness, and symmetry which can show a vast difference between the debris covered ice, smoother glacier ice and surrounding bedrock (Racoviteanu & Williams, 2012). Although relatively little research has been done so far, this method could help to improve debris-covered glacier analysis.

While the above methods are being investigated, there are other methods such as pixel and object-based classification (Rastner, et al., 2014) and energy balance modelling (Ranzi, et al., 2004) which are under investigation to better map debris cover.

In order to validate or update an accurate inventory of glaciers a thorough investigation into manual and semi automatic techniques is needed in order to assess the relative accuracy of both methods in the Caucasus region.

1.4 Study Rationale

Globally, the main source of errors in glacier inventories is from insufficient knowledge of glacier area, with only 40% of world glaciers appearing in inventories in 2003 (Dyurgerov, 2003). In the Caucasus region, where glacial meltwater is an important water source for domestic and agricultural practices as well as posing significant hazards from outburst floods and debris flows, the most accurate inventory of the region is of significant importance and interest (Tielidze, 2016). Although studies (see: Alifu et al., 2016, Paul, 2000, Fischer et al., 2014) have approached the differences in justifying the methodology used, there are relatively few comparing these digitization methods. Related work has used a variety of methods, from ice-core sampling (Popovnin, 1999) to hydrological models (Shahgedanova, et al., 2009), as well as the more typical remote sensing methodologies. The large focus (as with many glacier related articles) is to track the retreat of the glaciers and how this will impact on local communities, created using reconstructions (Solomina, et al., 2016), or pre-existing inventories combined with modern satellite data (Tielidze, et al., 2015). This study aims to use manual outlines from Tielidze & Wheate (2017) to compare methods for glacier delineation in the Caucasus and combine current research to create reproducible glacier delineation techniques for mountainous regions.

1.5 Aims and Objectives

1.5.1 Aim

- To evaluate the efficiency and accuracy of manual versus semi automatic methods of glacier digitization in the Caucasus mountain range

1.5.2 Objectives

- Examine available data and methods of glacier delineation
- Study the challenges of shadow, water and notably debris cover
- Select sample areas in the west, central and east Caucasus
- Determine optimum thresholds for band ratios of ice
- Compare glacier extents for manual, ratio, semi automatic methods
- Identify robust glacier outlines for the Caucasus region and methods which can be applied to other areas and for updates
- Compare outlines qualitatively and quantitatively

2. Methodology

2.1 Study Area

Tielidze & Wheate (2017) outline three areas of the Caucasus (Figure 5), each of which focuses on a different section of the mountain range (west, central and east). This offers a wide array of glacier environments to test the robustness of glacier delineation. Although these areas do not include all glaciers in the Caucasus range, they offer a good representation of a variety of glacier environments and therefore will offer an accurate portrayal of the relevant accuracy of different delineation methodologies and how each performed. As discussed in section 1.1, the environment differs drastically between the western and eastern sections of the Caucasus and therefore each must be assessed separately to identify influencing factors.

Figure 5: Study areas of the Caucasus used in this research

2.2 Data

Table 1 shows an overview of all scenes used for research, with a detailed description of Landsat and ALOS PRISM datasets in sections 2.1.2 and 2.1.3 respectively.

Database Sensor	Region	Scene No.	Acquisition Date	Number of Bands	Spatial Resolution
Landsat 8	West	LC817203020132355LGN00	23/08/13	11	30m (15m Panchromatic)
Landsat 8	Central	LC81710302014215LGN00	03/08/14	11	30m (15m Panchromatic)
Landsat 8	East	LC81700302014240LGN00	28/08/2014	11	30m (15m Panchromatic)
ALOS DSM	West	N043E041	01/03/2017	-	30m
ALOS DSM	Elbrus	N043E042	01/03/2017	-	30m
ALOS DSM	Central	N043E042	01/03/2017	-	30m
ALOS DSM	East	N042E045	01/03/2017	-	30m

Table 1: Satellite scenes used in this study

2.2.2 Landsat

As a result of cost and availability, many studies utilize imagery from the Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM) and Landsat Operational Land Imager (OLI), launched in 1972, 1982 and 2013 respectively. Landsat 8 OLI has 11 bands (see Table 2) which allows pan-sharpening with the use of band 8 in panchromatic (Loyd, 2013). MSS and TM have been widely used due to the high spatial coverage of the sensor, achieving near global repeat analysis at a scale of 80m (MSS) and 30m (TM & OLI) (Paul, 2002). Landsat is preferable for glacier mapping as a result of a dense time series when Landsat satellites are combined (Winsvold, et al., 2016) and free availability of the data (Alifu, et al., 2016) Landsat also provides convenient and thorough coverage of glaciers in the Caucasus (Tielidze, 2017).

Scenes should be captured at the end of the ablation season (July/August) so that there is minimal snow cover and glacier extents can be found without snow patches being misidentified, as well as with minimal cloud cover (Bolch, et al., 2010). Several scenes (Table 1) meeting these criteria were chosen for the the month of August in 2013/2014 to test delineations. Landsat imagery will be used to create band-ratio glacier outlines as well as semi automatic and manual outlines.

Landsat-7 ETM+ Bands (µm)			Landsat-8 OLI and *TIRS* Bands (µm)		
			30 m Coastal/Aerosol	0.435 - 0.451	Band 1
Band 1	30 m Blue	0.441 - 0.514	30 m Blue	0.452 - 0.512	Band 2
Band 2	30 m Green	0.519 - 0.601	30 m Green	0.533 - 0.590	Band 3
Band 3	30 m Red	0.631 - 0.692	30 m Red	0.636 - 0.673	Band 4
Band 4	30 m NIR	0.772 - 0.898	30 m NIR	0.851 - 0.879	Band 5
Band 5	30 m SWIR-1	1.547 - 1.749	30 m SWIR-1	1.566 - 1.651	Band 6
Band 6	60 m TIR	10.31 - 12.36	*100 m TIR-1*	*10.60 – 11.19*	Band 10
			100 m TIR-2	*11.50 – 12.51*	Band 11
Band 7	30 m SWIR-2	2.064 - 2.345	30 m SWIR-2	2.107 - 2.294	Band 7
Band 8	15 m Pan	0.515 - 0.896	15 m Pan	0.503 - 0.676	Band 8
			30 m Cirrus	1.363 - 1.384	Band 9

Table 2: Bands of the Landsat TM and OLI sensors (NASA, 2017a)

2.2.3 DSM

In order to explore semi automatic delineations beyond simple band-ratios, a DSM is needed to include texture parameters, elevation and aspect (Racoviteanu & Williams, 2012). The ALOS PRISM DSM from The Japan Aerospace Exploration Agency(JAXA) provides global DSM coverage at 30m resolution (captured 2006-2011). For glaciological applications the DSM has been shown to have success in verifying outlines derived from ASTER and Landsat products (Aizen, et al., 2007). The DSM will be used to integrate texture parameters, aspect and height to augment simple band ratios and include a larger amount of debris-covered glacier.

2.3 Methods

2.3.1 Band Ratio

The principal methodology for this study is based on Bolch et al. (2010). Landsat 8 imagery is the preferred satellite imagery for glacier mapping and will be used throughout this study. Landsat 8 imagery has been acquired for the Caucasus region for 2013/2014 (Table 1) which is mostly cloud free, providing a good basis for glacier extent derivation. The software used to analyze the Landsat images is PCI Geomatica—a Canadian remote sensing package for Earth observation data. The Landsat 8 images are imported and a red/SWIR (Band4/Band6) ratio image created.

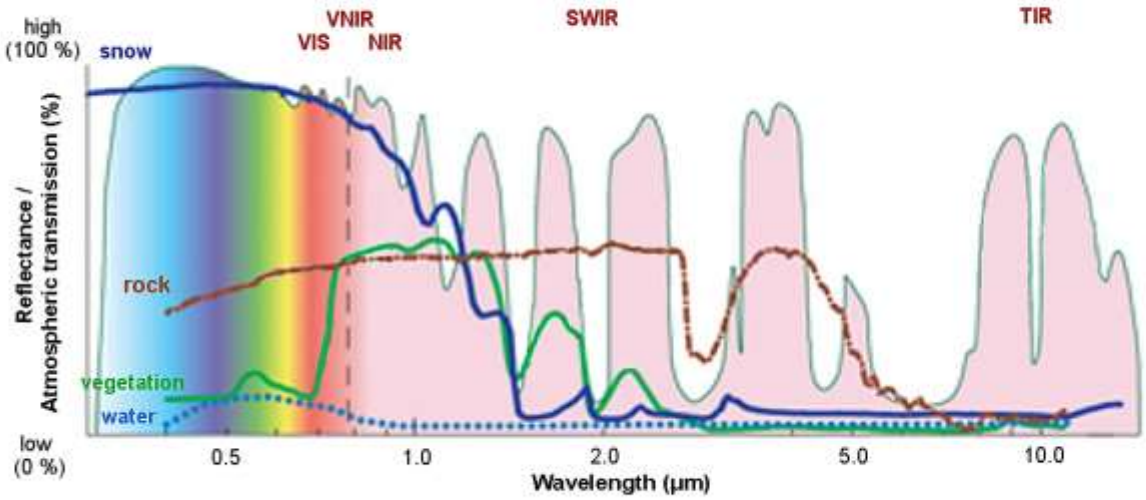


Figure 6:Typical reflectivity of surface types (EUMeTrain, 2014)

This ratio is used as it has been deemed most robust for glacier analysis by several studies and is superior to the previously accepted NIR/SWIR ratio (Winsvold et al., 2016, Paul, 2000, Sidjak & Wheate, 1999) in areas which are debris covered and shadowed (Bolch, et al., 2010). Spectral properties differ for different surfaces and the 4/6 band is preferable for glaciers and snow because it stretches the values between the red and mid infrared bands (Figure 6). While rocks, particularly metamorphosed ones such as in the Caucasus region, do not reflect well in the visible to short wave infrared region (Longhi, et al., 2001), allowing a high contrast between glaciers and bedrock.

The ratio is given as:

$$R_{red}/_{SWIR} = DN_{red}/DN_{SWIR}$$

where R is the ratio between bands and DN is the digital number (brightness value) of a pixel in the respective band.

Other ratios will also be tested for the western study area to assess which is most appropriate for semi automatic glacier extent delineation such as Paul et al. (2016) which incorporates the panchromatic band:

$$R_{panchromatic}/_{SWIR} = DN_{panchromatic}/DN_{SWIR}$$

and Alifu et al. (2016) which uses the thermal band:

$$R_{TIR}/(_{NIR}/_{SWIR}) = DN_{TIR}/\ (DN_{NIR}/\ DN_{SWIR})$$

The best performing band ratio tested in the western area will then be compared to the manual and a semi automatic methods in the central and eastern Caucasus.
The glacier areas are then extracted by applying a standard threshold value of 2.0 (Paul, et al., 2002) although other values will be tested as the threshold value has been found to range between 1.6-2.8 (Winsvold, et al., 2016). To reduce clutter, a sieve function is then applied to the outlines with a minimum pixel size of >11 as the smallest glacier size (0.01km^2) will be 12 pixels (Tielidze, 2017). These areas are then converted to vector outlines, smoothed and compared to the manual extents. Simple band ratio methods (such as the 4/6 ratio) are widely used to find areas of clean ice, but do not perform well in debris covered glacier areas. Therefore, the above methodologies such as Alifu et al (2016) and Paul et al. (2016) will be tested in order to assess the capabilities of different band ratios in assessing debris cover. From hereon these methodologies will be referred to as band ratio methods, a form of semi automatic delineation. One subsequent method using the calculated band-ratio outlines to assess debris cover is that of Tieldilze et al. (2017) where the relative debris cover might be found by using the equation:

Manual – Band-ratio image = Debris covered glacier

This methodology will be tested and used as a way to compare the debris covered glacier found with the semi automatic methodology against manual outlines.

2.3.2 Manual Extents

Manual extents were provided by Tielidze & Wheate (2017) and offer an up to date depiction of glacier extents in the Caucasus region. L Tielidze is a native of Georgia and the Caucasus region, therefore enabling a comparison between local knowledge and little knowledge of the area/digitizing glaciers. A local understanding and knowledge of the area has been found to be important when digitizing extents (Williams, et al., 1997) and this study can provide an investigation into whether this is significant in producing accurate glacier delineations.

2.3.3 Semi automatic methodology

Although solving the problem of debris cover is beyond the principal focus of this research, it is still an important aspect to consider. Normally, manual delineation is required after using a band ratio method in order to include debris covered areas. In order to try and include debris-covered glacier in this analysis and further improve the band ratio method a semi automatic method will be used (Figure 7). From the most successful of the band ratio outlines a ‘clean-ice’ file will be generated, this being a relatively robust and well-researched method to obtain clean glacier ice extents. However, to try and improve the area of correctly classified glacier to include debris cover, a DSM will be introduced in order to analyze texture parameters. Texture parameters in this context were defined by Racoviteanu and Williams (2012) and included:

entropy (measure of uniformity) (Cornell, 2017):

$$\sum_{i,j} p_{(i,j)} Log_2\, p_{(i,j)}$$

homogeneity (measure of similarity) (The Mathworks Inc., 2017a):

$$\sum_{i,j} \frac{p(i,j)}{1+|i-j|}$$

where *p* is the normalized symmetric Grey Level Co-occurrence Matrix of dimension N x N and *p(i,j)* is the normalized co-occurrence matrix such that SUM (i,j=0,N-1)(P(i,j)) = 1 (PCI Geomatics, 2017)

and variance (measure of variability, the opposite of homogeneity):

$$\frac{\Sigma(X-\bar{X})^2}{N-1}$$

where *X* is an individual data point, $\bar{x}$ is the mean of data points and *N* is the total number of data points (The Mathworks Inc, 2017b).

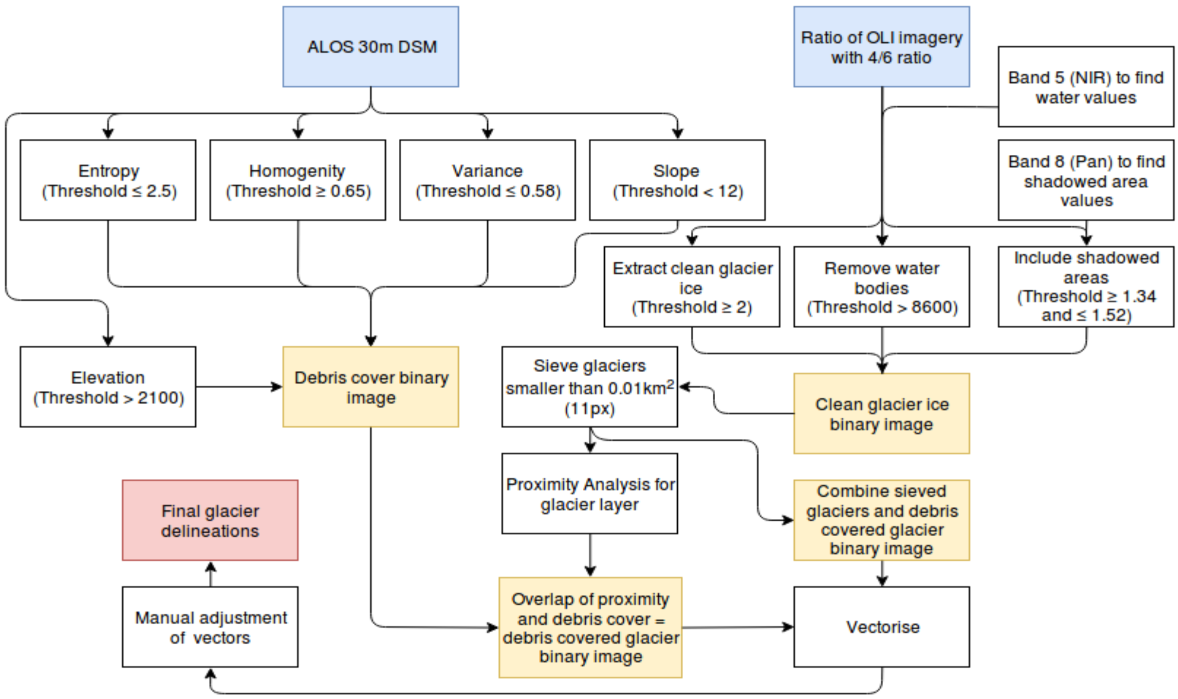


Figure 7: Methodology to extract semi automatic glacier outlines with texture analysis

All these parameters are based on second-order statistics computed from a gray level co-occurrence matrix, which calculates how often pairs of pixels occur in a spatial relationship (The Mathworks Inc., 2017c; PCI Geomatics, 2017).
Although Racoviteanu and Williams (2012) used Matlab and had more variables, comparable parameters were found in PCI and used for analysis as well as slope and elevation. Once the original Landsat image had been queried to find appropriate thresholds for each of these parameters, a binary image of debris cover is created. This may include some areas of bare rock, and therefore a buffer is applied to the clean ice portion so when debris and clean ice layers are overlapped only debris cover within a certain distance of the clean glacier ice (queried individually for each different scene) is included. Once the semi automatic outline has been generated manual correction must be done. In this case, generated vector outlines were overlaid with Landsat imagery, particularly the panchromatic band (Band 8) due to its higher 15m resolution. Vectors were also exported as KMLs and added to GoogleEarth (Figure 8) to further help with manual corrections in 3D as local knowledge of the area was limited.

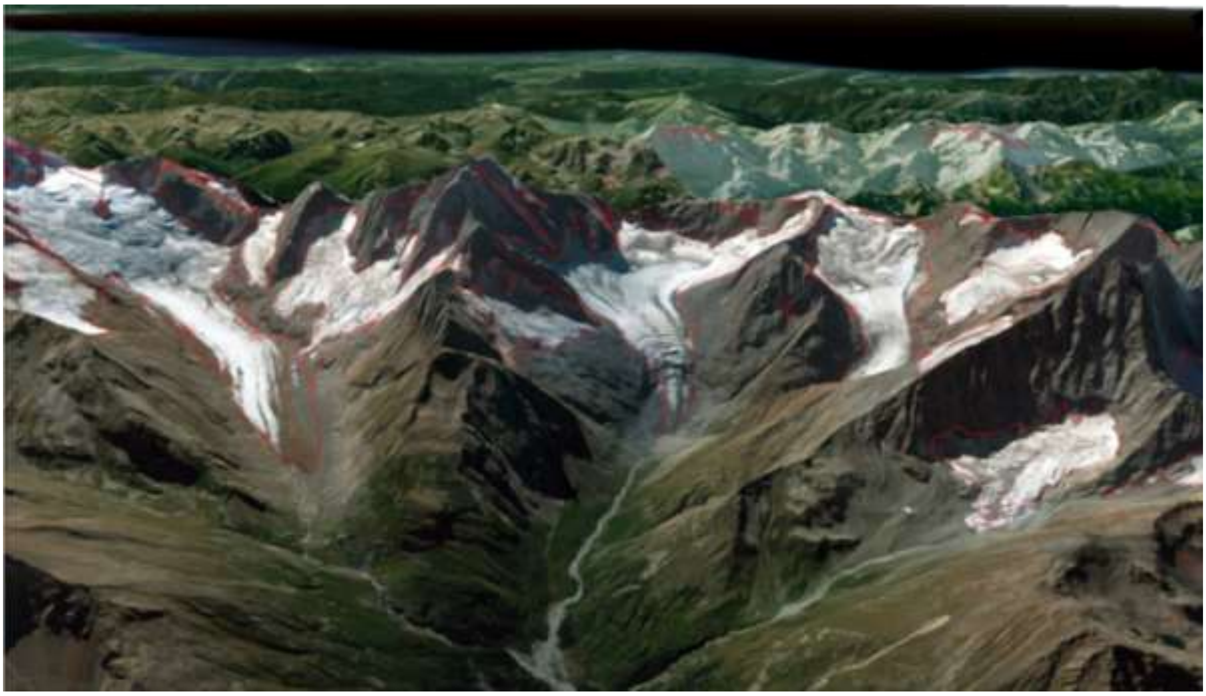


Figure 8: KML imported into GoogleEarth to digitize outlines further using 3D and topographic data

2.4 Assessing Accuracy

A comparison between all three methodologies (manual, band ratio and semi automatic) will be undertaken; the approach to this will be two fold, qualitative and quantitative.
For each individual area of the Caucasus (west, central and east) the three generated outlines will be compared qualitatively with problematic or interesting areas chosen to compare – these will include looking at how the methods work on debris-covered areas, cloud covered glacier, shadowed glacier, glacier size and the aspect (i.e. if the glacier is on the Russian or Georgian slopes of the Caucasus). Visually comparing the outlines allows a good assessment of how they perform, particularly in problematic areas such as these. However, a more quantitative approach is also needed in order to assess the relative accuracy of glacier outlines.
To compute the accuracy between glacier outlines, Gjermundsen et al. (2011) suggest using a confusion matrix in order to compare and contrast the overall accuracy of the glacier outlines. The most accurate and up-to-date data available glacier delineations in the Caucasus region are the manual outlines provided by Tielidze & Wheate (2017). Therefore, the glacier area for band ratio and semi automatic images will be calculated as a percentage of the overall image and a confusion matrix (Table 3) will be used to compare semi automatic and band ratio outlines to manual delineations (respectively) by calculating user's and producer's accuracy, thereby allowing classified outlines to be compared to a presumed 'ground truth' (manual outlines). The producer's accuracy is the probability of land cover being classified correctly whereas the user's accuracy shows the probability of classification being present in the ground truth i.e. the reliability (Humboldt State University, 2015).

		Ground Truth	
		Positives	Negatives
Classification Results	Positives	True Positive	False Positive
	Negatives	False Negative	True Negative

Table 3: Construction of a confusion matrix

Another type of accuracy clarification is needed, and that is to assess the inaccuracies with regard to the satellite imagery used, otherwise known as position accuracy- the precision of object localization in space (Novotny & Hecht, 2012). Due to the resolution of the satellite imagery there is a certain inaccuracy in the defined glacier delineations. Granshaw and

Fountain (2006) suggest calculating the area of a buffer around each glacier having a width equal to twice the root-mean- square error of the mapping and digitizing errors. Tielidze (2016) clarifies this further stating that based on a 15m pixel size the buffer size should be half of this – 7.5m. Because Landsat imagery has a resolution of 30m the buffer should be 15m to create a ± percentage of the uncertainty in final glacier calculations (Tiwari, et al., 2016).

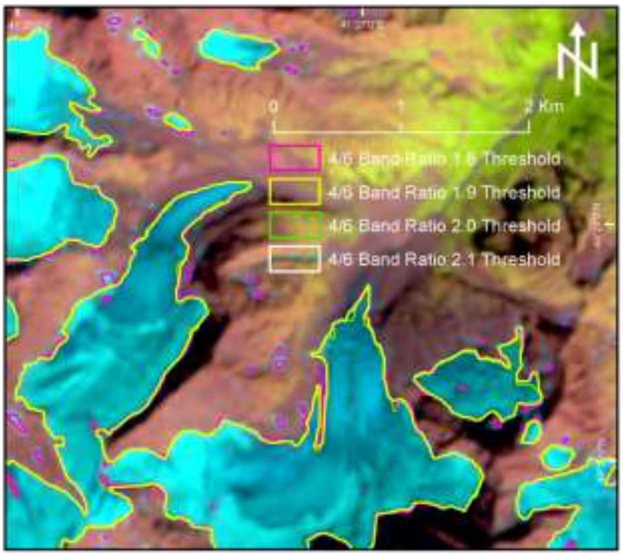
3. Results

3.1 West Caucasus

The band ratio techniques were tested on the west Caucasus to assess the efficacy of each, and find the most suitable band ratio technique before comparing with other methods in other areas.

3.1.2 Choosing the best threshold

To assess the best threshold for this scene, a range of thresholds were tested with a 4/6 band ratio image (Figure 9). These figures show areas where the results between thresholds differed.



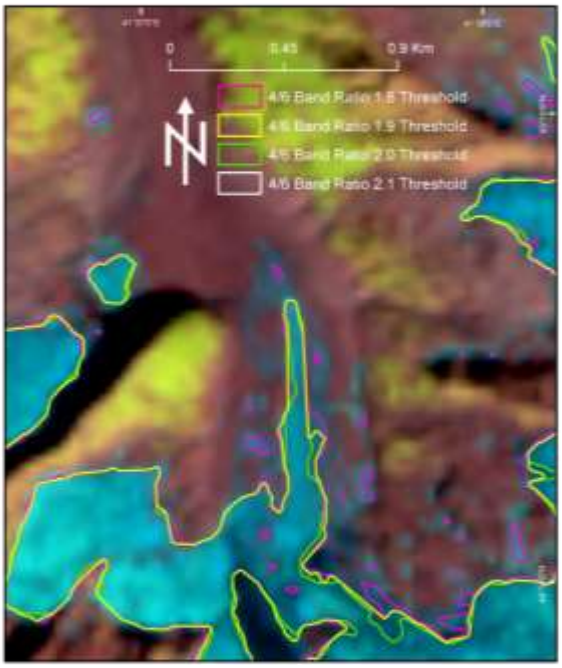


Figure 9: Comparison of thresholds for two sample regions in the West Caucasus

A lower threshold such as 1.8 picks up smaller snow patches/areas of ice and this decreases as the threshold increases. It is important to choose the correct threshold as this can influence future glacier delineations. The accuracy in picking up glacier ice can be seen, but this fails for debris covered glacier ice as on the tongue, and if shadow is not accounted for, then important glacier areas may also be missed. Although the 1.8 threshold picks up more debris covered glacier ice this is at a detriment to other areas, and bare rock and smaller snow patches are included, in this case 1.9 appears to be the most accurate threshold but this will differ across areas. The 4/6 ratio seems to be a robust ratio to find clean glacier ice, however care must be taken in choosing the correct threshold.

3.1.3 TIR/NIR/SWIR band ratio methodology

This section looks at the Alifu et al. (2016) methodology. Originally this was used with TM imagery, compared to Landsat OLI for this study. The original methodology used the thermal band as part of the band ratio but in Landsat 8 there are two thermal bands (Table 2), therefore three different equations were tried, as follows:

Band 10/ (Band 5/Band 7)

Band 11/ (Band 5/Band 7)

((Band 10+Band 11)/2)/ (Band 5/Band 7)

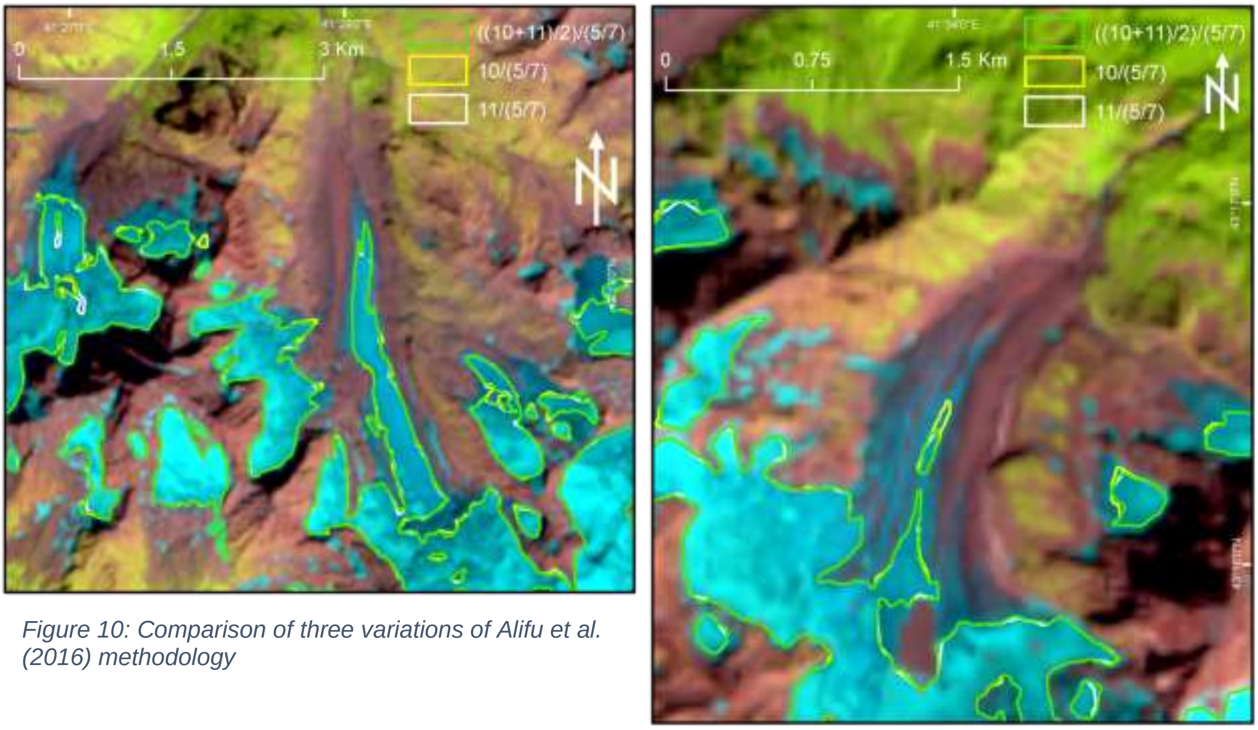
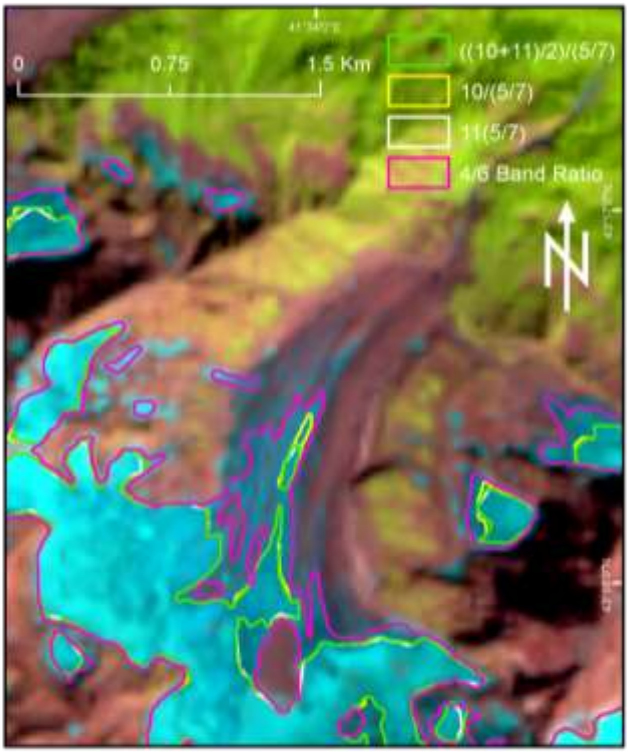


Figure 10: Comparison of three variations of Alifu et al. (2016) methodology

While Alifu et al. (2016) methodology produced an increased debris cover assessment for TM imagery, when applied to Landsat OLI data here the result was less promising. Three combinations of the bands were tried but produced a reduced glacier coverage result. Between the three ratios there was little difference (Figure 10). The results are disappointing, as the method was used as a way to delineate a greater amount of debris cover. Instead of producing an increased assessment of glacier ice, the total area is actually reduced. This becomes increasingly clear when analyzed against a simple 4/6 Band Ratio delineation (Figure 11) although the 4/6 ratio is not ideal for assessing debris cover, it suggests that the Alifu et al. (2016) method for Landsat 8 imagery needs further review



The glacier areas with clean ice become fragmented and not representative of the entire area. Therefore, this method requires additional investigation for area analyses, as it does not include a greater amount of debris cover was the case in TM imagery in the Caucasus region.

Figure 11: Comparison of Alifu et al. (2016) methodologies and a simple 4/6 band ratio

3.1.4 Incorporating the Panchromatic Band

Paul's (2016) methodology attempts to encompass the panchromatic band in order to make delineations more accurate, based on the higher resolution (Figure 12). When comparing Paul et al. (2016) delineations to a 4/6 band ratio it is clear that extra snow patches are included and 'false nunatuks' have been created between glacier ice in some locations (Figure 12). Where there is less debris the delineations are fairly accurate and correspond well with the 4/6 ratio but the longer tongues caused the ratio to identify extra glacier area despite them being too small and isolated to be part of the glacier. As a way to include debris cover and create a more accurate area assessment this method does not significantly improve the results from a 4/6 ratio and due to the extra filtering that would be needed.

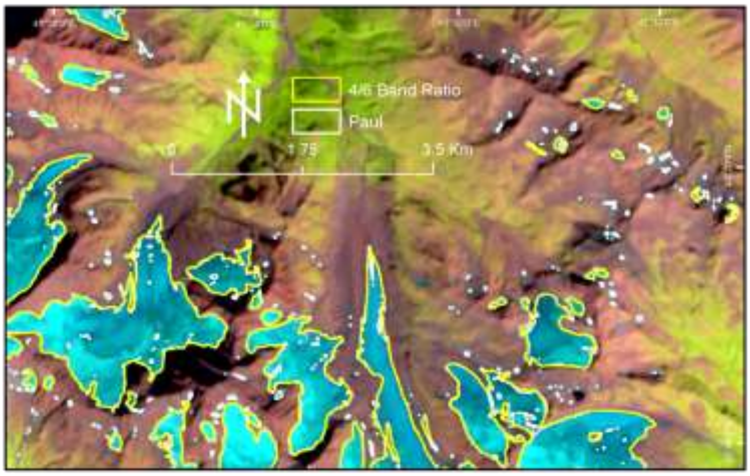
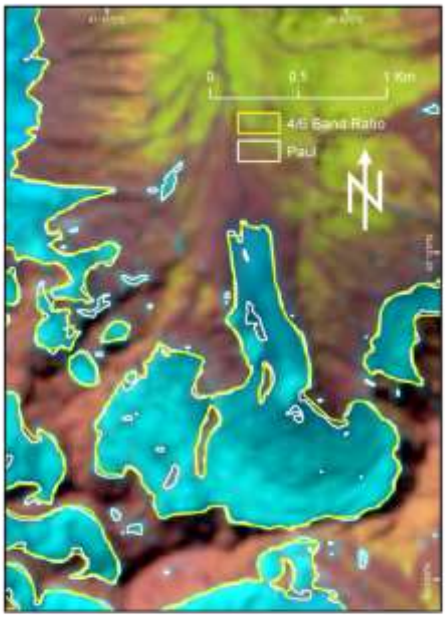


Figure 12: Comparison of Paul methodology (incorporating the panchromatic band into band ratio) with 4/6 Band Ratio



3.1.5 Comparison of Band Ratio methods

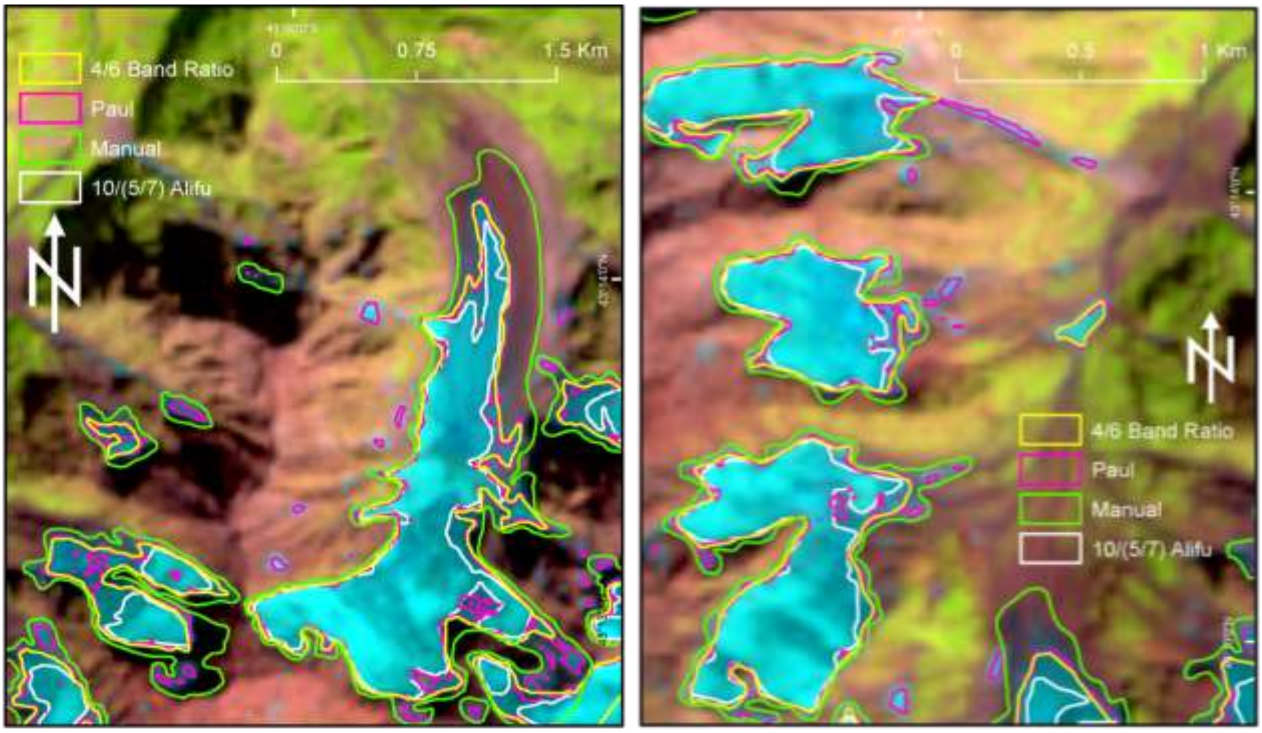


Figure 13: Comparison between all band ratio techniques and manual outlines

Figure 13 shows all band ratio outlines compared alongside the manual outlines. When the delineations are compared directly it is easy to see where each fails. The Alifu et al (2016) methodology covers the least amount of area and, although the Paul et al. (2016) methodology picks up more debris cover it also identifies debris cover and snow patches in areas which are not glacier. The 4/6 band ratio performs quite well but it is clear that manual is the best in identifying debris cover, as well as problematic sections such as those in shadow.

3.1.6 Comparing topography

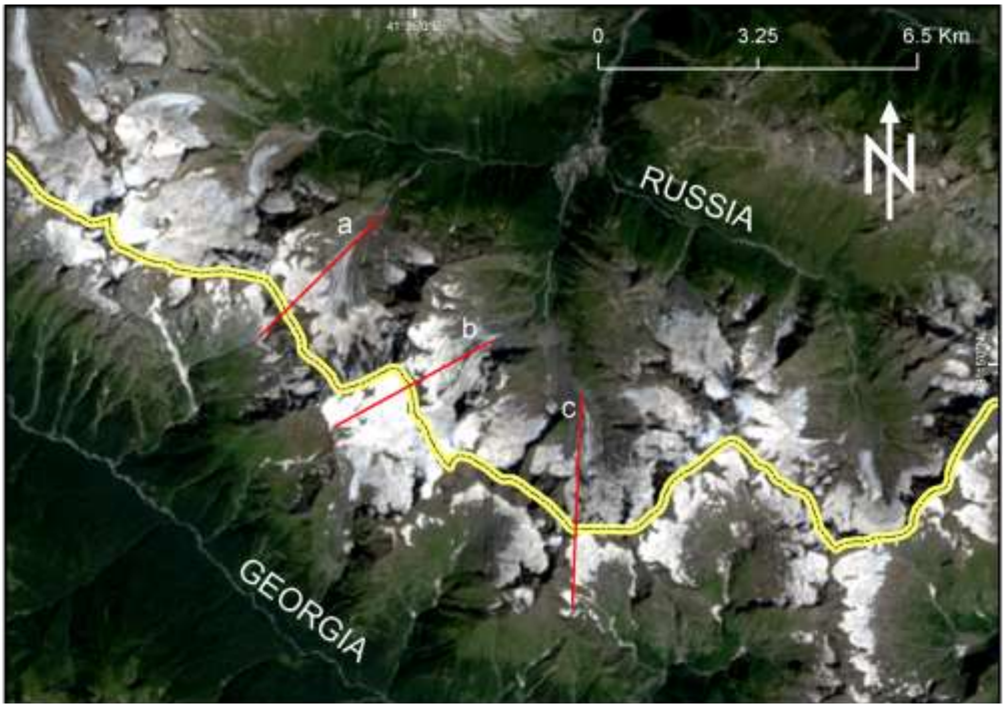
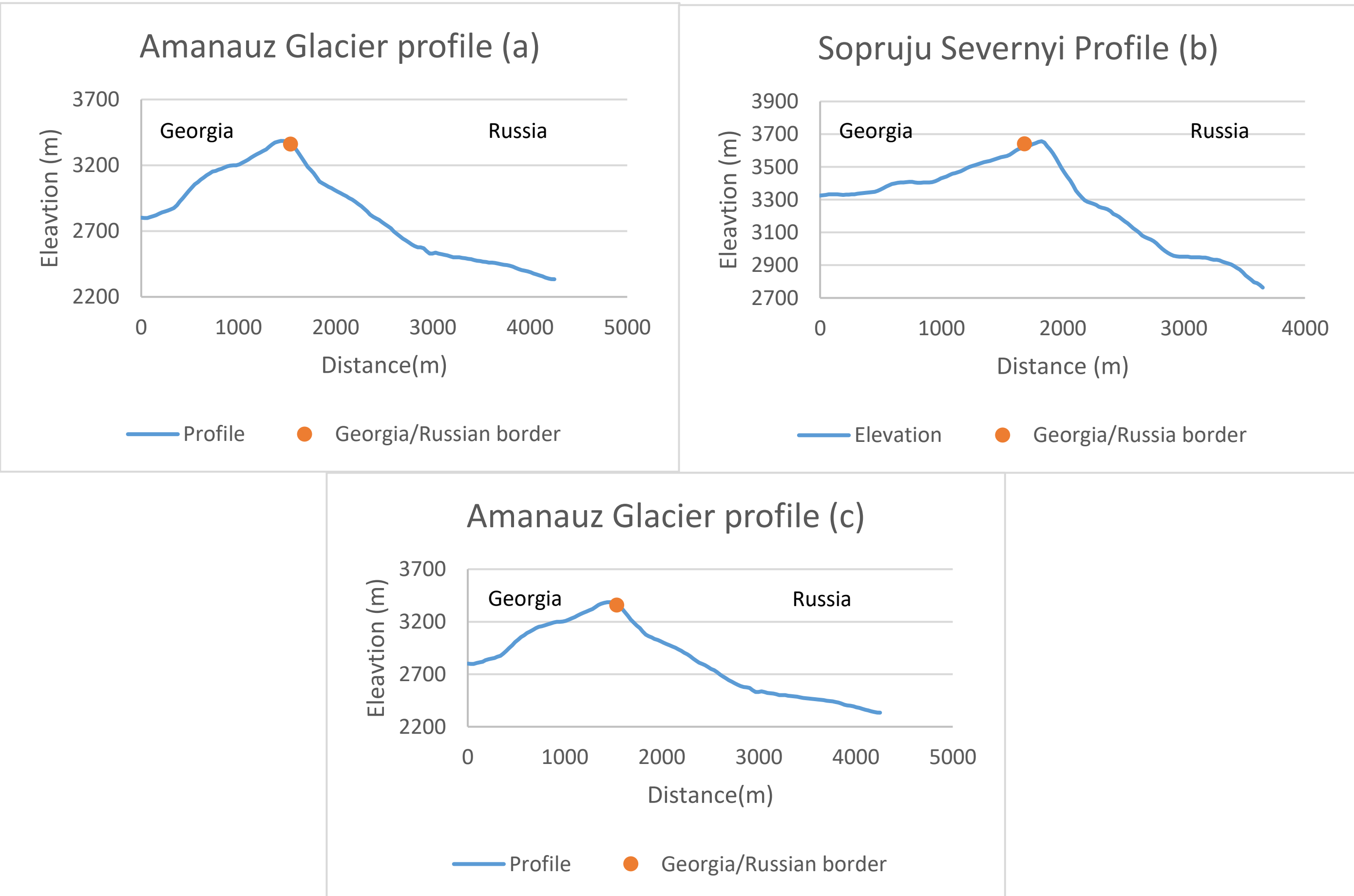


Figure 14: Cross sections across the Caucasus (above)

Figure 15: Profiles of cross sections shown in figure 14 (below)



An important distinction when looking at glacier outlines is the topography of the region. There are stark differences between the elevation and gradient of north and south slopes in the Caucasus (i.e. Russia and Georgia) and these should be taken into account. These are illustrated in cross sections (Figure 14 and 15).

3.1.7 Semi-automatic methods

3.1.7.1 Including shadow and excluding water

Incorporating areas of shadowed ice and excluding water is important to get accurate glacier extents. Excluding water bodies can be done by querying the infrared band and shadow encompassed by querying the blue band. Figure 16 shows that by including these parameters the semi-automatic method encompasses a more accurate area than the 4/6 band ratio as shadowed glacier is included in the assessment while water (which has a similar spectral property to ice) can be excluded.

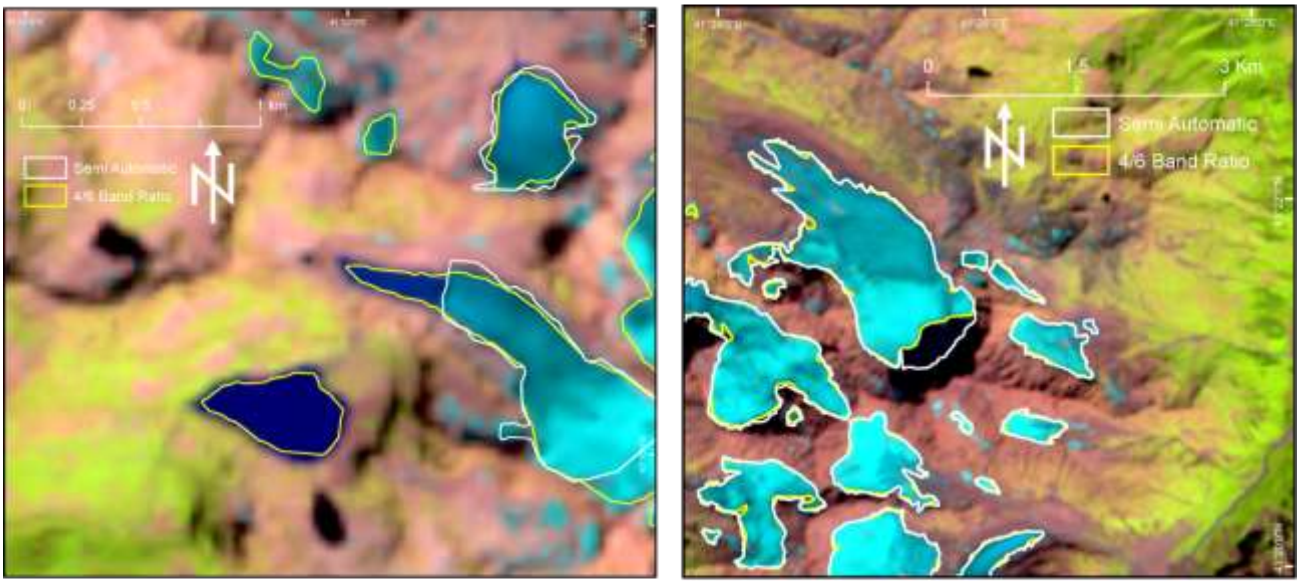


Figure 16: An example of excluding water bodies and including shadows with a semi automatic method compared to a band ratio technique

3.1.7.2 Texture Analysis

Entropy, homogeneity, variance and slope (Figure 17) were included to try and improve a simple 4/6 band ratio technique. Each layer was queried in OLI imagery to assess the thresholds for extracting debris covered glacier area. By creating the query encompassing these texture values, elevation and NIR (for water) debris cover may be extracted. The overall area of debris identified (Figure 18) is much greater than actual debris cover, because other areas which meet all the criteria are still included (for instance bare areas of rock and valleys).

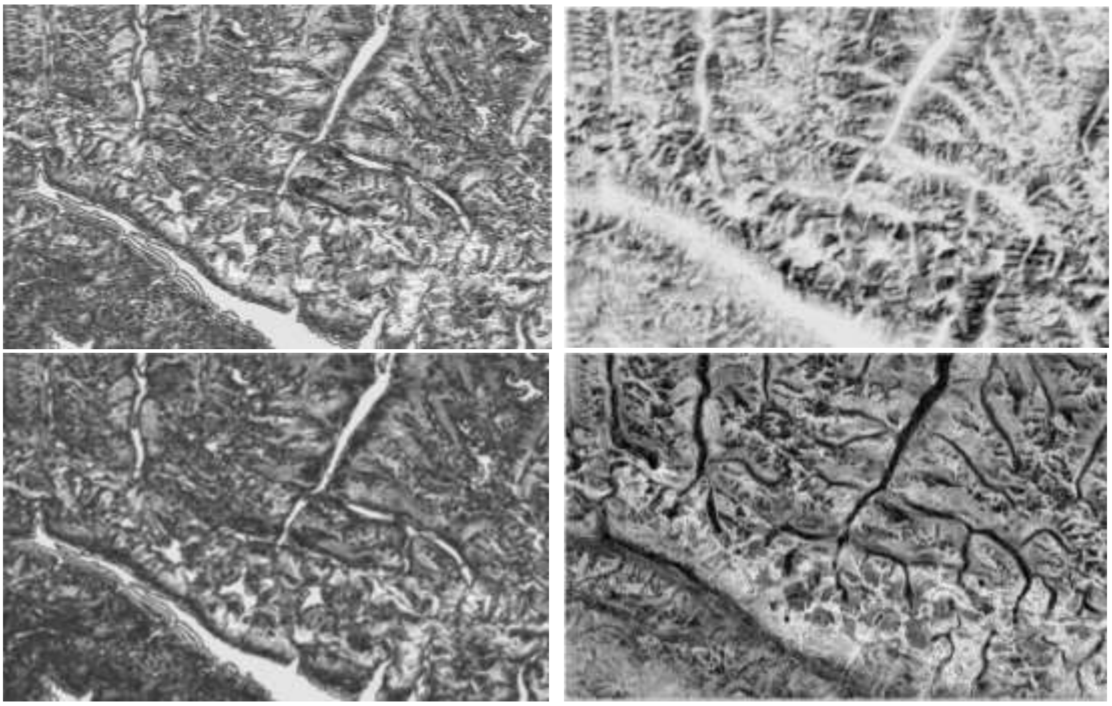


Figure 17: Texture layers clockwise from top left: Entropy, Homogeneity, Slope, Variance

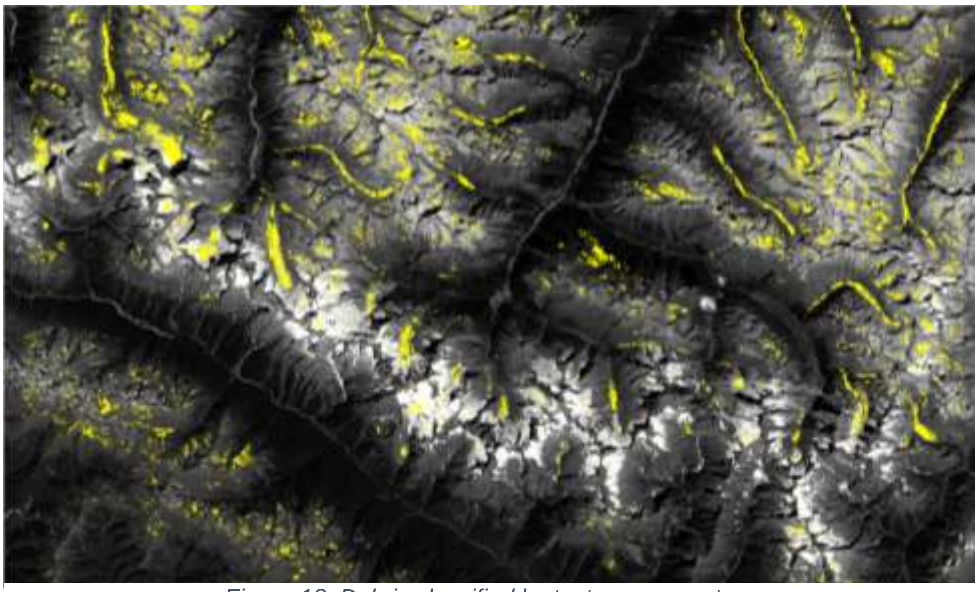


Figure 18: Debris classified by texture parameters

Therefore, to reduce this area further, a proximity analysis was applied to the clean ice layer (Figure 19). This was successful in reducing excess debris polygons while combining classified debris covered ice with clean ice, creating a more accurate depiction of glacier area. However, in order to make these outlines more accurate, they were edited using the panchromatic band and GoogleEarth to improve the general precision of the delineations[i].

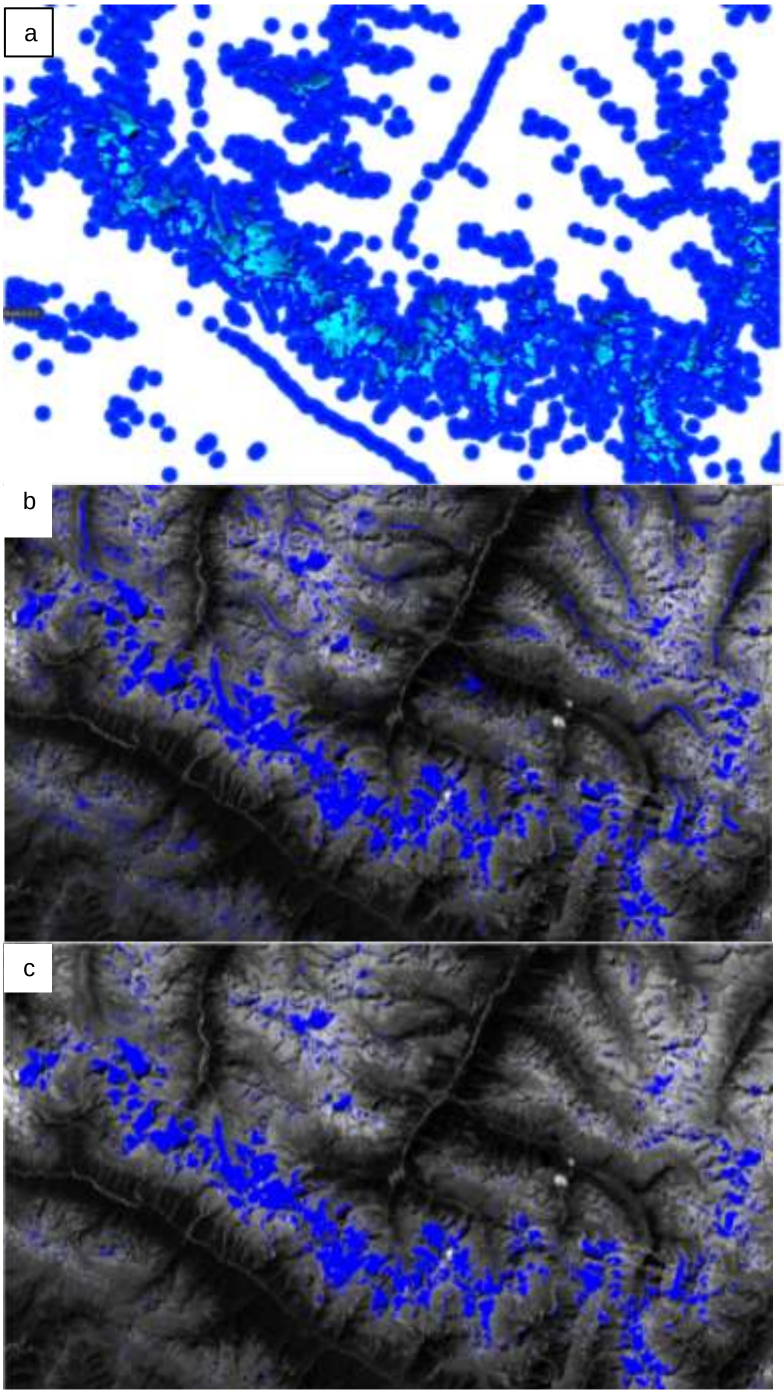


Figure 19: Proximity buffers applied to clean ice layer(a) Clean ice and debris covered-ice before proximity is applied(b) and after proximity is applied(c)

[i] The queries used in PCI Geomatica to gain outlines and proximity values can be found in the appendix

3.1.7.3 Comparison of methodologies

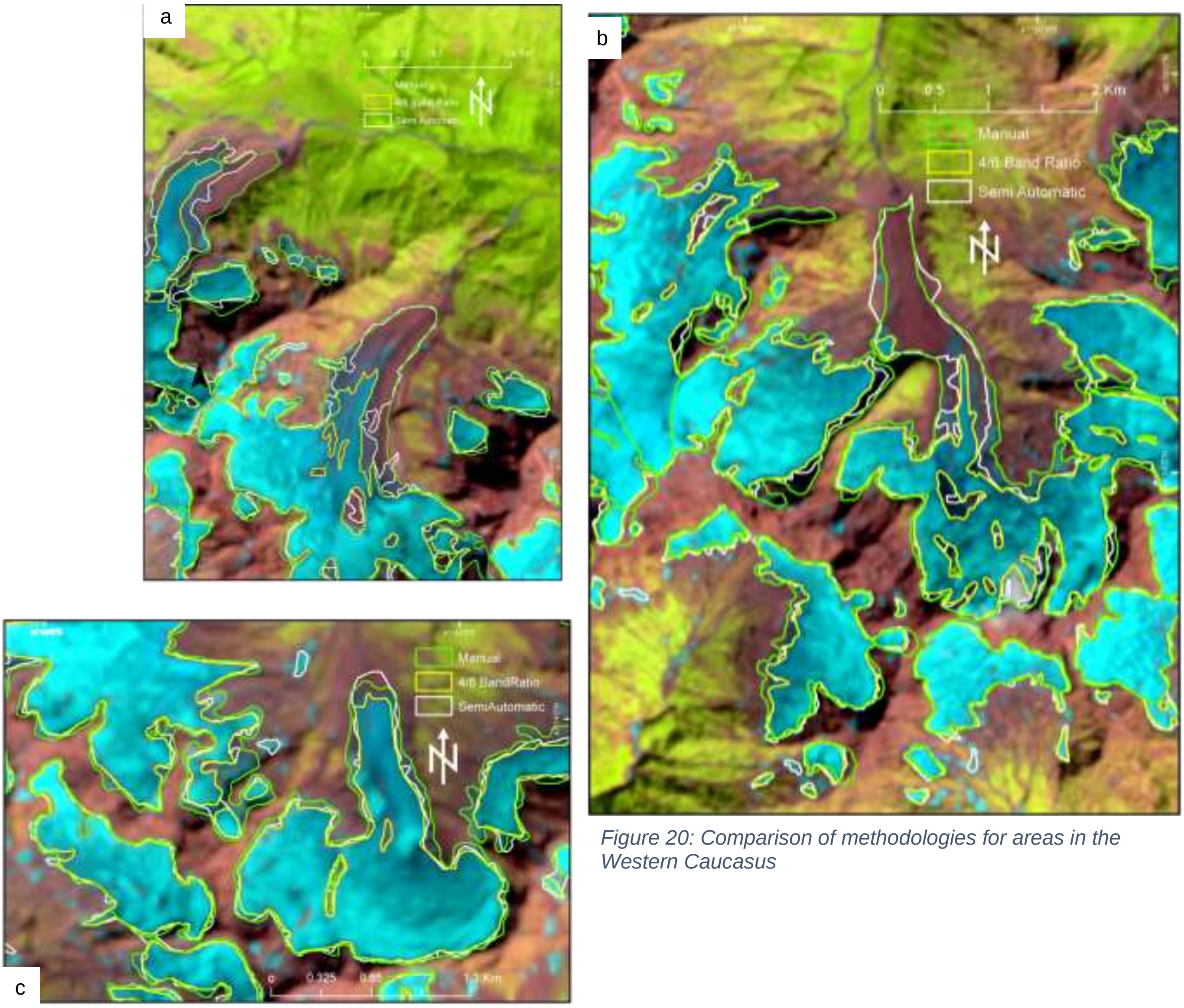


Figure 20: Comparison of methodologies for areas in the Western Caucasus

When the outlines are compared (Figure 20), the differences between their effectiveness are clear to see. The shortfall of the band ratio can clearly be seen (Figure 20a) where the debris tongue becomes stunted as a result of the ratio only picking up clean ice.

The difference between the Georgian and Russian delineations are marked (Figure 20b) with the long glacier tongue on the Russian side compared to the mainly clean ice on the Southern Georgian slopes. However, there are still differences in clean ice delineation with manual areas being larger than areas delineated by both the band ratio and semi-automatic techniques (Figure 20c).

3.1.7.4 Subjectivity of outlines

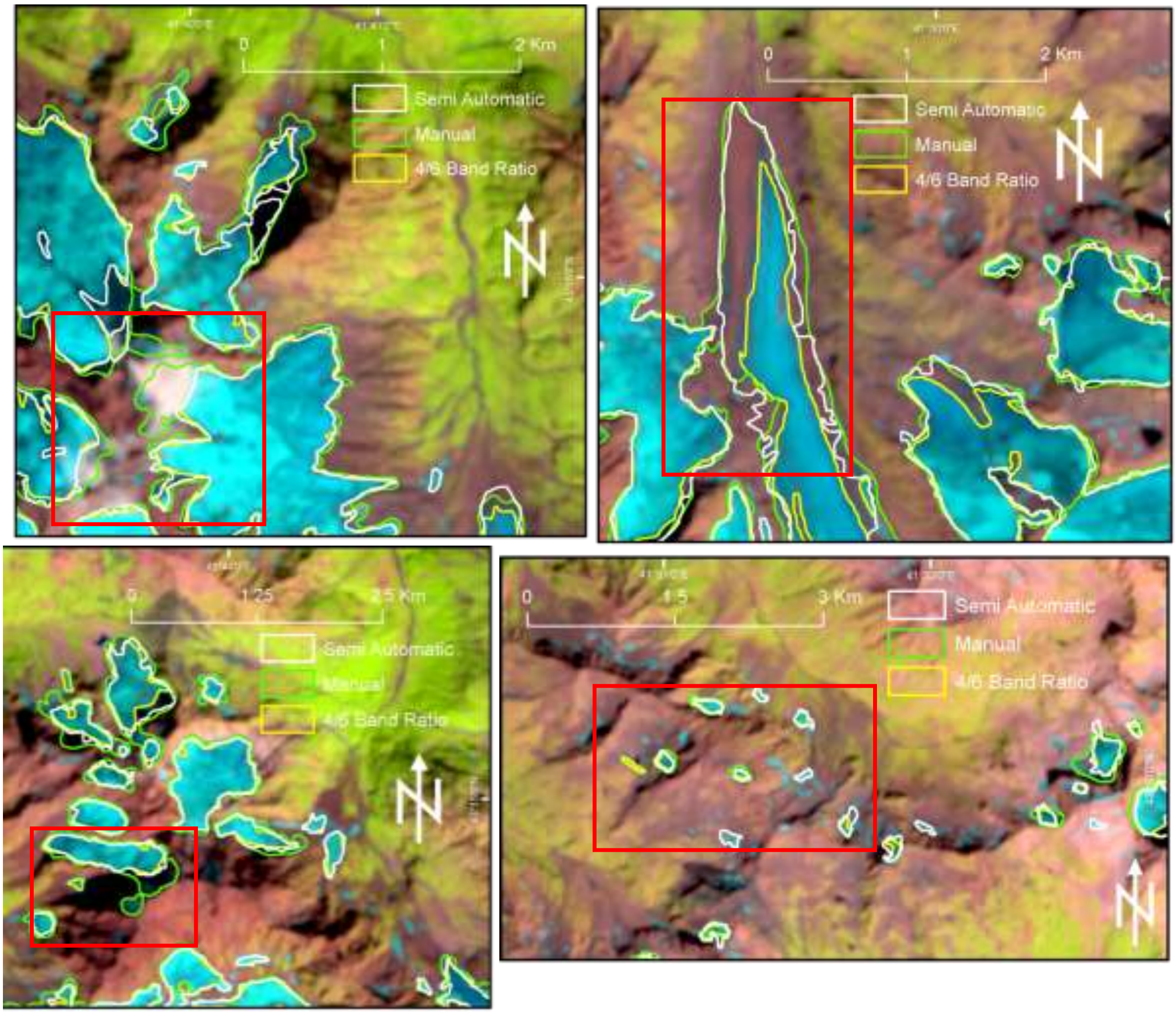


Figure 21: Examples of areas which require local knowledge/additional parameters for a more accurate delineation. Clockwise from top left: Performance on areas with cloud, debris cover, shadow, bare rock

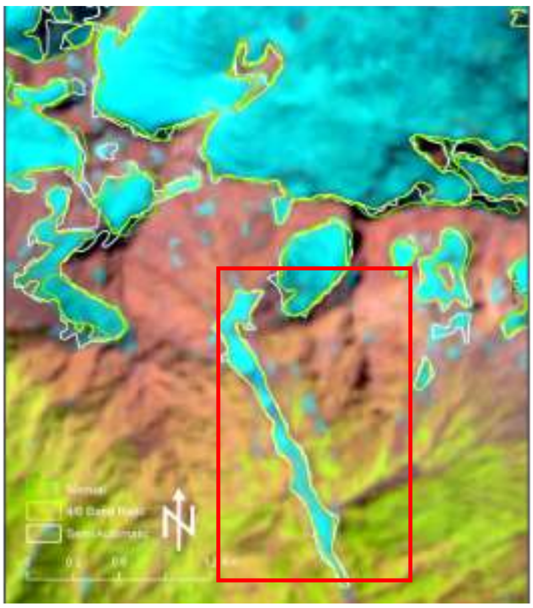


Figure 22: Snow patch which has been identified as a glacier by band ratio and semi automatic techniques

Figure 21 shows the difference of delineation in areas which may be difficult to analyze. These include cloud, shadow and debris cover which can all lead to underestimation of glacier area. On the other hand, bare rock can lead to overestimation for techniques such as the semi automatic method. Other areas which may have caused problems are snow patches - Figure 22 shows an area which may have caused problems, with snow patches which were misidentified as glacier by band ratio and semi automatic methods.

3.2 Elbrus

As a result of the unsuitability of both Alifu et al. (2016) and Paul et al. (2016) methodologies the chosen band ratio technique to be tested from this point forward is the 4/6 band ratio, with threshold chosen appropriately according to the results of querying the scene.

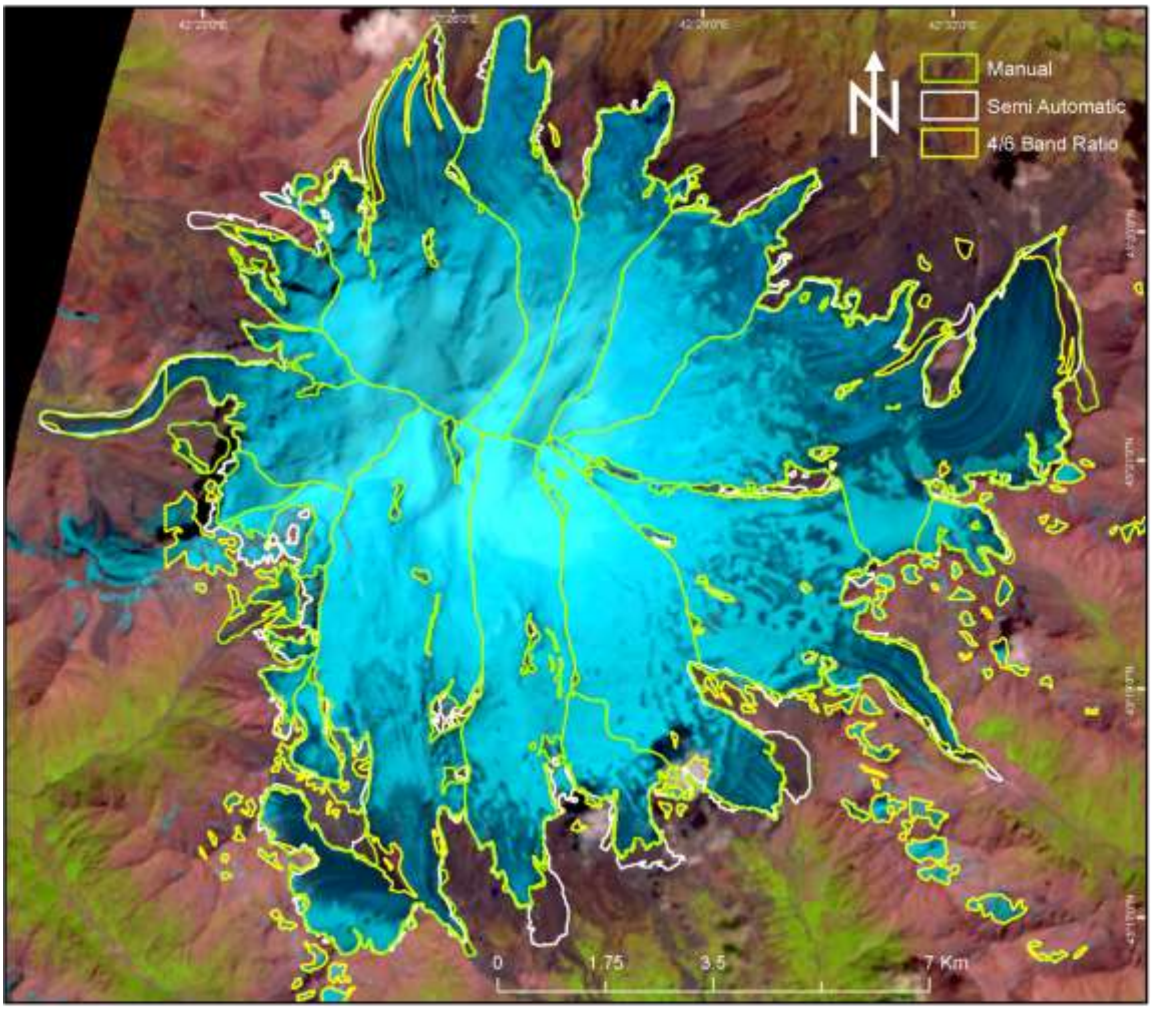


Figure 23: Comparison of manual, semi automatic and 4/6 band ratios for Elbrus

Elbrus is the largest glacier complex in the Caucasus region, Figure 23 shows how different the polygons for the derived method can be. The 4/6 and semi automatic method both over-estimated the glacier coverage of Elbrus. When looking at the outlines visually the differences are clear (Figure 24).The semi automatic and manual methods show the subjectivity in manual glacier delineation and the large differences between all outlines show

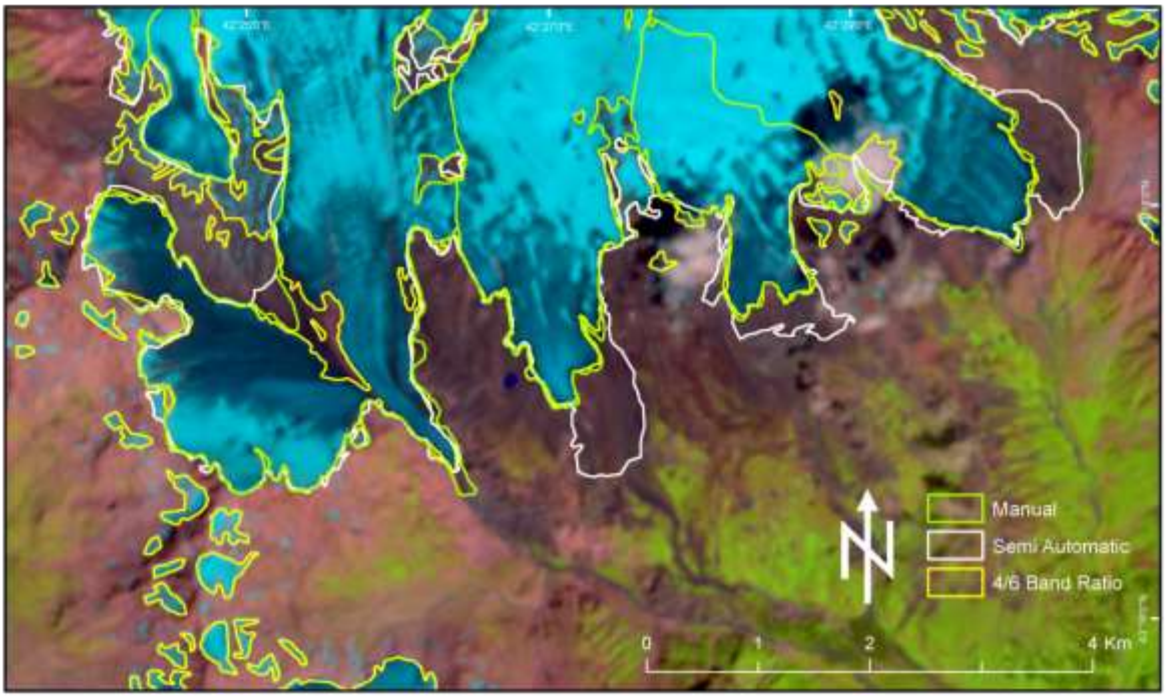
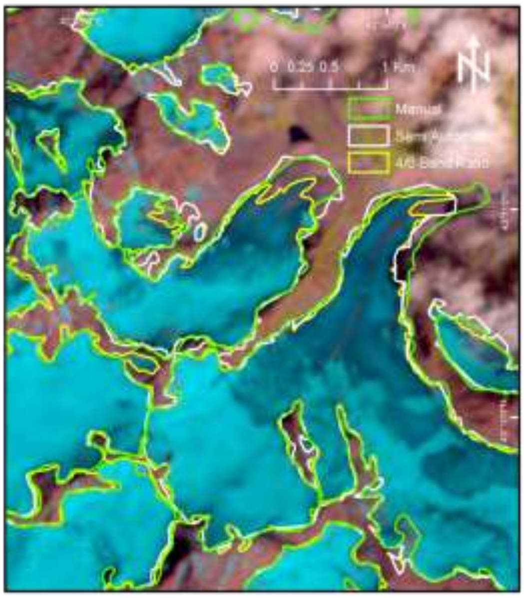


Figure 24: Close up comparison of Manual, 4/6 band ratio and semi automatic techniques on Elbrus

how one must be careful in assessing the robustness and accuracy of outlines. The biggest problem with the band ratio method here is its inclusion of snow patches as parts of the glacier. The semi automatic method fails when compared to manual outlines - this is probably as a result of the knowledge of the digitizer.

3.3 Central Caucasus



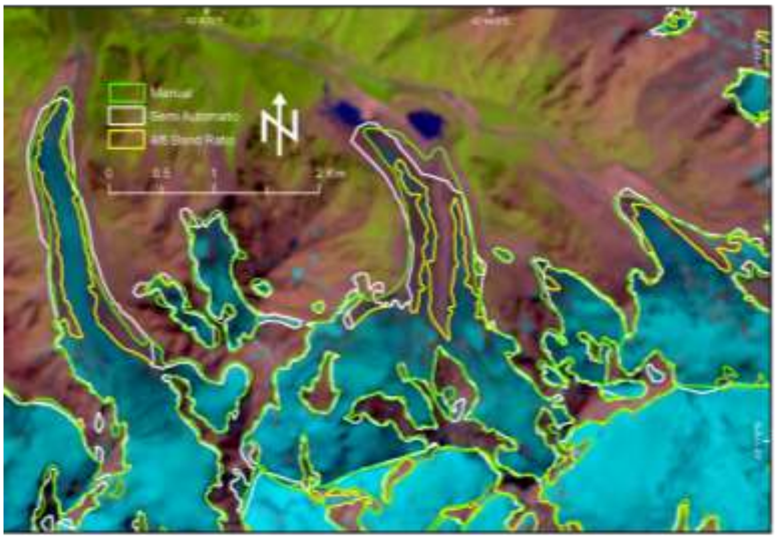
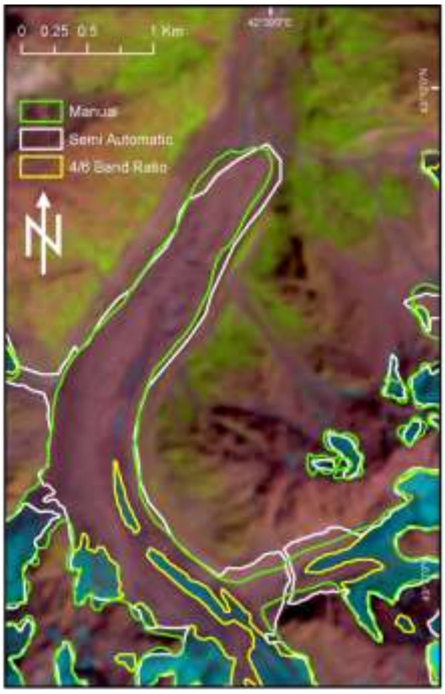


Figure 25:Comparison of methodologies in the Central Caucasus

Comparisons of the methods in the Central Caucasus show similar results to the western Caucasus (Figure 25). The manual and semi automatic outlines differ slightly, potentially as a result of the subjectivity of these outlines whereas the band ratio only identifies clean ice.

Areas which were covered by cloud were included in manual outlines. However, the agreement between all outlines is generally relatively successful.

3.3.1 Dealing with debris cover



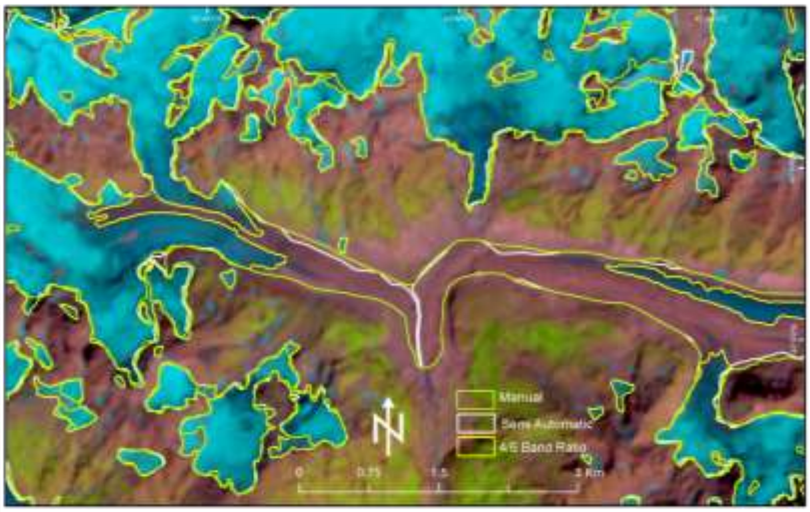
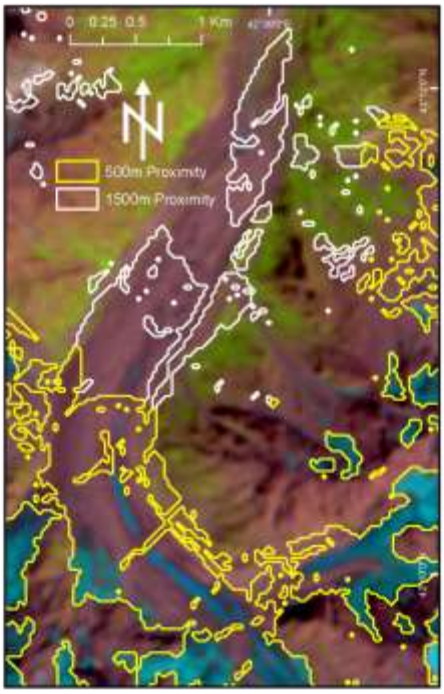


Figure 26: Comparison of 4/6 band ratio, manual and semi automatic outlines. The semi automatic techniques have undergone manual corrections here

This central area of the Caucasus has much longer debris covered tongues than the western portion, making delineation difficult using a simple 4/6 band ratio. This means the semi automatic technique could be useful in identifying these areas. The difference in delineations between methods is evident when they are compared side by side (Figure 26). The 4/6 ratio shows relatively good agreement on areas with ice but this fails as the debris covered tongue increases. The differences in manual delineations can be seen between the semi automatic and manual method here where the glacier area differs as a result of subjectivity of the digitizer.

3.3.1.1 Comparing proximity for debris covered areas

Before editing (Figure 27) the differences between two proximity buffers are clear, and how the methodology is a trade off between including areas of debris and bare rock. While the 1500m buffer identifies more of the debris tongue the 500m cuts the tongues short, and they are often fragmented. Debris tongues in both areas became problematic for using the proximity method alone, and must be combined with manual editing to exclude excess polygons.



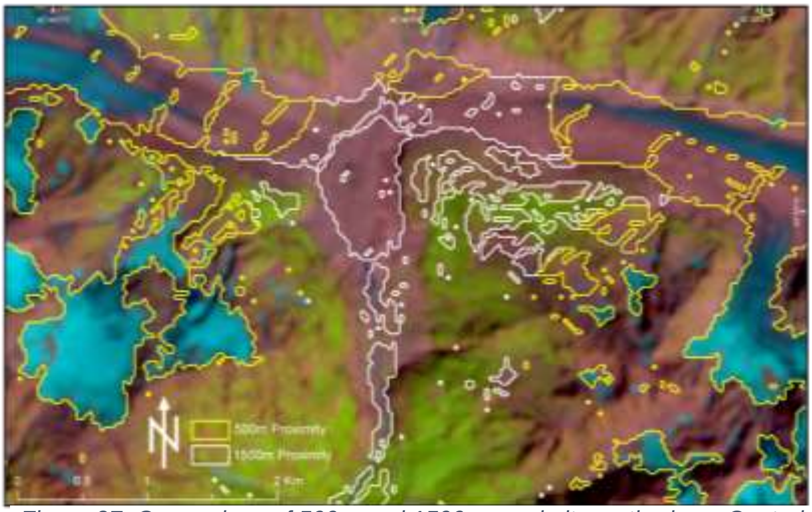


Figure 27: Comparison of 500m and 1500m proximity methods on Central Caucasus areas

3.3.2 The importance of editing

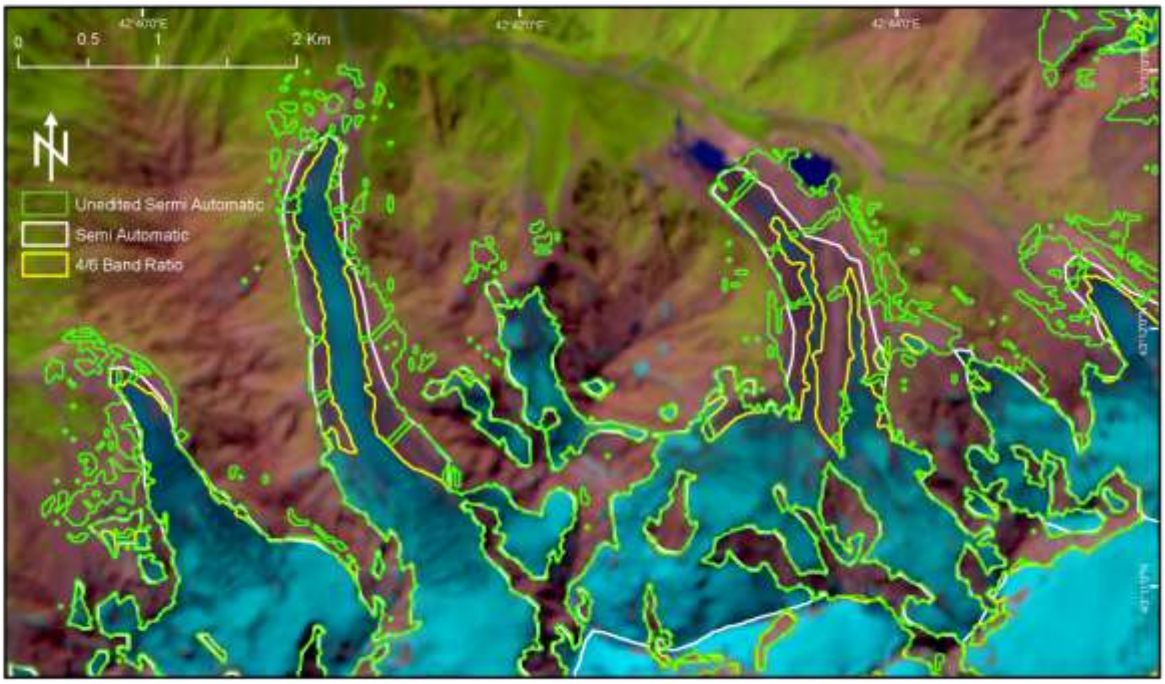


Figure 28: Comparison of edited and unedited semi-automatic methods

Figure 28 shows how much extra area is identified as glacier using the semi automatic approach. Once edited these outlines are much more representative of the clean and debris covered glacier ice. However, due to subjectivity and lack of local knowledge there are some

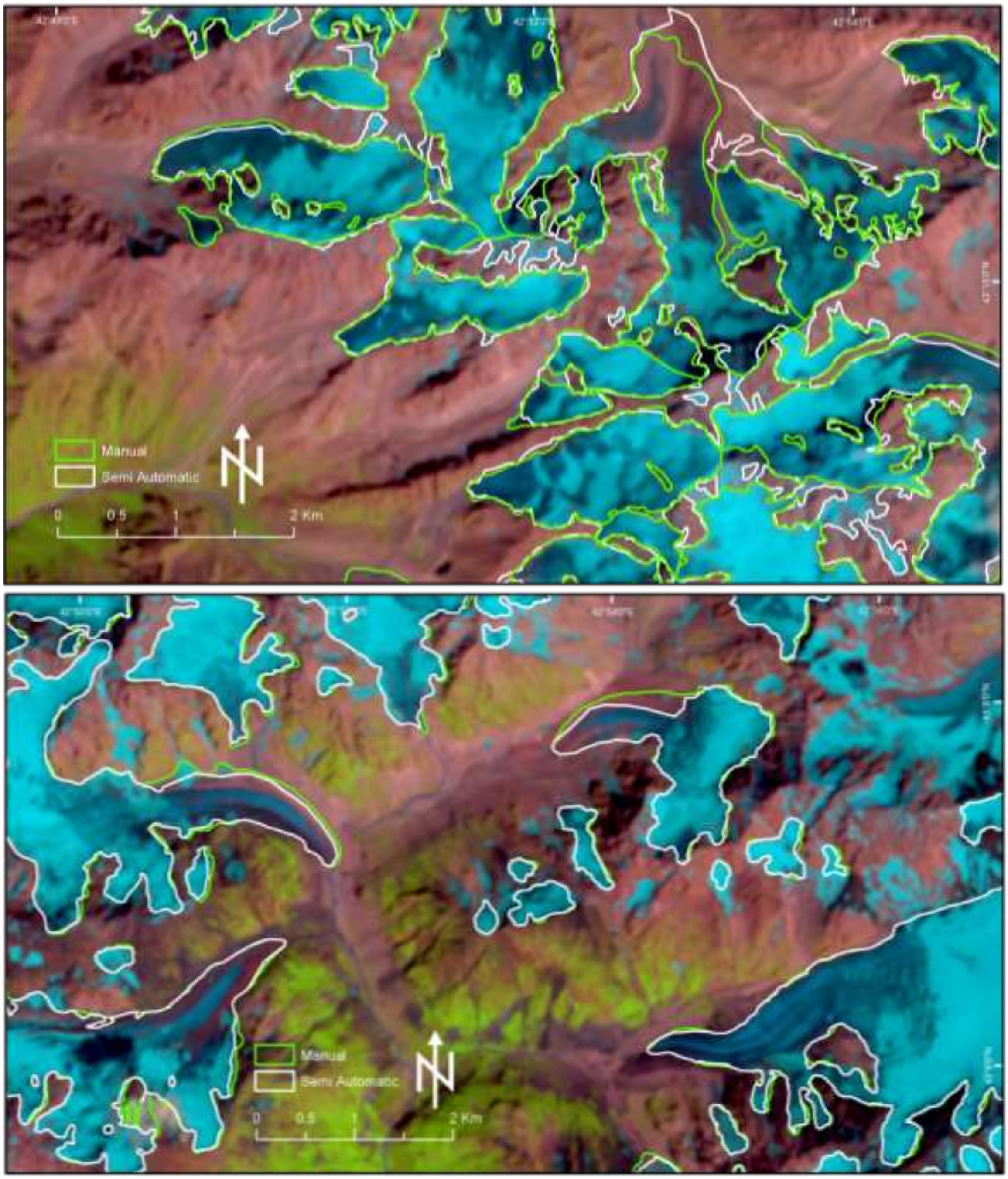
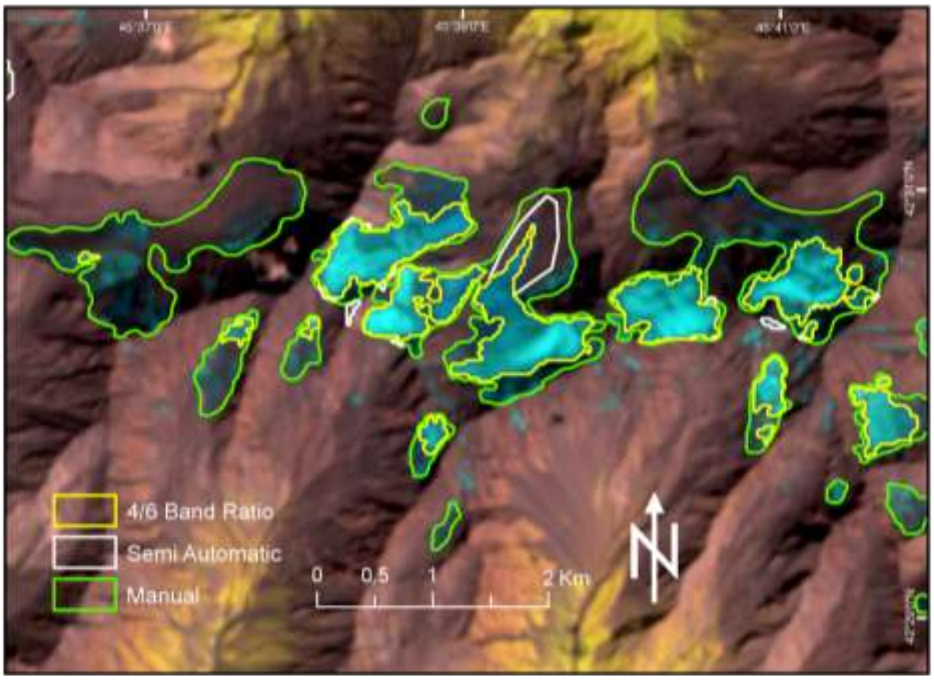


Figure 29: An instance of overestimation (top) of semi-automatic method compared to manual outlines and underestimation(bottom)

areas where the semi automatic method does not correspond well with the manual outlines (Figure 29). In the top image the semi automatic extents over-estimate areas while in the bottom image it is underestimated.

3.4 East Caucasus

Compared to the west and central areas, the east Caucasus does not have many clean ice glaciers. This becomes problematic for the 4/6 ratio (which only picks up clean glacier ice) and the semi automatic method (which relies on clean ice to create a proximity buffer to include debris), and both of which fail for the Eastern section (Figure 30). In most places the manual outlines are comparatively larger than both the 4/6 band ratio and semi automatic method. Whereas in the west and central areas there was a relatively good agreement between methods, here the outlines differ vastly.



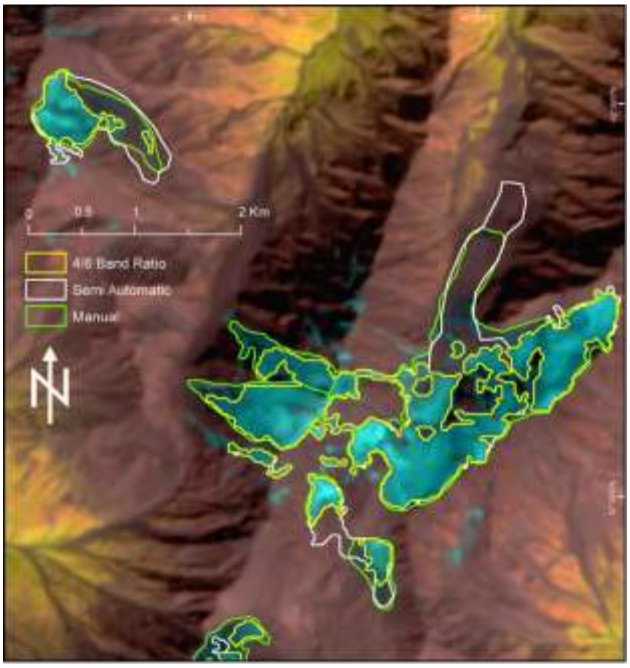


Figure 30:Comparison of 4/6 band ratio, semi automatic and manual methods. Show examples of under and over estimation

3.5 Assessing accuracy qualitatively

While the success of the outlines has been assessed visually and qualitatively so far, it is important to provide a quantitative assessment of accuracy. Therefore, a number of quantitative assessments will be undertaken and results compared.

The first quantitative method looks at the relative area of Georgian and Russian glaciers and compares the total area of each different method. Bar charts have also been included which analyze Tieldize's (2017) method of debris analysis by subtracting band ratio delineations from manual outlines to find the amount of debris cover.

3.5.1 West Caucasus

Generally, the performance of all algorithms was good for the western Caucasus. The semi automatic method and band ratio methods over-estimated total area on the Georgian side of the Caucasus but performed better than the 4/6 band ratio in identifying a larger area of glacier (Figure 31). As can be seen in the debris cover comparison (Figure 32) the larger amount of debris cover on the Russian glaciers may have caused this discrepancy. When comparing the areas side by side (Table 4) the semi automatic method seems to be increasing the amount of glacier area identified, however this must be analyzed with a confusion matrix to test how many pixels were correctly classified to verify this result.

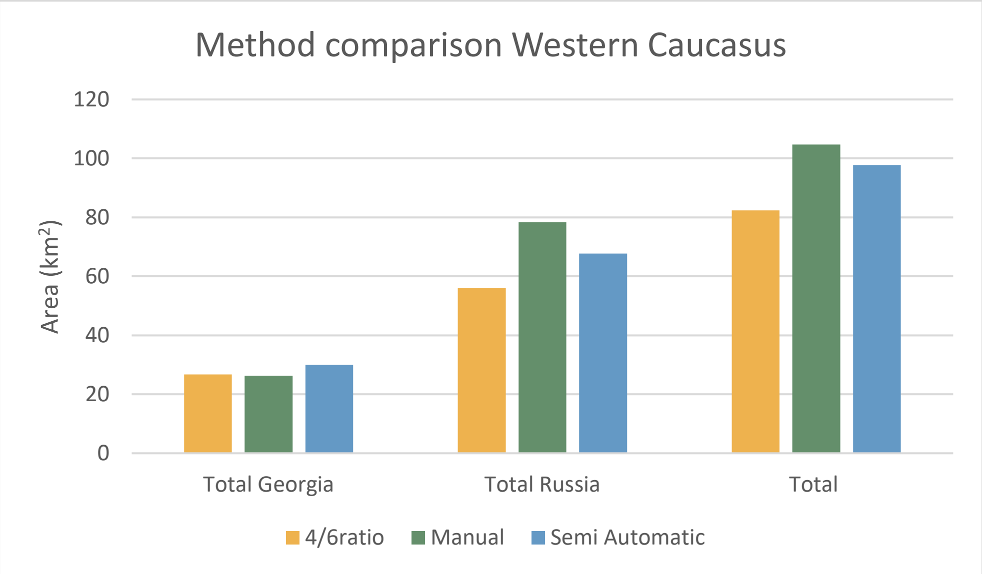


Figure 31: Comparison of Area(km^2) in Russia and Georgia for each method

	Georgia Area (km^2)	Russia Area (km^2)	Total Area (km^2)
4/6 Ratio	26.74	55.97	82.37
Semi Automatic	30.05	67.76	97.81
Manual	26.31	78.38	104.69

Table 4: Comparison of area(km^2) for each method

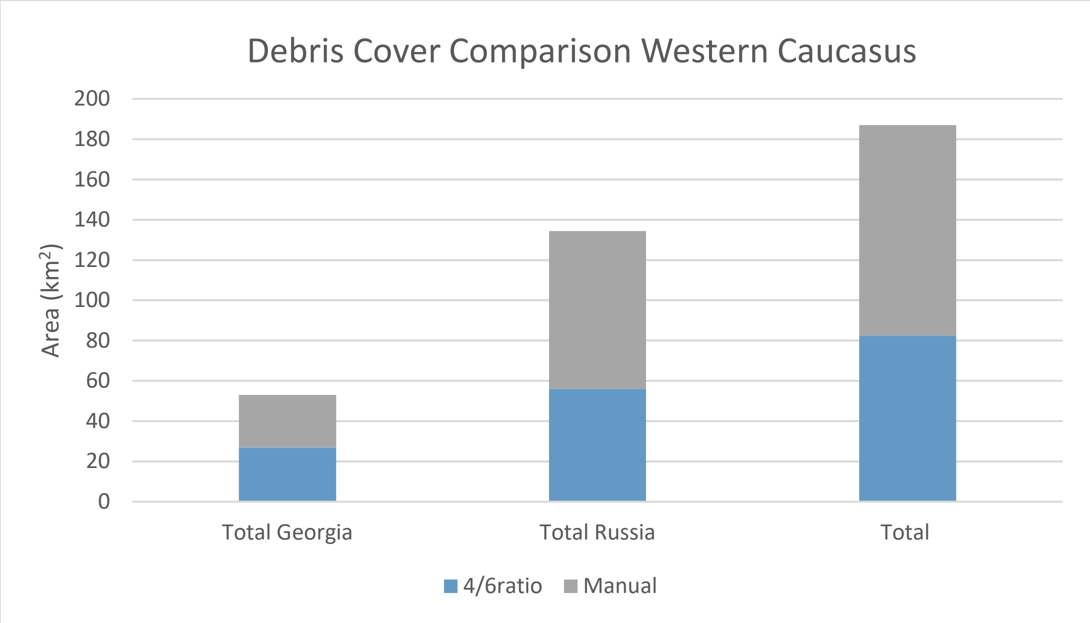


Figure 32: Comparison of 4/6 ratio(clean ice) and Manual methodology(clean and debris covered ice) to show debris cover in each country

3.5.2 Elbrus

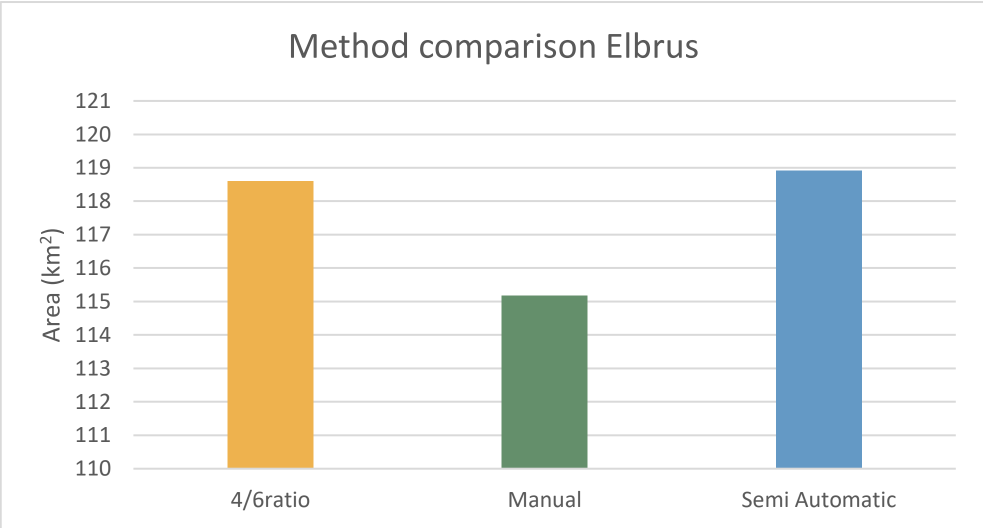


Figure 33: Comparison of total area(km^2) for each method

	Total Area (km^2)
4/6 Ratio	118.61
Semi Automatic	118.92
Manual	115.18

Table 5: Comparison of total area (km^2) for each method

When analyzing the Elbrus glaciers, the 4/6 ratio and semi automatic method overestimate the area, in excess of 3km^2 (Figure 33; Table 5). This problem has been discussed in section 3.2.1 and is largely a result of inexperience of the digitizer.

3.5.3 Central Caucasus

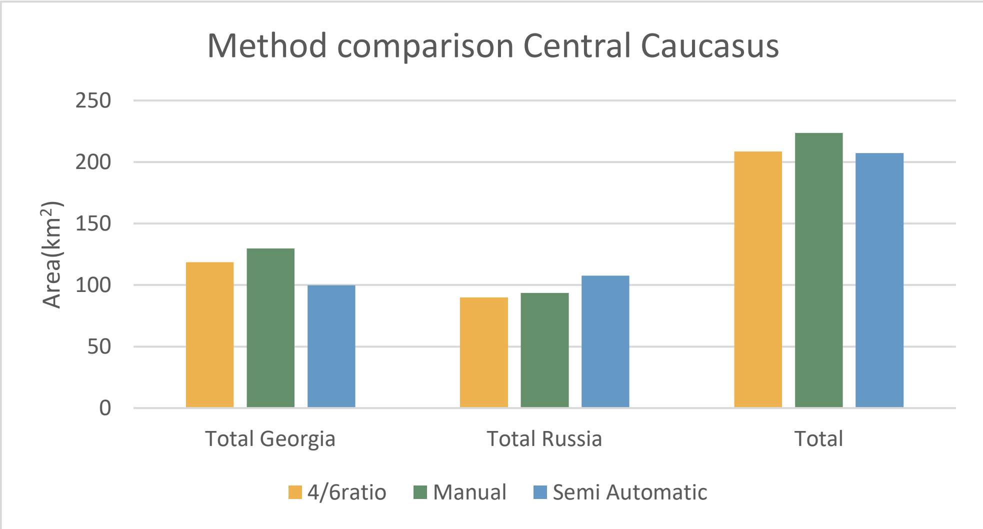


Figure 34: Comparison of area(km^2) for each method in Georgia and Russia

	Georgia Area(km^2)	Russia Area(km^2)	Total Area(km^2)
4/6 Ratio	118.63	89.90	208.53
Semi Automatic	99.86	107.51	207.37
Manual	129.71	93.72	223.71

Table 6: Comparison of area(km^2) for each method

For the central Caucasus the semi automatic was not so successful in analyzing glacier area. In Georgia, the area was vastly underestimated while overestimations occurred in Russia (Figure 34). Even in total, the semi automatic method predicts a reduced area when compared with both the 4/6 ratio and manual methodology (Table 6). When it comes to analyzing debris cover (Figure 35) it is clear that Georgia has more and Russia has less, which may account for the discrepancies in the semi-automatic methodology.

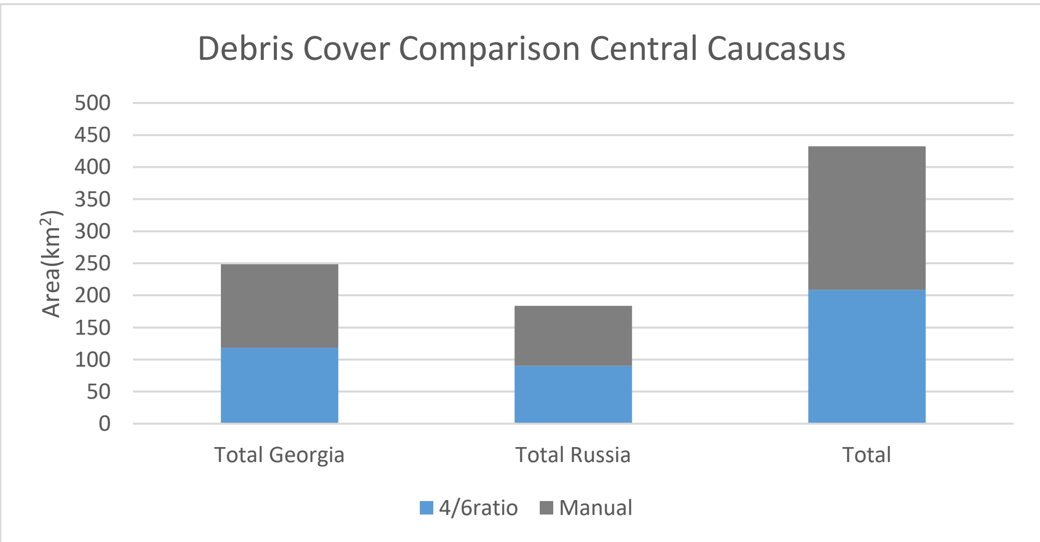


Figure 35: Comparison of 4/6 ratio(clean ice) and Manual methodology(clean and debris covered ice) to show debris cover in each country

3.5.4 East Caucasus

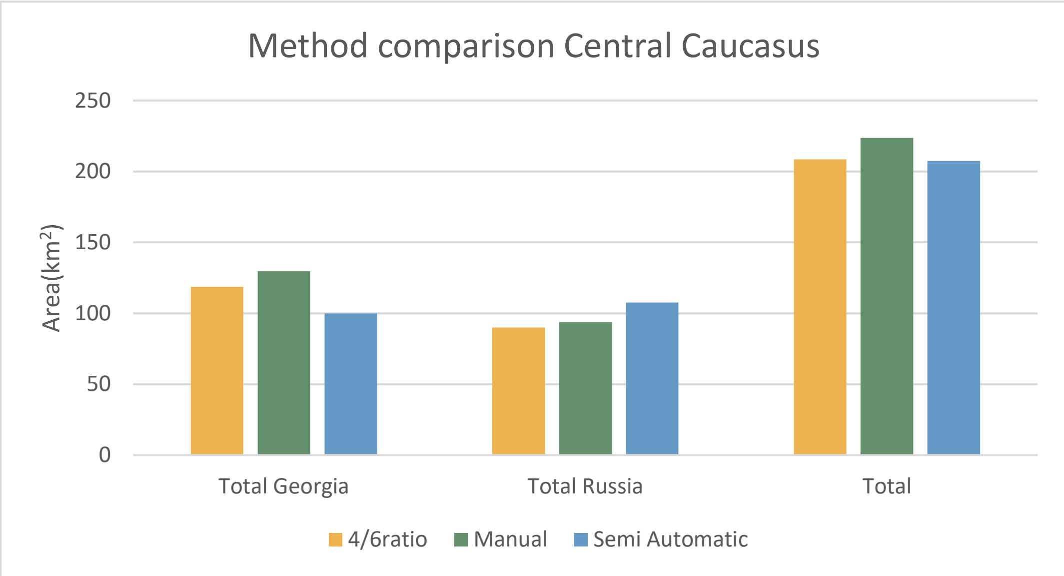


Figure 36: Comparison of area(km^2) for each method in the east Caucasus

	Total Area(km^2)
4/6 Ratio	8.69
Semi Automatic	11.96
Manual	25.34

Table 7: Comparison of area(km^2) for each method east Caucasus

Due to the high number of debris covered glaciers in the eastern Caucasus both the semi automatic and 4/6 band ratio techniques failed in identifying an accurate number of glaciers (Figure 36). This is one area where local knowledge would help, with differences between the 4/6 ratio and manual method of 16km^2 (Table 7).

3.6 Confusion Matrices

All calculations for the users accuracy and overestimation of bare rock can be found in the appendix[ii].

3.6.1 Western Caucasus

The accuracy results for the western Caucasus confirm trends found in both the qualitative and quantitative results so far. The user's accuracy (i.e. the reliability) suggests that the semi automatic method performs better than band ratio methods, for instance the Alifu et al. (2016) method had the largest over-estimation of non glacier area. Although from these figures Paul et al. (2016) seem to have performed as well as the band ratio, from visual analysis it is clear that this is not the case (see section 3.1.5). Using a 1.9 threshold seems like a mistake from this data, with it performing the worst of the band ratio methods.

[ii] Assessing the producer's accuracy was unsuccessful as non-glacier area was larger than the ground truth area in the classified image, meaning the producer's accuracy was always calculated as 100%. Over-estimation was calculated instead to show how much each method over-estimated non-glacier area by.

However, from visual analysis the tendency for this threshold to pick up smaller patches of snow is evident. This shows how important it is to look at all assessments of these methods together.

Method	User's Accuracy (%)	Overestimation (%)
4/6 1.8	76.94	2.06
4/6 1.9	69.17	2.76
4/6 2.0	71.68	2.53
4/6 2.1	71.10	2.58
Paul	71.41	2.56
Alifu 10/(5/7)	59.41	3.63
Alifu 11/(5/7)	53.94	4.12
Alifu ((10+11)/2)/(5/7)	54.94	4.03
Semi Automatic	81.48	2.76

Table 8:Comparison of user's accuracy and overestimation for all methods tested in western Caucasus

3.6.2 Elbrus

Method	User's Accuracy(%)	Overestimation(%)
4/6 Ratio	39.59	47.52
Semi Automatic	-	5.30[iii]

Table 9: Comparison of user's accuracy and overestimation for Elbrus

As seen in section 3.2.1 the Elbrus glaciers were overestimated in the semi automatic method. The 4/6 ratio has a user's accuracy is one of the lowest producer's accuracies in this research, and the overestimation of bare rock here was very high almost 50%, while the semi automatic method over-estimated glacier area by 5% (Table 9).

3.6.3 Central Caucasus

In quantitative terms, the semi automatic method worked relatively well for estimation of the central Caucasus. However, the 4/6 ratio method performed poorly – overestimating bare rock by 15% and having a midrange user's accuracy of 62%. On the other hand, the semi automatic method was more successful, with the highest user's accuracy of the research.

Method	User's Accuracy(%)	Overestimation(%)
4/6 Ratio	62.33	15.26
Semi Automatic	90.40	3.89

Table 10: Comparison of user's accuracy and overestimation for central Caucasus

[iii] The semi automatic method over-estimated glacier area and under estimated non glacier, therefore user's accuracy could not be calculated

3.6.4 East Caucasus

Method	User's Accuracy(%)	Overestimation(%)
4/6 Ratio	34.82	11.37
Semi Automatic	54.81	7.88

Table 11: Comparison of user's accuracy and overestimation for the east Caucasus

The user's accuracy for both methods was low, and both methods significantly over-estimated bare rock cover. There is still an increase in user's accuracy for the semi automatic method compared to the band ratio method; with a 20% increase.

3.7 Uncertainty of glacier outlines

It is important to assess the accuracy of glacier outlines with regard to the satellite imagery, as the resolution of the pixels (30m) can cause differences with reality. A buffer of 15m was applied to the outlines to find the uncertainty in glacier outlines. As can be expected the largest difference came from the eastern Caucasus where delineations were difficult to capture, whereas the lowest came from Elbrus, which also had a relatively high user's accuracy. Generally, there is a relationship between the size of the glacier and the relative uncertainty.

Region	Method	Area (km^2) without buffer	Area (km^2) with 15m buffer	Uncertainty %
West	4/6 Ratio	82.37	92.97	±11.40
	Semi Automatic	97.81	108.56	±9.90
	Manual	104.69	115.25	±9.16
Elbrus	4/6 Ratio	118.61	122.12	±2.93
	Semi Automatic	118.92	121.41	±2.05
	Manual	115.18	118.23	±2.66
Central	4/6 Ratio	208.53	229.64	±9.19
	Semi Automatic	207.37	225.89	±8.20
	Manual	223.71	237.26	±5.71
East	4/6 Ratio	8.69	10.54	±17.55
	Semi Automatic	11.96	15.84	±24.46
	Manual	25.34	28.34	±10.59

Table 12: Comparison of area, buffered area and subsequent uncertainty in outlines for all areas

4.Discussion

4.1 West Caucasus

The West Caucasus was used as a test region for all of the methods and to optimize the semi automatic method. The band ratio techniques made for an interesting comparison, particularly between techniques which had been found preferable for increased debris analysis and better delineation in other studies.

4.1.1 Thresholds

The area of glacier identified by just changing the threshold of a 4/6 band ratio image varied significantly, particularly when analyzed qualitatively (Figure 9). There is a clear underestimation of glacier ice (which decreases as the threshold increases) and an overestimation of non glacier area (which increases as the threshold increases). Although in numerical terms this may not seem ideal, when compared these differences become clear, it is therefore important to choose the correct threshold and query the image appropriately before beginning analysis and take into careful consideration that this threshold can have a wide range (Winsvold, et al., 2016). The 4/6 ratio has been proven to be a robust band ratio technique for clean glacier ice delineation in past studies, and appears to perform well in the Caucasus range in identifying clean glacier ice.

4.1.2 TIR/NIR/SWIR band ratio

Alifu et al.'s (2016) method attempts to take this ratio and improve it by incorporating the thermal band. However, all iterations of the equation in this research were unsuccessful in identifying clean glacier ice, nor increasing the identification of debris covered ice. Much of the clean ice which would have been identified successfully using a 4/6 band ratio becomes fragmented (Figures 10 and 11) and has an average user's accuracy of 56% - the lowest identified across all methods and regions. There are several explanations for why this method may not have performed well. The first is the coarse resolution of the thermal bands in Landsat OLI compared to Landsat TM. While Landsat TM has a resolution of 60m, this is decreased to 100m in Landsat 8 (NASA, 2017) (Table 2) so while the ratio may have been effective in Alifu et al's (2016) study, when applied to OLI imagery the result is less satisfactory perhaps as a result of this coarse resolution. Although the thermal band is seen to improve the identification of debris cover (Alifu, et al., 2016) the dynamics of glacier temperature are complicated. Debris cover can hinder or amplify glacial melt depending on a number of factors such as thickness and composition (Robson, et al., 2015) and it has been found that using thermal bands to delineate debris cover is only successful if debris cover does not exceed 40-50cm (Shukla, et al., 2010). Debris cover varies between glaciers and in the Georgian Caucasus varies from ~10-80cm although material on the tongue can reach up to 1.5m, for instance on the Khalde Glacier (Tielidze, 2017).

While there has been found to be a significant difference between the temperature of supraglacial and periglacial debris cover and surrounding rocks, future studies may examine the possibility of using a higher resolution thermal sensor (Bhardwaj, et al., 2014), as well as combining field measurements of debris thickness. Further investigation into the usefulness of the Alifu et al. (2016) method is needed before it is discounted as a viable method

4.1.3 Panchromatic band ratio

The Paul et al. (2016) methodology which incorporates the panchromatic band to improve accuracy was also relatively unsuccessful in improving glacier area identified (Figure 12) and instead of identifying glacier area, identified snow patches and small areas of bare rock. This may be due to the thresholds chosen, however the focus of this method was to identify small glaciers as the resolution of Landsat imagery is too coarse for this (Paul, et al., 2016). Therefore, this method may be unsuitable for the Caucasus region due to the larger size of glaciers, but in the future with continued warming temperatures and reduction of glacier size this technique could become more useful. While it may seem visually that this method was inefficient and overestimated area, the user's accuracy was similar to a 4/6 band ratio at 71.4% for Paul et al.'s (2016) method compared to an average of 72.22% for the 4/6 band ratio (Table 8). Manual editing to reduce the outliers would be time-consuming and therefore for the Caucasus region when identifying clean ice, a 4/6 ratio would suffice. However, the practicality of this panchromatic method should not be underestimated, particularly in other regions which may have smaller glaciers e.g. the Swiss Alps. When glaciers of <1km^2 were mapped using medium-resolution satellite imagery (30m) the uncertainty increased while high resolution satellite imagery (25cm) performed significantly better (Fischer, et al., 2014). Although beyond the scope of this research, the recent release of Sentinel 1 and 2 data may mean that this method can be further investigated, with a 10m resolution in NIR and 20m in SWIR. Although in some cases manual editing can be harder because of the accuracy of this method (e.g. on medial moraines), there is a possibility for a more accurate delineation of debris covered glacier (Paul, 2016).

4.1.4 Comparison of methodologies

When comparing all the outlines according to the Georgian and Russian sides of the Caucasus (Figures 14 and 15) it is clear there are differences in how well the methodology worked as a result of the ratio of debris cover (Figure 20). On the Georgian slopes, glaciers were overestimated in both the band ratio and semi automatic methods (Figure 21). However, because there is relatively little debris cover on the Georgian side the band ratio performed well in producing a fairly accurate area cover. The overestimation could be as a result of inexperience of the digitizer[iv] in what constitutes a glacier, for instance large snow patches which are not glacier but were not deleted in manual corrections (Figure 22). This shows that for areas which are mostly clean ice, such as the Georgian Caucasus, a simple 4/6 ratio would be best as it can most accurately portray glacier ice and does not require much manual editing to improve delineations. This shows the importance of understanding the topography to assess which method would be most appropriate.

On the other hand, Russian glaciers were under-estimated (Figure 20). Again, this could be due to inexperience and lack of local knowledge of the digitizer, however it is more likely due to the combination of field measurements and GPS points allowing more accurate manual delineations than solely semi automatic methods.

When compared to manual outlines (considered the most accurate), the semi automatic method performs best for the Western Caucasus at 81.4% (Table 8). This may be because the overestimations in Georgia and the underestimations in Russia cancelled each other out compared with the band ratio method, and the semi automatic calculated a larger amount of area compared to the band ratio method overall – making it closer to the 'real' area of the manual delineations (Figure 20).

4.2 Elbrus

All of the estimations for Elbrus were relatively close in estimated area (Figure 33), probably as a result of the large ice area, meaning that delineations are less likely to differ as much as they would on smaller glaciers. As well as this there are fewer anomalous regions e.g. shadow and debris cover to complicate delineation. However, although the area estimates are similar, when the visual analysis and user's accuracy are considered the picture is quite different. As a result of inexperience in digitizing it is clear that the outlines for Elbrus glaciers have been overestimated (Figure 24). As previously discussed by Fischer et al. (2014) manual outlines can vary considerably depending on the experience of the digitizer which seems to be the case with the manual adjustment of the semi automatic method. The band ratio method also picks up small patches of snow cover which were too big to be sieved out, creating further inaccuracies. Therefore, an understanding of the topography and local knowledge of the region can be invaluable when creating glacier extents, particularly for manual adjustments.

4.3 Central Caucasus

The topography of the central Caucasus is different to the western region. This made for interesting comparisons with the western region, namely with the proximity analysis.

[iv] "inexperience of the digitizer" means the inexperience of the author in correcting the semi automatic delineations for both the Caucasus region and glacier area.

4.3.1 Proximity Analysis

The central region had much longer debris tongues than the western region, therefore the proximity analysis used had to be edited manually to find the best trade off between identifying bare rock and debris covered glacier. Figure 27 shows how much difference changing this distance can make between the 500m proximity used for the western Caucasus and a large distance such as 1500m. Although a local knowledge of the area would have made finding the ideal distance easier, by querying the image a relatively good idea of distance between the clean ice glacier tongue and surrounding debris cover could be found. The importance of editing the derived outlines can be seen (Figure 28) with a large amount of outliers or fragmented sections which would cause an overestimation unless edited. While using buffers and proximity has been attempted before to identify vegetation, watersheds and other geomorphometric parameters (Frey, et al., 2012), it has not been used combined with other techniques in identifying debris cover on glaciers. While Winsvold et al. (2016) hint at the idea, this study is novel in its use of using a buffer from clean ice polygons to determine debris cover. A better understanding and knowledge of glacier dynamics and the Caucasus region would have allowed for a more complete picture of the glaciers. However, a 90% user's accuracy for the central region was the highest user accuracy obtained in this study and this is indicative of the potential for integrating proximity into a semi automatic method.

4.3.2 Comparison of Methodologies

Overall, Georgian glaciers were underestimated by ~10km^2 for the 4/6 ratio and ~30km^2 for the semi automatic method (Table 6). The estimates for overall area can be deceiving as they make it seem like the 4/6 ratio was far more accurate (Figure 34), while this may have been true of western areas where in Georgia there were very few debris covered glaciers, in the central Caucasus these tongues can be long, and even

longer than Russian areas. The under-estimation may have come from the digitization method, this can be seen in Figures 25 and 29 where the manual delineations show slightly more area, which would add up across the whole of the Georgian Caucasus.

On the other hand, semi-automated Russian glaciers were over-estimated largely for the same reasons as underestimation in the Georgian glaciers, because of inexperience by the digitizer in the Caucasus region. This may largely be due to the semi automatic method including snow patches as glacier and these were not corrected during manual changes(Figure 29).

While the 4/6 ratio can again be said to perform the best with regards to clean glacier ice cover, the large amounts of debris cover mean that it is inefficient in creating an accurate portrayal of glacier area. The semi automatic method performed relatively well and the differences were largely a result of subjectivity between the digitizer of manual adjustments and L. Tieldize's manual outlines. However, though the method was successful in producing a relatively good depiction of glacier area in the Caucasus area, a large amount of manual editing would be needed in order to reduce the anomalies which occur when using the proximity method.

4.4 East Caucasus

Of the three areas the 4/6 ratio and semi automatic methods performed the worst in the east Caucasus region. The user's accuracy for both methods was very low (Table 11) and the overall area (Figure 36) was vastly underestimated. This can also be seen in the visual interpretation.

The principal problem with these delineations was the geography of the region. As a result of the Caucasus climate (see section 1.1) the snowline in the eastern Caucasus is higher than in the centre and west and therefore glacier formation is not as widespread (Tielidze, 2017). This leads to the formation of rock glaciers, which have a different spectral signature to those of the central and west Caucasus, therefore the 4/6 ratio and the semi automatic method (which relies on the 4/6 ratio to identify clean ice areas) both vastly underestimated the glacier area (Figure 31). This again points to the importance of understanding the topography and geography of the region under analysis. While satellite images can be invaluable in their uses for analysis, without some capacity of local knowledge it is very difficult to analyze the region thoroughly.

4.5 Uncertainty in outlines

Assessing the uncertainty in glacier delineations (Table 12) shows that the smaller the glaciers, the larger the uncertainty in outline accuracy. This is an important consideration when finding glacier delineations and one which will become increasingly vital as future climate change causes glaciers to melt and overall area to decrease. More accurate satellite imagery such as that from Sentinel satellites will mean these uncertainties will be less in the future, but currently it is an important consideration when creating glacier outlines.

5.Conclusion

This study has assessed the aptitude of different methods for delineating glacier outlines in the Greater Caucasus and found that the success of the methodology depends on a variety of factors.

Alternative band ratio methodologies such as incorporating the thermal and panchromatic bands proved to be unsuitable for this region. The panchromatic band would be better suited to analyzing smaller glaciers, of which there are few in the Caucasus region. The resolution of the thermal band was too coarse to accurately delineate glacier outlines and the temperature dynamics of debris covered glacier are not understood well enough to make this technique more accurate – particularly without fieldwork.

In general, the semi automatic technique performed well and often identified more glacier area than a 4/6 band ratio alone. However, a large amount of post-processing in the form of manual editing was needed in order to make the accuracy of outlines as precise as possible and reduce outliers. In some cases, particularly where there was less debris cover, this method was completely unsuccessful and overestimated areas.

The importance of local knowledge or an understanding of the topography of region has been highlighted in this study, with the major downfall of each method being one of lack of understanding of glacier dynamics and the local environment.

As a result, there is no clear 'best option' for glacier delineation and the type of glacier and region should determine which method is used. For instance, in areas with a large amount of glaciers, manual delineation would be too time-consuming and laborious whereas the 4/6 ratio or the semi automatic method could be preferable.

Therefore, future studies should focus on the integration of field data in order to create more accurate outlines. Where this is not possible, further research should be given to the use of different band ratios and the use of different, higher resolution satellite images such as those from Sentinel 1 and 2. In addition, continuing to research the capabilities that can be extracted from satellite imagery alone, such as exploring plan and profile curvature, more complex band ratios or movement dynamics could prove useful in improving the accuracy of future glacier inventories.

5.1 Limitations of this Study

Evidently, this study only uses sample areas of the Caucasus region. While these are assumed to be representative of the whole area, in reality there could be areas where these methods do not perform so well. Using a wider variety of methods would also have allowed for a better cross analysis of methods. For instance, pixel and object based classification, more texture and slope parameters and a more thorough investigation into proximity.

The lack of knowledge of the area also lead to digitization errors within the semi automatic method and therefore a comparison of outlines by local experts may have made for an interesting comparison and a clearer and more accurate picture of the results.

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7. Appendices

7.1 Thesis Task Description

TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Sciences | Institute for Cartography

Task of Master Thesis

Course of Studies: International Master Course in Cartography

Name of the Graduand: Kate Doyle

Topic: Glacier extents of the Central Caucasus as derived from manual interpretation and digital classification of Landsat satellite data

Goals of this Study:

The aim of this study is to compare and contrast the results of manual versus semi-automated methods of glacier digitisation in the Caucasus mountain range. Glacier extents in the Caucasus are relatively understudied and this paper seeks to find the most robust method of digitising these outlines. Glacier extents will be created using a semi-automated method and analogised against manual outlines. Data will be synthesised to derive robust glacier outlines and results will be compared to assess whether the semi-automated results fit within the error margins of manual digitisation.

The results have to be submitted as a written document along with a digital version. This document has to be delivered in two copies. All data, relevant for further scientific treatment, have to be stored on digital media, and to be added to the final submission. The contents of the digital media should be structured in such a way, that an easy continuation of project work will be facilitated. The results should furthermore be presented on a A0 poster; the suitable poster template is available through the institute's homepage.

Supervisors: Dr. Roger Wheate (University of Northern British Columbia)
Dr. Nikolas Prechtel (TU Dresden)

Delivered: April 27th 2017
To be filed: September 28th 2017

R.D.Wheate

Dr. Roger Wheate | Dr. Nikolas Prechtel

Supervision

7.2 Queries to obtain semi-automatic layer

Reproject DSM and clip to composite extent

Extract Clean Ice:

Find clean ice without water:

```
if %10>1.8 and %5 >8500 then
%11=1
endif
```

Find shadowed ice:

```
if (%10>= 1.38 AND %10 <= 1.69) then
%12=1
endif
```

Combine:

```
if %11=1 or %12=1 then
%13=1
endif
```

Extract Debris covered Ice

Query aspects and find debris:

```
if (%5>8500 ) and (%9>1900) and (%15<24) and (%16>=0.8) and (%17<=0.65) and
(%18<=1.25) then
%19=1
else
%19=0
endif
```

Make proximity layer and query using debris:

```
if %20<>255 and %19=1 then
%21=1
else
%21=0
endif
```

Combine:

```
if %14=1 or %21=1 then
%22=1
else
%22=0
endif
```

(NB: Parameters such as elevation,texture, slope etc. are edited according to the DN when the Landsat image is queried)

7.3 Accuracy Assessment Results

7.3.1 Western Caucasus

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	568081	170281	738362	User's Accuracy	76.93800602
46 18	Non Glacier	0	8261638	8261638	Overestimation	102.0611046
	TOTAL	568081	8431919	8829719		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	510702	227660	738362	User's Accuracy	69.16688562
46 19	Non Glacier	0	8261638	8261638	Overestimation	102.7556279
	TOTAL	510702	8489298	8772340		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	525000	213362	738362	User's Accuracy	71.10333414
46 20	Non Glacier	0	8261638	8261638	Overestimation	102.5825629
	TOTAL	525000	8475000	8786638		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	529289	209073	738362	User's Accuracy	71.68421452
46 21	Non Glacier	0	8261638	8261638	Overestimation	102.5306483
	TOTAL	529289	8470711	8790927		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	405682	332680	738362	User's Accuracy	54.94351009
Alifu 101157	Non Glacier	0	8261638	8261638	Overestimation	104.0268044
	TOTAL	405682	8489298	8667320		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	438671	332680	738362	User's Accuracy	59.41137274
Alifu 1057	Non Glacier	0	8261638	8261638	Overestimation	103.627501
	TOTAL	438671	8489298	8700309		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	398244	340118	738362	User's Accuracy	53.94
Alifu 1157	Non Glacier	0	8261638	8261638	Overestimation	104.12
	TOTAL	398244	8489298	8659882		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	527259	211103	738362	User's Accuracy	71.41
Paul	Non Glacier	0	8261638	8261638	Overestimation	102.56
	TOTAL	527259	8472741	8788897		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	601649	136713	738362	User's Accuracy	81.48
Semi Automatic	Non Glacier	0	8261638	8261638	Overestimation	102.76
	TOTAL	601649	8398351	8863287		

7.3.2 Elbrus

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	1564883	2394984	3959867	User's Accuracy	39.52
4/6	Non Glacier	0	5040133	5040133	Overestimation	147.52
	TOTAL	1564883	7435117	9000000		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	3959867	0	3959867	User's Accuracy	100
Semi Automatic	Non Glacier	209964	4830169	5040133	Overestimation	95.83
	TOTAL	4169831	4830169	9000000		

7.3.3 Central Caucasus

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	1617157	977186	2594343	User's Accuracy	62.33
4/6	Non Glacier	0	6405657	6405657	Overestimation	115.26
	TOTAL	1617157	7382843	9000000		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	2345317	249026	2594343	User's Accuracy	90.40
Semi Automatic	Non Glacier	0	6405657	6405657	Overestimation	103.887595
	TOTAL	2345317	6654683	9000000		

7.3.4 East Caucasus

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	46551	87122	133673	User's Accuracy	34.82
4/6	Non Glacier	0	766327	766327	Overestimation	111.37
	TOTAL	46551	853449	812878		

			Manual			
		Glacier	Non Glacier	TOTAL		
	Glacier	73262	60411	133673	User's Accuracy	54.81
Semi Automatic	Non Glacier	0	766327	766327	Overestimation	107.89
	TOTAL	73262	826738	839589		