Glacier parameter extraction using Landsat 8 images in the eastern Karakorum

H Wang 1, R Yang 2, X LI 3 and S CAO 4

1 School of Land Science and Technology, China University of Geosciences (Beijing), Haidian District, Beijing 100083, China
2 Beijing Jiao tong University School of Civil Engineering, Haidian District, Beijing 100044, China
3 Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China
4 Shandong University of Science and Technology, College of Geomics, Qingdao 266590, China
Email:14121165@bjtu.edu.cn

Abstract. Changes in glacial melt and river runoff directly impact upon water resources and utilization. Glacier area data provide the basis of analysing glacier change. In this study, Landsat images from the end of the 2014 melt season were analysed using remote sensing and geographic information systems (GIS) technology. We compared the band ratio method and Normalized Difference Snow Index (NDSI) method for extracting glacial parameters. The results show that the band ratio method is better for glacier boundary extraction. However, for debris covered glaciers, textural analysis is needed for area extraction and needed to revise boundary extraction results through the visual interpretation of the remote sensing image. Accurate area extraction is particularly important for glaciers, as these are major contributors to runoff.

1. Introduction
Investigating glacier change primarily relies on identifying accurate glacial boundaries from remote sensing images. Accurate area extraction is particularly important for glaciers of > 2 km², as these are major contributors to runoff. At present, there are numerous automatic and semi-automatic glacier identification methods, with the most commonly used automatic methods including statistical thresholding, unsupervised and supervised classification, principal component analysis, band ratios, and the Normalized Difference Snow Index (NDSI) method. With the rapid development of remote sensing technology and greater understanding of glacier change, automatic boundary extraction methods have become possible.

Sidjak [1] used a combination of bands in a supervised classification to extract glacier areas and found that only the PC2-4 and TM4/TM5 combinations, and the NDSI were able to deal with shadowed areas and moraine-covered glaciers. Paul [2] compared supervised classification and unsupervised classification using the NDSI method, and the TM3/TM5, and TM4/TM5 bands, and found that only the TM4/TM5 method effectively identified shadowed glacier areas. Shangguan [3] compared different classification methods and found that: (1) TM3/TM5, TM4/TM5, and TM3/TM5 gave the highest accuracy when identifying thin snow cover; (2) supervised and unsupervised classification can both identify of icy water, but fail to identify shadowed areas; and (3)
identification accuracy of NDSI is low for shadowed glacier areas. Zhiguo [4] found that when extracting the outline of densely shadowed and moraine covered glaciers, TM3/TM5 is more accurate than NDSI and TM4/TM5, but it still unable to consistently extract moraine covered glaciers. In contrast, Song [5] argued that the NDSI index is better than ratio methods for marine glacial extraction; however, the differences in these conclusions may reflect differences between continental and oceanic glaciers. In summary, past studies have shown that both NDSI and band ratio methods are suitable for bare ice extraction, and that appropriate method selection for a given glacier of region depends on the spatial resolution and image quality.

Despite these past studies, method suitability varies with glacier type and region; therefore, understanding which method to choose remains a research focus. In this study, we compared the accuracy of the NDSI and band ratio methods using Landsat 8 Operational Land Imager (OLI) data on two glaciers (the Sizagaer glacier, Tibet Autonomous Region, and the Kowloon glacier, Xinjiang Uygur Autonomous Region) from different regions and with different sizes and morphological characteristics.

2. Materials and methods

2.1 Study area

The Sizagaer glacier is located in the Ali area of the Tibet Autonomous Region, China (N34°17'20.74", E79°37'49.43"). The glacier has a maximum elevation of 6515.6 m, a mean elevation of 6102.2 m, and a glacier terminus elevation of 5569.9 m. The glacier is 79.58 km in length and covers an area of 23.8 km². The ice is west facing, has a mean slope of 14.8%, and is not covered by moraine.

Kowloon glacier is located in the Hetian area of the Xinjiang Uygur Autonomous Region, China (N34°34'17.54", E78°26'21.09"). The glacier has a maximum elevation of 6520.9 m, a mean elevation of 5901 m, and a terminus elevation of 5284.2 m. The glacier is 6.78 km in length and covers an area of 8.9 km². The ice faces to the north, has a mean slope of 17.3%, and is not covered by moraine.

2.2 Data types and analysis

Glacier extraction was performed using a Landsat 8 OLI image, a Landsat Thematic Mapper (TM) image, and high-resolution Google Earth images. The Landsat 8 image was acquired on 20 August 2014 along Worldwide Reference System (WRS) path 146 and WRS row 36. The image is mostly free of clouds (0.95% cloud cover) and contains little seasonal snow cover. High-resolution Google Earth images were used for 3D glacier visualization, which helped with manual glacier boundary delineation. Second glacier catalogue data were used to determine detailed feature information at the time of image acquisition. The Landsat 8 OLI land imager includes nine bands (Table 1), which have been adjusted from those in previous sensors (i.e., TM and ETM+) to avoid atmospheric absorption features; for example, a relatively large adjustment of Band 5 to exclude 0.825 m of moisture absorption features.

We completed radiometric calibration and atmospheric correction of the remote sensing image, and used the Landsat TM3/TM5 and TM4/TM5 band-ratios to automatically delineate the target glaciers. The NDSI was calculated as:

\[
\text{NDSI} = \frac{(B3-B6)}{(B3+B6)}
\]  \hspace{1cm} (1)

Landsat 8 band ratios were calculated as:

\[
\text{Band ratio 1} = \frac{B4}{B6} \hspace{1cm} (2)
\]

\[
\text{Band ratios 2} = \frac{B5}{B6} \hspace{1cm} (3)
\]
where B3, B4, B6, refers to the values of the 3rd, 4th, and 6th bands of the Landsat 8 image, respectively. Data analysis was performed using the ARCGIS and ENVI software.

| Table 1. Spectral ranges of remote sensing sensors |
|-----------------------------------------------|
| **OLI** & **ETM+** & **TM** |
| band & Spectral range/μm & band & Spectral range/μm & band & Spectral range/μm |
| B1 Coastal & 0.433–0.453 & B1 Blue & 0.450–0.515 & B1 Blue & 0.45–0.52 |
| B2 Blue & 0.450–0.515 & B2 Green & 0.525–0.605 & B2 Green & 0.52–0.60 |
| B3 Green & 0.525–0.600 & B3 Red & 0.630–0.690 & B3 Red & 0.63–0.69 |
| B4 Red & 0.630–0.680 & B4 NIR & 0.775–0.900 & B4 NIR & 0.76–0.90 |
| B5 NIR & 0.845–0.885 & B5 SWIR 1 & 1.550–1.750 & B5 SWIR 1 & 1.55–1.75 |
| B6 SWIR 1 & 1.560–1.660 & B7 SWIR 2 & 2.090–2.350 & B7 SWIR 2 & 2.08–2.35 |
| B7 SWIR 2 & 2.100–2.300 & B8 Pan & 0.520–0.900 |
| B8 Pan & 0.500–0.680 |
| B9 Cirrus & 1.360–1.390 |

3. Results and discussion
The results showed that visual interpretation of all three data types could effectively distinguish between cloud, ice, and snow (Figure 1). By comparing clouds and glacier spectral curves, we found that both glaciers and clouds were highly reflective in visible wavelengths; however, in 1.6 um near infrared band reflectance snow produced low reflectivity while clouds produced high reflectivity. These results confirm the band ratio operations can be used distinguish clouds from glaciers. In addition, the band ratio method was better than the NDSI. We also compared the spectral curves of water and glaciers and found significant differences among the red band, the near infrared wave band, and the infrared wavelengths. Based on the ratio operation of the red band, near-infrared bands, and the infrared wavelengths, spectral differences between water and glaciers were further magnified.
Figure 1. Remote sensing images obtained using different band operations: (a) Normalized Difference Snow Index (NDSI); (b) B4/B6; (c) B4/B6; (d) Landsat Image. Red circle encloses clouds.

3.1 Glacier area extraction
Combined with visual interpretation of remote sensing images, data show that the NDSI threshold value is ~0.70–0.95. Without the influence of compound glaciers, the contrast between high reflectivity visible light and near infrared bands, and low reflectivity infrared wavelengths was highlighted. To reduce the influence of glacial lakes, the band ratio method was used to refine the glacier threshold to 7. After automated delineation, we visually confirmed the results and manually adjusted for shadow, seasonal snow, proglacial lakes, and debris cover. Using this method, we were able to extract the boundaries of both the Sizagaer glacier (Figure 2; Table 2) and Kowloon glacier (Figure 3; Table 2).
Figure 2. Sizagaer glacier extraction using: (a) Normalized Difference Snow Index (NDSI); (b) Band ratio (B5/B6); (c) Band ratio (B4/B6); (d) Artificial extraction.
Figure 3. Kowloon glacier extraction using: (a) Normalized Difference Snow Index (NDSI); (b) Band ratio (B5/B6); (c) Band ratio (B4/B6); (d) Artificial extraction.

Table 2. Glacier area extraction using different methods

|                  | NDSI          | B5/B6         | B4/B6         | Artificial extraction |
|------------------|---------------|---------------|---------------|-----------------------|
| Sizagaer glacier | 7813252.79    | 7667881.39    | 7614462.60    | 8916504.43            |
Kowloon glacier / m²  22095625.89  21864908.14  21840155.06  23807296.93

In addition, high resolution images from Earth Google are used to manually delineate the glacier boundary. And the glacier area extracted by these four methods was calculated in ARCGIS.

3.2 Discrimination of other objects
The test area contained abundant proglacial lakes; therefore, the results also allowed us to consider the automated classification of proglacial lakes and other surface features (Figure 4). The results show that the B5/B6 band ratio method is best at accurately distinguishing glaciers and pro-glacial lakes; however, snow remains indistinguishable from lakes.

![Figure 4. Delineation of lakes using different wave band operation. Blue denotes the B4/B6 band ratio, green denotes the B5/B6 band ratio, and red denotes the Normalized Difference Snow Index (NDSI).](image)

4. Conclusions
In this study, we used four different methods to extract glacier boundaries. As the choice of threshold for each method affects the final result, we first followed the objective logic method to analyse the data and select the optimal threshold for each band operation. The results showed that the NDSI method extracts the smoothest glacial boundaries and provides the highest resolution images of small-scale glacier features; however, the method fails to distinguish glaciers and lakes. Using the band ratio method, extraction using the B5/B6 ratio was superior to that of the B4/B5 ratio; however, it also failed to completely eliminate the influence of lakes.

This study uses Landsat 8 to extract the characteristics of the glacier. Due to a single glacier types in the study area, for the glacier that have seasonal snow, turbid/frozen/multihued proglacial lakes and debris cover, how to improve the band operation for different types of glacier boundary extraction remains to be further research and analysis.

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