

# Visualization of Snow Cover Changes in the Greater Caucasus Mountains Using Integrated Multi-Sensor Image Fusion

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**Abstract.** The main goal of the current research was to visualize recent snow cover changes in the parts of the Greater Caucasus Mountains along Shahdag, Bazarduzu, and Tufandag mountains, using multi-sensor and multi-spectral satellite image processing. Accordingly, accessible satellite imagery from the valid sites was obtained, and a few necessary pre-processing operations, such as atmospheric and radiometric corrections, were subjected to available Sentinel-2 and Landsat (8 and 9) images from 2017 to 2023, adjusted to annual, spring-summer months. Next, we employed a harmonized method to combine the Harmonized Landsat and Sentinel (HLS) image bands using object-oriented functions within the eCognition software. This integration led to diverse products, especially High Optimized Natural Color (HONC) images and Scene Classification maps of the study area. Finally, it became possible to evaluate changes in the snow covers with higher accuracy in the annual and monthly time scales. Examining the amount of snow cover, represented by the Normalized Difference Snow Index (NDSI) in recent years shows a significant reduction in snow packs on an annual scale, with rapid melting from the middle of spring to the end of summer months. The final results indicate the fact that the methods of optimization and fusion of Landsat and Sentinel sensors can be very effective in extracting and identifying snow cover with high accuracy on a daily scale.

**Keywords:** Snow Cover Changes, Greater Caucasus Mountains, Azerbaijan, HLS Images, Integrated Processing Methods

## 1 Introduction

Snow is a common global meteorological phenomenon, mostly on the earth's higher grounds [9]. It is a valuable source of fresh water and is therefore regarded as an important component of the hydrological cycle [2, 13, 14]. According to the investigation of many researchers, the spatial and temporal models of NDSI can provide the necessary information for the optimal

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management of water resources [3, 4, 9]. In the present research, to extract as accurately as possible the temporal and spatial changes of snow cover in the Caucasus Mountains (a sampled area), the Republic of Azerbaijan, two types of standard-scale satellite images of Landsat (8 and 9) and Sentinel-2 were integrated and fused in different ways applying a Harmonized method following a set of object-oriented functions. The main goal of the current research was to detect changes in the NDSI levels in a sampled part of the Caucasus Mountains from 2017 to 2023 on annual and monthly scales.

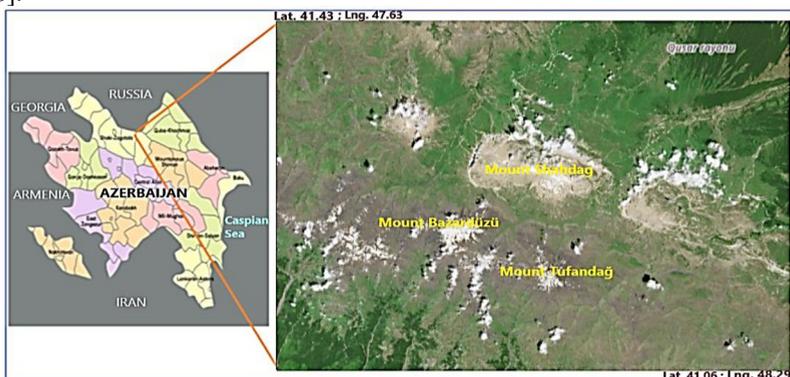
Many studies have been conducted on the modelling and changes of snow cover out of the country. For example, Rasouli et al. studied the spatial and temporal changes in the snow cover values of the Snowy Mountains region of NSW, Australia. In this research, a few object-oriented methods based on image pixel segmentation functions, supervised classification, and thresholding are used to extract the NDSI layers in the eCognition software environment.

In the case of the Georgian Caucasus region, Tielidze [5] experienced glacier area loss over the last century at an average annual rate of 0.4 % by comparing recent Landsat and ASTER images. He indicated a higher rate of glacier melt in the eastern Caucasus than in the central and western sections. In another research, Shahgedanova [7] studied snow cover in two sub-watersheds of the Caucasus Mountains, namely Akhty and Shaki, using Sentinel-1 radar images in 2015, 2016, and 2017. She found that Snow accumulation was expected to reduce its quality towards 2017 due to higher overall temperatures than the previous years caused by global warming.

It should be noted that with a brief review of previous research sources inside and outside the Republic of Azerbaijan (despite the very acceptable results obtained), it is clear that none of the mentioned researchers in the Caucasus Mountains and with emphasis on the simultaneous processing of Sentinel- 2 and Landsats 8 and 9 satellites have not applied integrated methods [10]. Therefore, the present research tried to fill this lack of research by referring to different methods and processing multi-sensor higher-resolution imagery.

## 2 Data and Methods

For the current study, a small part of the Caucasus Mountains, located in the Republic of Azerbaijan, has been selected, covering the highest peaks of Shahdag, Bazarduzu, and Tufandag mounts in the Greater Caucasus range at 4,466 meters above sea level (Figure 1). Land cover in this area includes snow zones, forest cover, pastures, agriculture, and lands affected by winter ice and snow and glacier patches. The climate of the Caucasus Mountains is under the effect of Siberian and North Atlantic Anticyclones in winter with heavy snowing events [8].



**Fig. 1.** The geographic location of the sampled study area, along the Caucasus Mountains.

In recent years, the Caucasus Mountains snow cover and glaciers responded to the temperature rise with the most significant shrinkages due to global warming [9]. In the first stage, the Sentinel-2, and Landsat (8 and 9) imagery for 2017 to 2023 was received from the official sites [12]. Then, all images were pre-processed, processed, and post-processed in different software environments. Such images provide a wide range of parameters characterizing snow covers in mountainous areas [1]. Lastly, selected images were combined through the implementation of dissimilar normalized differential indices, and harmonized and fusion algorithms in the eCognition software environment to improve the final accuracy of the NDSI maps [11].

According to the main objectives of the current research, in the first stage, all images were pre-processed, processed, and post-processed in eCognition, and ArcGIS software environments. Then, to produce snow cover maps by processing Sentinel 2 images, an optimized and enhanced color image was produced for each specific image taken on a specific day. The main purpose of implementing this method was to produce clear images from each satellite image by combining the specific spectral range of the Sentinel-2 and Landsat sensors [4]. For this purpose, by applying equation 1, it was possible to calculate the values of the third root of the lower limit of the visible bands of sentinel images (especially the L2A series) in optimized color mode.

$$S2\_HONCL2A = \{(0.6 * B04), (0.6 * B03) \& (0.6 * B02)\} \quad (1)$$

Then, equation 2 was applied to remove unwanted reflections of the pixels that increase the quality of the output images.

$$S2\_HONCL2A = \{(0.6 * B04 - 0.035), (0.6 * B03 - 0.035) \& (0.6 * B02 - 0.035)\} \quad (2)$$

After that, in the eCognition software environment, through the implementation of the snow cover calculation algorithm (equations 3 and 4), the NDSI value was calculated by processing Landsat and Sentinel images [9].

$$NDSI_{Landsat\ 8\ \&\ 9} = \{(B03 - B6) / (B03 + B6)\} \quad (3)$$

$$NDSI_{Sentinel-2} = \{(B03 - B11) / (B03 + B11)\} \quad (4)$$

To more accurately identify the snow cover, thresholding at the limit ( $NDSI = < 0.4$ ) was applied in the above equations so that the representative pixels of the snow cover can be identified more reliably. Among the other combined products, we can mention the short-wave infrared combination, which is produced based on the combination of red bands (band 4), visible and near-infrared (band 8 A), and short-wave infrared (band 12). By performing this type of combination between different bands, it is possible to distinguish between cloud types (blue clouds vs. ice clouds) and snow and ice cover (which all appear white). In the third stage, to extract the NDSI layers in the study area with high spatial accuracy, we tried to perform the fusion process between multiple bands of Sentinel and Landsat by implementing object-oriented functions in the recognition software environment. The method of fusion of different bands of Landsat and Sentinel sensors is presented in Table 1.

**Table 1.** Fusing bands of Landsat and Sentinel images.

Band Name	Bands Used	Spatial Resolution (m)	The Combination of HLS Sensors
Ultra Blue (Coastal and Aerosol)	1	30	Both Satellites
Blue	2	30	Both Satellites
Green	3	30	Both Satellites
Red	4	30	Both Satellites
Visible and Near Infrared (VNIR)	5	20	Sentinel-2
Visible and Near Infrared (VNIR)	6	20	Sentinel-2
Visible and Near Infrared (VNIR)	7	20	Sentinel-2
Visible and Near Infrared (VNIR)	8	10	Sentinel-2
Visible and Near Infrared (VNIR)	Band 5 from Landsat and Band 8A from Sentinel	30	Both Satellites
Short Wave Infrared (SWIR)	Band 6 from Landsat and Band 11 from Sentinel	30	Both Satellites
Short Wave Infrared (SWIR)	Band 7 from Landsat and Band 12 from Sentinel	30	Both Satellites
Cirrus Clouds	Band 9 from Landsat and Band 10 from Sentinel	30	Both Satellites
Thermal Infra-Red (1)	Band 10 (First Thermal Band) from Landsat	30	Landsat (8 & 9)
Thermal Infra-Red (2)	Band 11 (Second Thermal Band) from Landsat	30	Landsat (8 & 9)

In the final stage, equation 5 was applied to create more accurate NDSI values.

$$NDSI_{HLS} = \{(B_{RED} - B_{SWIR1}) / (B_{RED} + B_{SWIR1})\} \quad (5)$$

In the above formula, B<sub>RED</sub> represents the combination of red bands (Band 4) of Landsat and Sentinel and B<sub>SWIR1</sub> represents the combination of short-wave infrared bands 1 (Band 6 of Landsat and Band 11 of Sentinel). The main purpose of combining the desired bands from both satellites was to improve the quality of the output NDSI values compared to each of the satellites.

### 3. Result and Discussion

#### 3.1 Elementary products

By implementing the initial stages of image processing, several types of basic image products were produced, including true-color, false-color, optimized-color images and a scene classification map in a combined mode, which are presented in Figure 2.

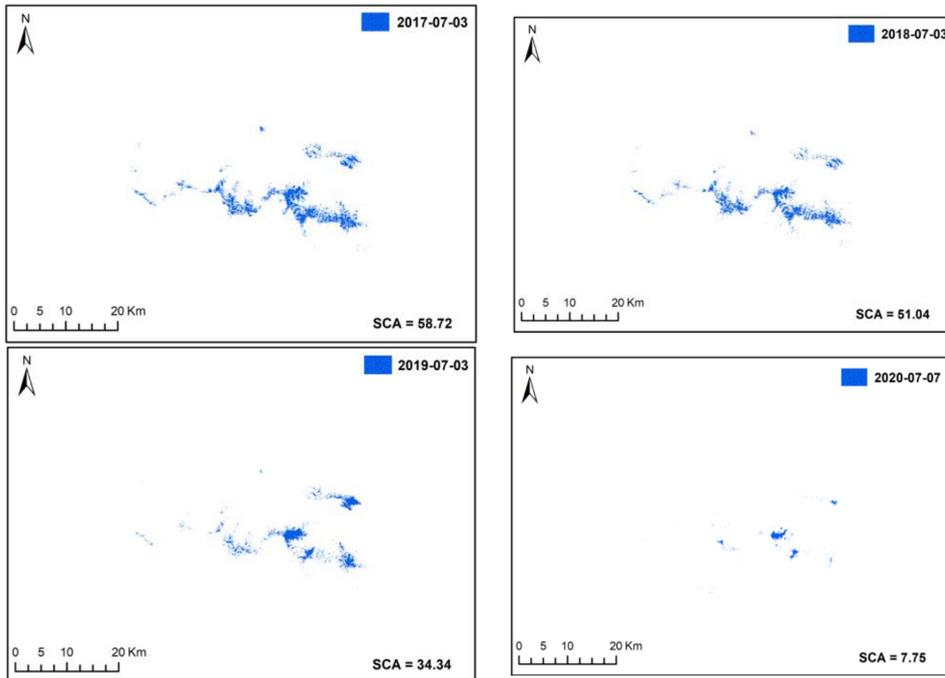


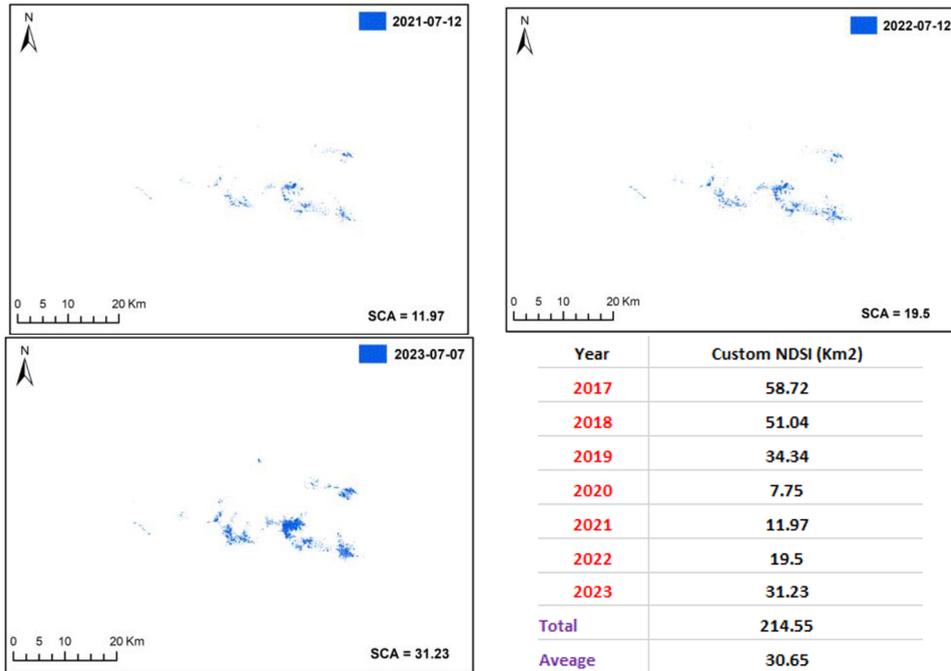
**Continuation of table 2.**

Combined Products	Bands Combination	Applications
HLS-SWIR	Please notice Table 1 range.	Various Harmonized Landsat-Sentinel products are produced by combining Landsat (8 and 9) sensor bands (OLI) and Sentinel-2 multi-spectral sensors (MSI). The common use of this type of product is to identify the ranges of vegetation, water, and snow levels.
Scene Classification Map	Processing of selected bands as needed for the fuzzy spectral thresholding process.	It is a type of classified map of the general landscape of Sentinel-2 images, which is produced by processing the sensor bands of Sentinel-2 and by applying basic knowledge methods in the software environment. This map can be used to distinguish between pixels containing cloud cover, water sources, snow surfaces, and other users.

### 3.2 Annual Snow Cover Changes

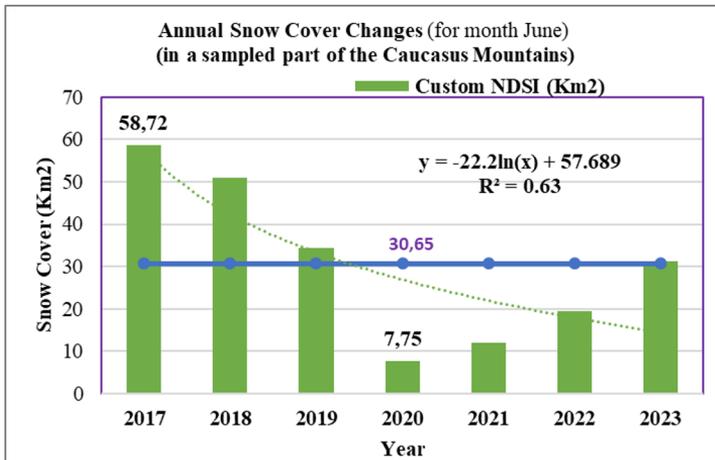
Based on fusion images of HLS, the spatial distribution of NDSI values for the years 2017 to 2023 (adjusted for the month of July) was produced in the study area (Figure 3).





**Fig. 3.** NDSI maps extracted from the fusion method of HLS images.

Figure 4 shows the annual changes (by adjusting a logarithmic trendline) in NDSI values (in square kilometers) extracted from the projection of HLS images for 2017 to 2023, just adjusted for June month.

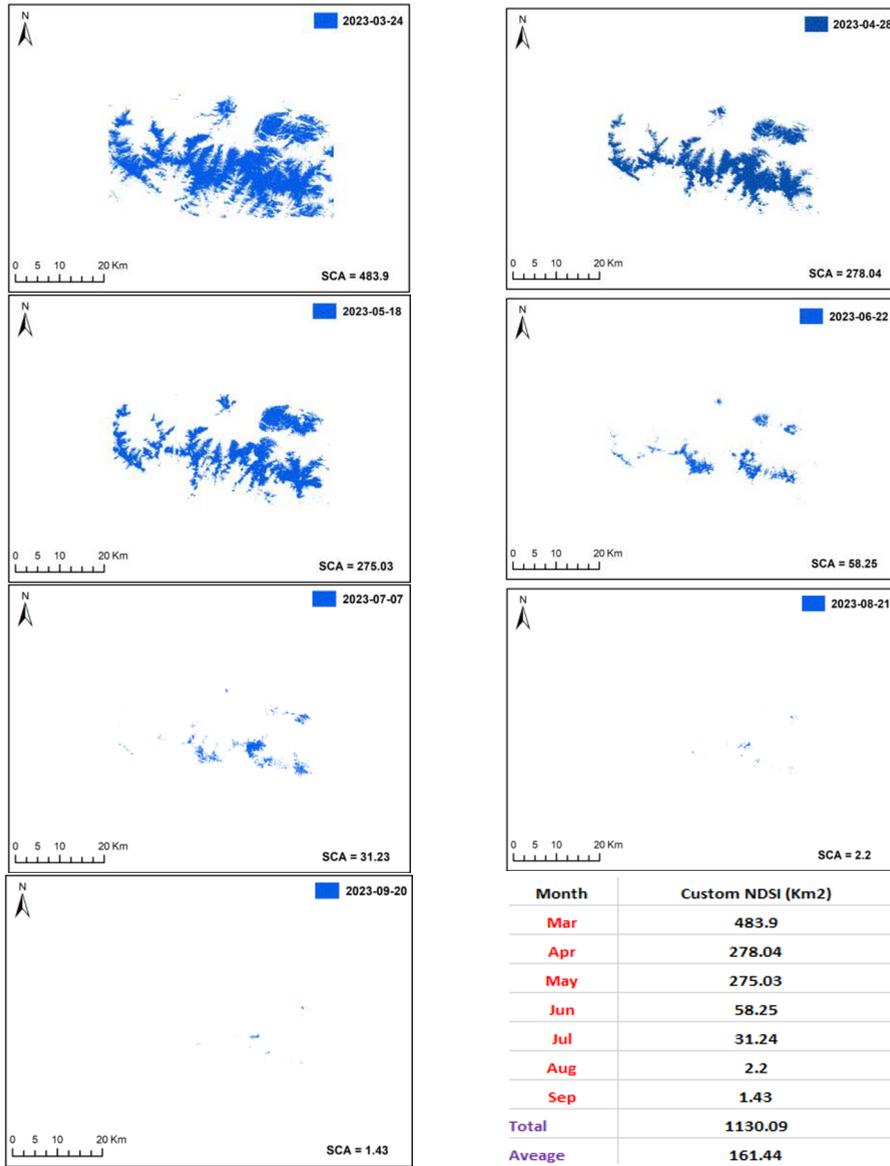


**Fig. 4.** Annual Changes in NDSI values (in square kilometers)

The logarithmic trendline function calculates an exponential curve that fits annual NDSI values and returns an array of values that describes the best curve with  $R^2 = 0.63$  regression value. In fact, it shows a best-fit curved line, as a negative trendline that highlights annual snow cover decreases in recent years.

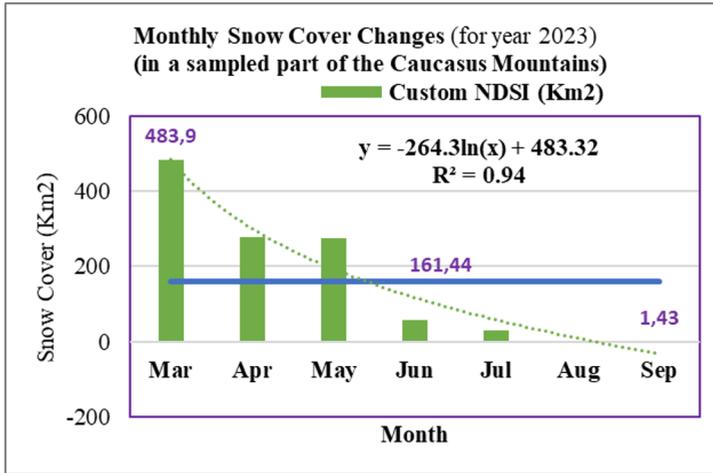
### 3.3 Monthly Snow cover changes

In order to investigate the trend of changes in NDSI values during the spring to summer months (March to September) in the sampled area, once again NDSI layers were produced (Figure 5).



**Fig. 5.** NDSI maps extracted from the fusion method of Landsat and Sentinel satellite images for spring and summer months.

To examine the trend of changes in snow cover during the spring to summer months (March to September) in the sampled area, outputs of NDSI values were graphically displayed (Figure 6).



**Fig. 6.** Changes in NDSI values (in square kilometers) extracted from the projection of Landsat and Sentinel images adjusted for 2023 spring and summer months.

Once again, the logarithmic trendline function, adjusted with  $R^2 = 0.94$  regression value, indicates monthly NDSI decreases in the spring and summer months. The simple interpretation of this type of mathematical relationship is that large amounts of snow packs quickly melt and become unavailable due to the temperature increases in the sampled area of the Caucasus Mountains.

## 4 Conclusion

The main goal of the current research was to investigate the temporal and spatial changes of snow cover in the Caucasus Mountains sampled area by implementing object-oriented processing methods and differential normalized snow indices for the years 2017 to 2023 for selected dates by processing available Sentinel-2 images and Landsat 8 and 9 images. An attempt was made to produce NDSI maps with high accuracy by fused integrated methods inside eCognition software based on fuzzy object-oriented algorithms. The final results show that optimization and fusion methods of Landsat (8 and 9) and Sentinel-2 satellites can be very effective in extracting and identifying snow cover (NDSI) maps, even on a daily and weekly scales.

By producing various output products, such as classified maps, it was possible to separate vegetation classes, water levels, cloud cover, cloud shadow, and snow cover in the sampled area (only for the month of June). By applying a few improved equations of adjusted NDSI maps for 2017-2023 were produced. It should be noted that in most of the mountainous areas of the Republic of Azerbaijan, snowfall is a common climatological and hydrological phenomenon that accumulates in high altitudes and throughout the year as snow cover and plays a significant role in the cycle of water resources, especially the water intake process, and of course the life of human communities living in this such geographical area (Imrani and Rafiq, 2021). Accordingly, the accurate and timely measurement of the temporal-spatial distribution of snow-related parameters is critical for managing water resources throughout the Caucasus Mountains and of course the associated watersheds. Some object-oriented and rule-set methods often have advantages due to the image segmentation scale, optimal threshold determination, and background heterogeneity. Such advanced methods take advantage of the combination of more rule-based and deep-learning functions to investigate the limits and changes of glaciers in future accurate research.

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