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Spatio-temporal analysis of snow cover change in Hunza Valley, Karakoram Region

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Abstract

Climate change alters the trend of glacier phenomenon that is urgent to quantify to analyze the loss on glacier and water resources. This study focuses on analyzing snow cover change and its impact on downstream region. Hunza Valley is selected as study region for this study. Changes in snow cover of glaciers were detected using the Normalized Difference Snow Index (NDSI) for the year 2016, 2017, 2018, 2019 and 2020. Volume of downstream glacial lakes is also calculated using Surface Volume Tool. The results showed the irregularity in data by increasing and decreasing values of snow cover that indicated that Karakoram Glaciers are surging and retreating. As a consequence of glacier surging the amount of water reaching the glacial lake increases providing the basis for increase in lake volume, thus, causing the phenomena of Glacial Lake Outburst Floods (GLOF). Three lakes were studied i.e., Batura Lake, Borit Lake and Passu Lake in this study. Overall, from 2016 – 2020, there is an increase in volume of Passu Lake. The changing volume of these glacial lakes can lead to hazards like GLOFs, leaving devastating impacts on social life in the region.

1. Introduction

Globally, glacier retreat is considered to be one of the critical indicators of climate change. The glacier region has complex regional climate dynamics, due to this monitoring of climate and glacier mass balance is sparse and the region is lacking spatio-temporal climate-glacier responses [1]. Climate change causes fluctuations in flow of the streams in cold regions all over the world and it is urgent to quantify impact on the loss of glacier ice and water resources [2]. Due to the global warming and climate change, average global temperature rises to 0.85°C since 1980, this can be increased up to 3.7 °C by the end of the 21st century [3, 4]. Glacier retreat and surface lowering due to climate change, increases the number of direct and indirect hazards. Rabot [5] reported that in a survey it was evident that global cooling and glacier advances take place in Karakoram region within the Little Ice Age (LIA) that led to ice damming process which is then reason for GLOFs in 19th and early 20th century.

In Karakoram region, glaciers show unique response of surge, unlike other regions. This phenomenon is known as the "Karakoram anomaly." It is the stability or anomalous growth of glaciers in the region of central Karakoram, unlike other mountainous ranges of the world where glacier retreat is observed [6]. Karakoram glaciers show this anomalous behavior since at least 1970s. More than 200 surge type glaciers were discovered in Karakoram [7]. Shah et al., [8] recommended that it is necessary to monitor the surging glaciers continuously as the behavioral patterns of glaciers that were observed over five decades, are causing GLOFs that has serious impact on livelihood and infrastructure in the downstream population. Like all over the world's glaciers, Himalayan glaciers are also decreasing. Karakoram glaciers were also shrinking in past 1920-1990 except for some short-term advances in 1970's. After 1990, many Karakoram glaciers began to increase. Between 1997 and 2002, expansion of 13 glaciers were observed [9].

Although, Himalayans glaciers are receding day by day, Karakoram glaciers are behaving oppositely. It is observed that Karakoram glaciers are surging from 1860s and in recent years glaciers are surging with high rate. Rapid advance in glacier tongue caused by surge invokes the danger of Glacier Lake Outburst Flood (GLOF) and 35 GLOFs are reported since 1826 in Karakorum region [10]. Glacier melting rate varies with the presence of supra-glacial debris. In the period of 1980 to 2014, 24 glaciers of Karakoram Range show heterogeneity in surging and retreating [11]. Limited number of detailed ground observations of Karakoram Range are there because of the complexity of the region, due to this there is very limited understanding of surging mechanism exists [12].

The increase in global temperature led to faster melting of glaciers and resulted in sea level rise, flooding, change in water supply, GLOFs and erosion [13]. It is necessary to estimate that how impact of climate change is affecting rapidly declining glacier mass balance and how it is affecting water supplies [14, 15]. Monitoring of snow cover over the mountainous areas of complex river basins is a difficult task and the most useful technique to estimate snow cover is Normalized Difference Snow Index (NDSI) analysis [16]. Due to the sparse coverage of ground-based observations in high elevation areas, remote sensing in the Normalized Difference Snow Index (NDSI) is commonly used for snow detection for a wide range of sensors [17, 18]. Snow cover results in accumulation of snow into glacial ice, therefore, glacier advances. Aim of this research is to analyze snow cover extent of Hunza Valley in Karakoram region and to identify the potential glacial lakes by utilizing remote sensing techniques in the study region.

2. Study Area

The study area extends from 36° 43' 2.6436" N to 36° 23' 7.314" N and 74° 17' 58.1208" E to 74° 52' 43.2948" E (Figure 1). It includes four glaciers of Karakoram i.e., Batura Glacier, Passu Glacier, Ghulkin Glacier and Gulmit Glacier. Batura Glacier is the largest glacier of them all and the longest glaciers outside the polar region. It is situated in Gojal region of Pakistan. Passu glacier lies beneath the Batura Glacier, then lies Ghulkin Glacier and in the last Gulmit Glacier. The altitude of the study area ranges from about 1480-7500 meters (Figure 1). The climate of the Karakoram Range is for the most part semi-arid and strongly continental. The southern slopes are exposed to the moist monsoon (rain-bearing) winds coming in from the Indian Ocean, but the northern slopes are extremely dry. On the lower and middle slopes experience rain and snow fall in small quantities; average annual precipitation does not exceed 100 mm. At elevations above 4,900 meters, precipitation always takes a solid form, but snow in June is not infrequent even at lower elevations (Figure 2).

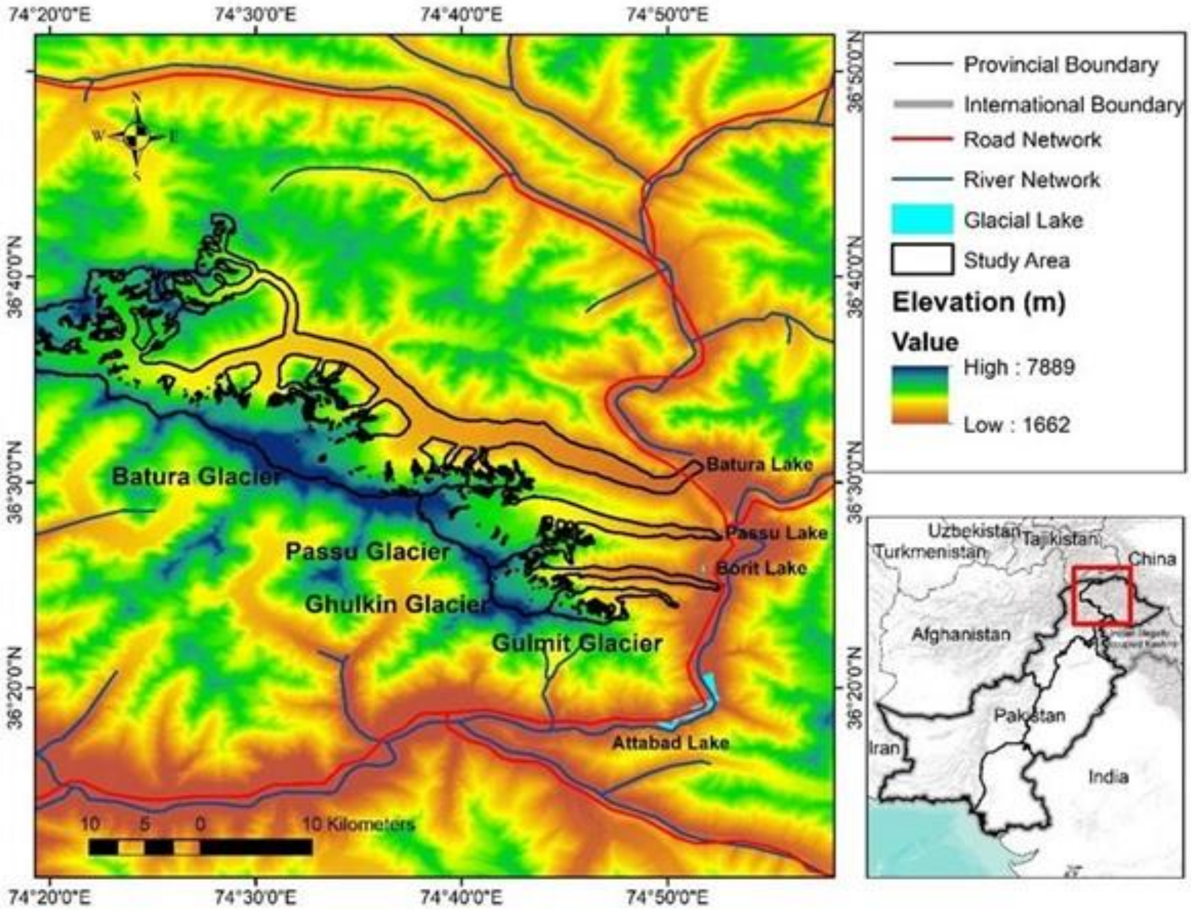

Figure 1. Location map of the study area.

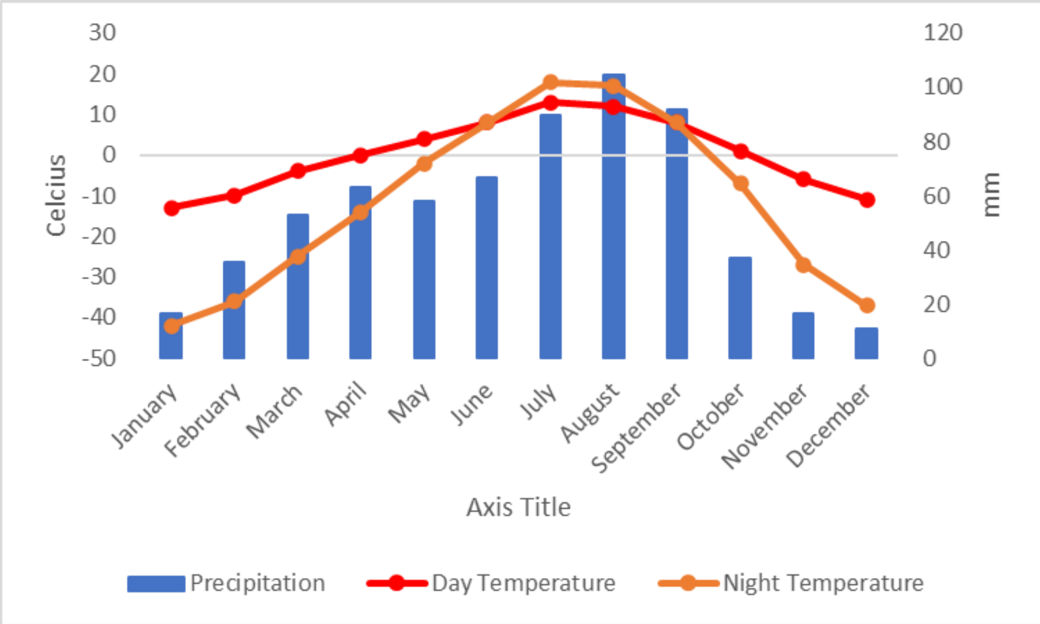

Figure 2. Temperature and precipitation of Hunza Nagar.

3. Method

3.1 Data Acquisition

To assess the spatial and temporal changes in the selected glaciers, Sentinel images for the years 2016, 2017, 2018, 2019 and 2020 were collected from United States Geological Survey USGS open-source website (https://earthexplorer.usgs.gov/). The images were selected considering the minimum cloud cover and consistent months of acquisition. Consecutive years were taken to analyze the behavior of glaciers in detail. The Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) was utilized for the elevation of the area, downloaded from USGS website. Glacier boundaries were acquired from Randolph Glacier Inventory (RGI) 6.0 from official Global Land Ice Measurements from Space (GLIMS) website (Figure 3).

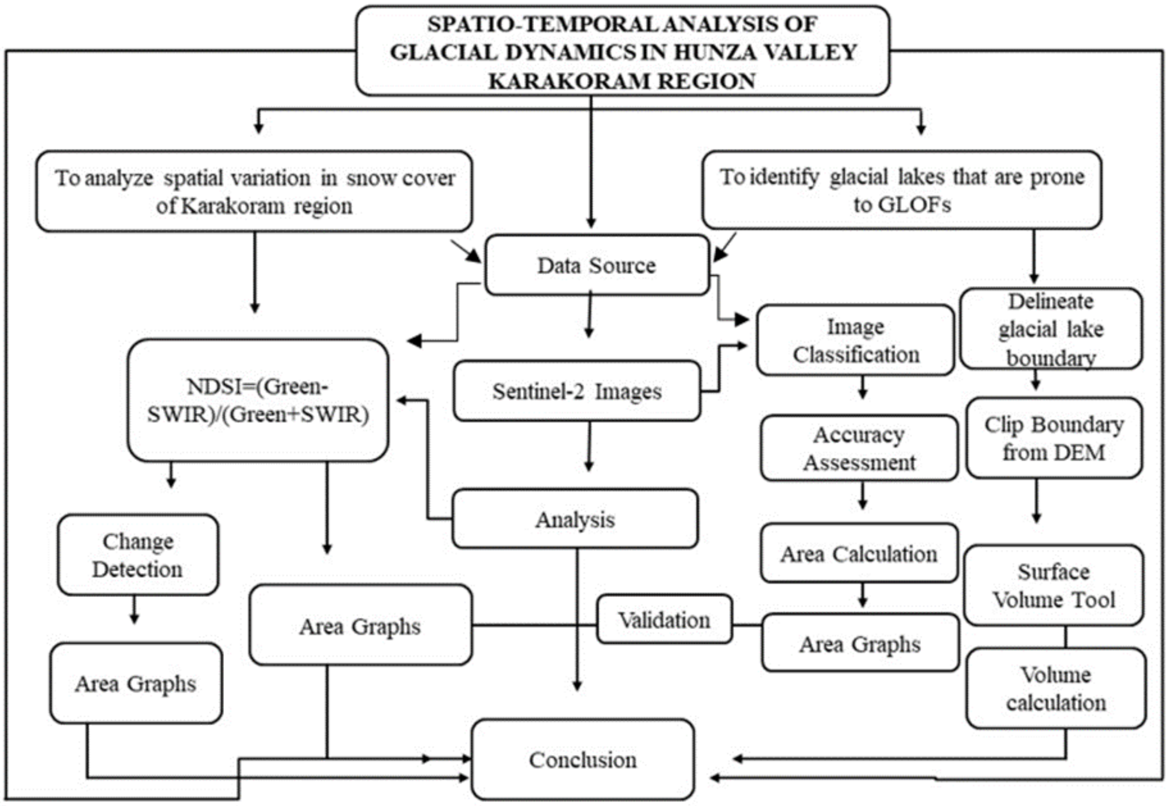

Figure 3. Research design.

3.2 Spatial extent of snow cover

The Normalized Difference Snow Index (NDSI) algorithm was used for mapping snow covered area. NDSI is an effective method to be applied on the satellite images to extract the snow cover [19]. NDSI is calculated using ERDAS Imagine 2015. To map the snow cover, NDSI threshold value is selected based on the reflectance characteristics of snow, which was calculated from Equation 1.

$$NDSI= (Green-SWIR)/ (Green+SWIR) \quad (1)$$

3.3 Validation of NDSI results

For image processing, ArcGIS 10.5 is used. Training samples were collected with the help of Google earth for visual interpretation and ground truthing. Accuracy assessment, of classified images are further done by calculating Kappa Coefficient value. Supervised Image Classification is done for the validation of NDSI. The total area of snow cover from NDSI is cross examined with the area extracted from image classification. Maximum Likelihood Classification is considered to be the most accurate technique to classify land cover classes [20].

3.4 Change detection in snow cover

For the detection of total change in snow cover, raster of two time periods is compared in this technique. Raster Calculator in ArcMap is used in this purpose that allows further interpretation and classification. The Equation 2 is used for change detection.

$$\text{Change Detection= Raster of Latest Year – Raster of Previous year} \quad (2)$$

After applying this formula, the output raster contains the subtracted cell values. Positive values in output raster indicate rise while the negative values indicate losses. It is further reclassified into five classes i.e., Significant Increase, Increase, No Change, Decrease, and Significant Decrease. Furthermore, area of resultant change is calculated.

3.5 Volume calculation of glacial lakes

Volume of glacial lakes is calculated with the Surface Volume tool in ArcGIS. Lakes are manually digitized and with the elevation values of SRTM-DEM, volume is calculated for each of the three lakes. SRTM-DEM is clipped according to the shape of glacial lake and then volume is calculated with Surface Volume tool.

4. Results

The values of snow cover area show abrupt increase or decrease, it shows continuous anomaly in the snow cover area of Karakorum**.** Year wise analysis is undertaken to detect change in snow covered areas and the following table shows the area at which change occurs. The most significant change is observed from 2017-2018, of about 41.54% increase is observed in that year and the highest decrease is observed from 2018-2019. The supervised classification shows that during the years of 2016, 2017, 2018, 2019 and 2020, the snow-covered areas are 89.8%, 81.2%, 90.5%, 97.6%, and 85.9%, respectively. Snow-covered areas in NDSI are 89.5%, 81%, 89.6%, 97.2% and 85.1% for 2016, 2017, 2018, 2019 and 2020, respectively. This indicates that the results are validated as image classification and NDSI show same results.

4.1 Spatial extent of snow cover

The results show that during the winter seasons of 2016, 2017, 2018, 2019 and 2020 the snow-covered areas decreased from 2016 to 2017 and then increased from 2017 to 2019 and then again decreased in 2020 and it shows the heterogeneity in the snow cover. The values of snow cover areas show no proper increase or decrease and it shows continuous anomaly in the snow cover areas of Karakorum as shown in the (Figure 4).

4.2 Validation of NDSI results

In order to verify the results, supervised classification is also applied. The results of supervised classification are shown in (Table 1). The supervised classification shows that during the years of 2016,2017,2018,2019 and 2020 (Figure 5) the snow-covered areas are 89.8%, 81.2%, 90.5%, 97.6%, and 85.9%, respectively and snow-covered areas in NDSI are 89.5%, 81%, 89.6%, 97.2% and 85.1% for 2016, 2017, 2018, 2019 and 2020 respectively. The kappa coefficient value in classified images is 90 for 2016, 90 for 2017, 80 for 2018, 90 for 2019 and 80 for 2020.

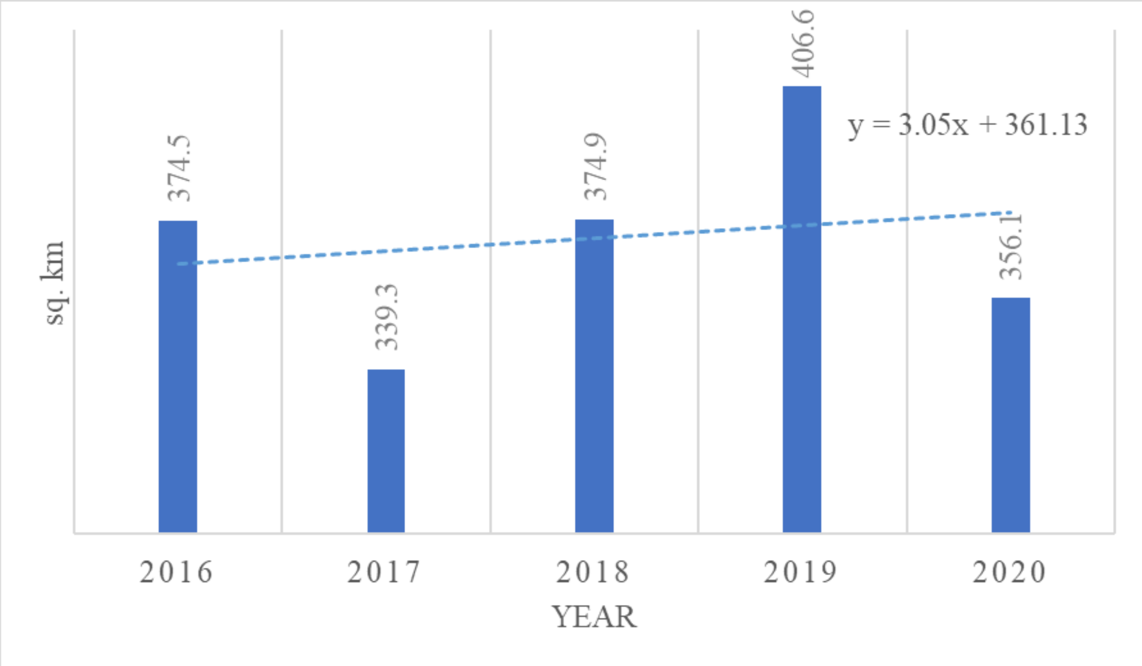

Figure 4. Temporal distribution of snow cover area (Km²).

Table 1. Snow cover area (km²).

Year	NDSI				Image Classification			
	Snow Area	Non-Snow Area	Snow Area	Non-Snow Area	Snow Area	Non-Snow Area	Snow Area	Non-Snow Area
2016	374.5	43.9	89.5	10.5	375.8	41.9	89.8	10.2
2017	339.3	79.1	81	19	340.09	78.36679	81.2	18.8
2018	374.9	43.5	89.6	10.4	378.8	39.6	90.5	9.5
2019	406.6	11.8	97.2	2.8	408.5124	9.959149	97.6	2.4
2020	356.1	62.3	85.1	14.9	359.785574	58.61	85.9	14.1

Year wise analysis is undertaken to detect change in snow-covered areas and the following table shows the areas at which change occurs. The most significant change is observed from 2017-2018, which is about increase of 41.54% (Table 2) in that year and the highest decrease is observed from 2018-2019 (Figure 6,7).

Table 2. Change detection in snow cover area.

Change Detection	2016-2017		2017-2018		2018-2019		2019-2020	
	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)
Significant Increase	9575.18	9.51	41831.47	41.54	8712.45	8.65	22515.41	22.36
Increase	8573.9	8.51	27494.65	27.30	7570.27	7.52	46332.31	46.01
No Change	12923.34	12.83	10236.05	10.16	13309.99	13.22	14183.67	14.08
Decrease	37039.66	36.78	11609.61	11.53	54304.08	53.92	9531.29	9.46
Significant Decrease	32594.21	32.37	9534.51	9.47	16809.5	16.69	8143.61	8.09
Status	Retreat		Surge		Retreat		Surge	

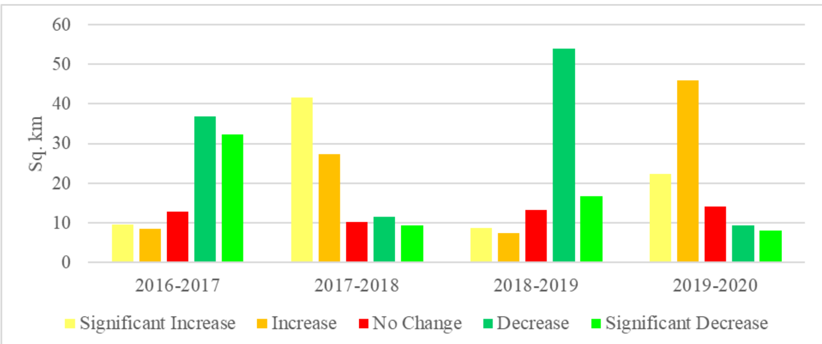

Figure 6. Change detection in snow cover area.

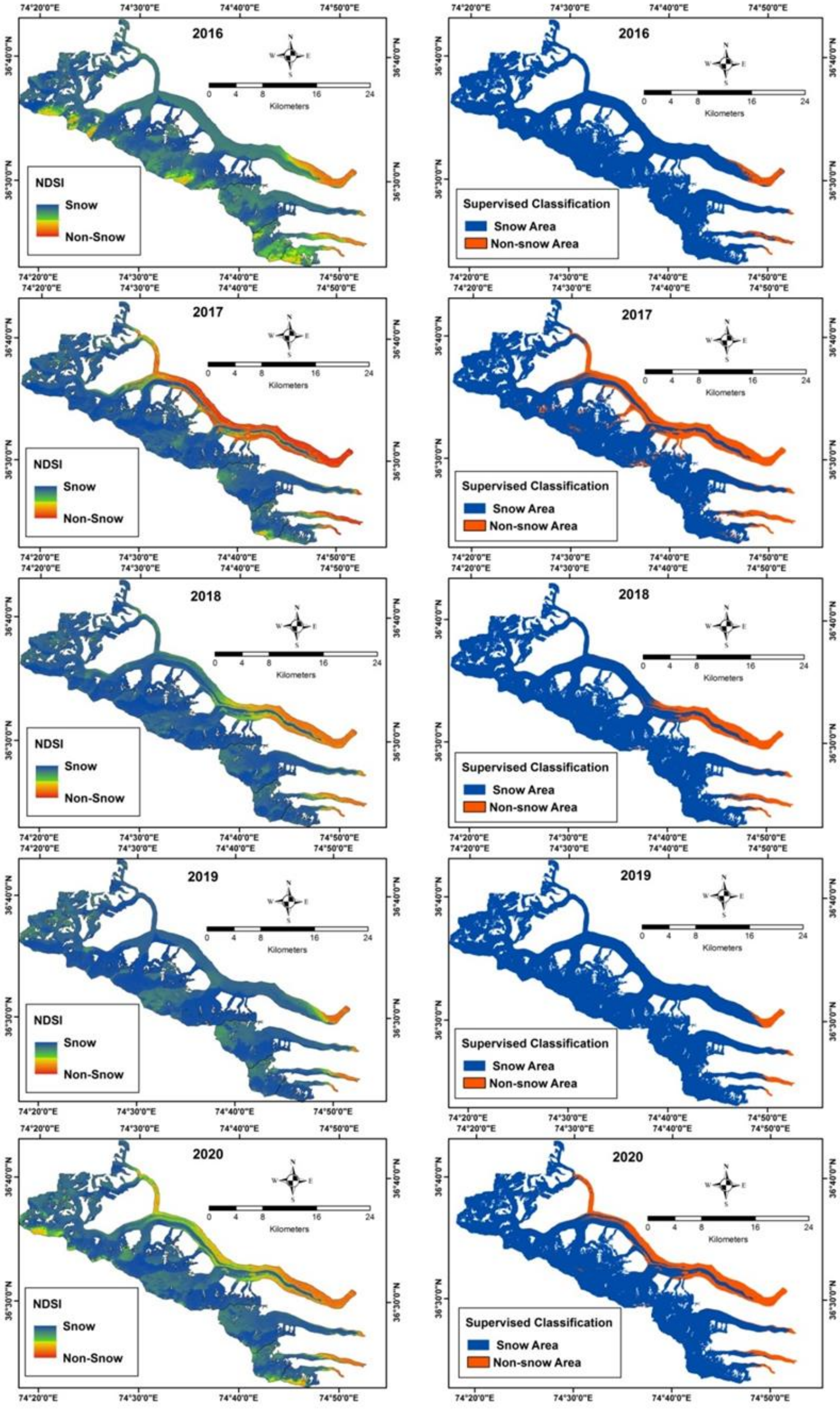

Figure 5. Spatial and temporal distribution of snow cover**.**

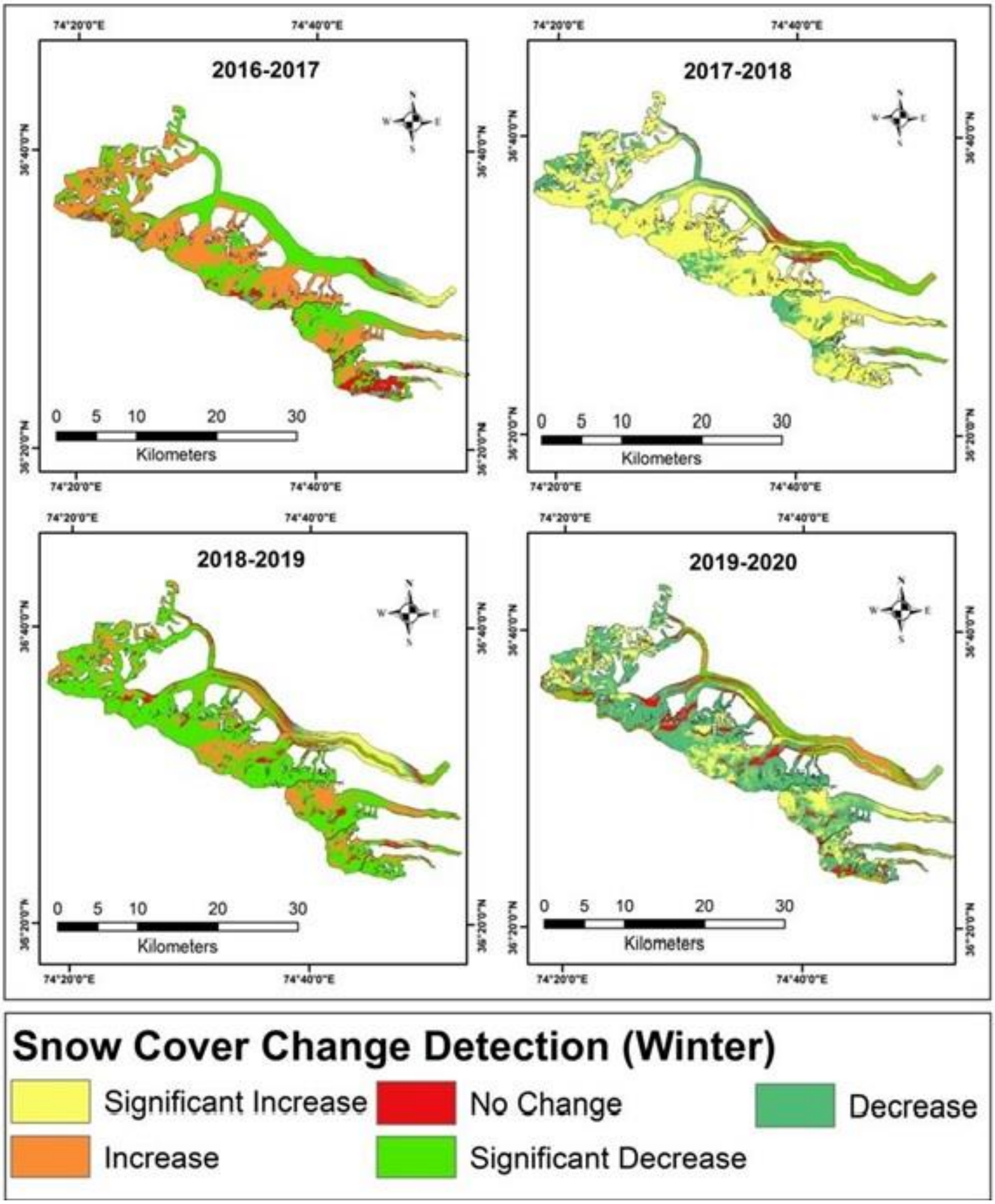

Figure 7. Snow cover change detection.

4.3 Volume of glacial lakes

The volume of glacial lakes increases with time, especially in Passu Lake there is a high increase in volume in 2020. Borit and Batura Lake show irregular increase and decrease in lake volume but increases from 2016 to 2020 (Figure 8, 9 & 10). The volumes of lakes are given in (Table 3).

Table 3. Volumes of glacial lakes.

	2016	2017	2018	2019	2020
Batura Lake	0.008014	0.007569	0.008459	0.008015	0.009351
Passu Lake	0.048712	0.054122	0.052316	0.055466	0.079814
Borit lake	0.064314	0.057788	0.067107	0.069434	0.071762

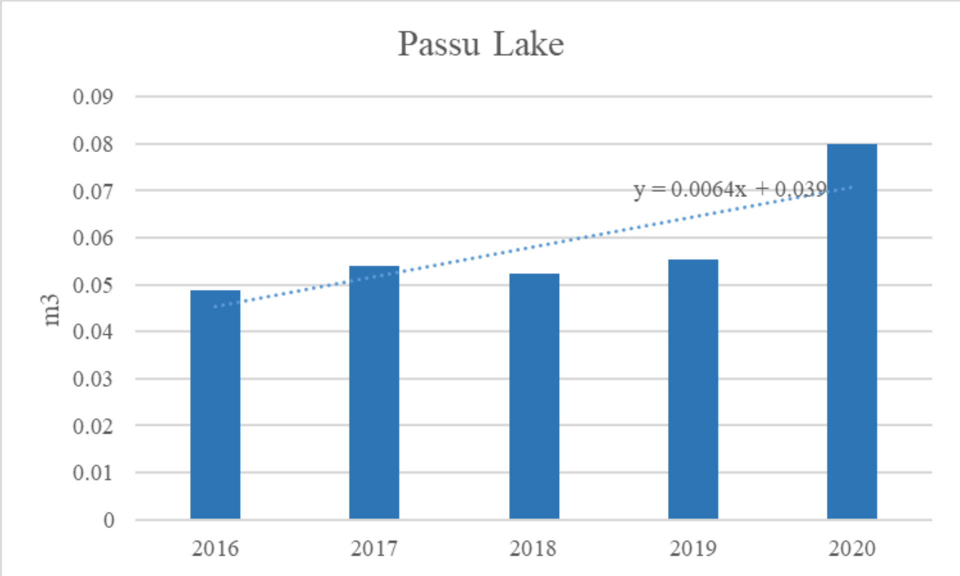

Figure 8. Volume of Passu Lake.

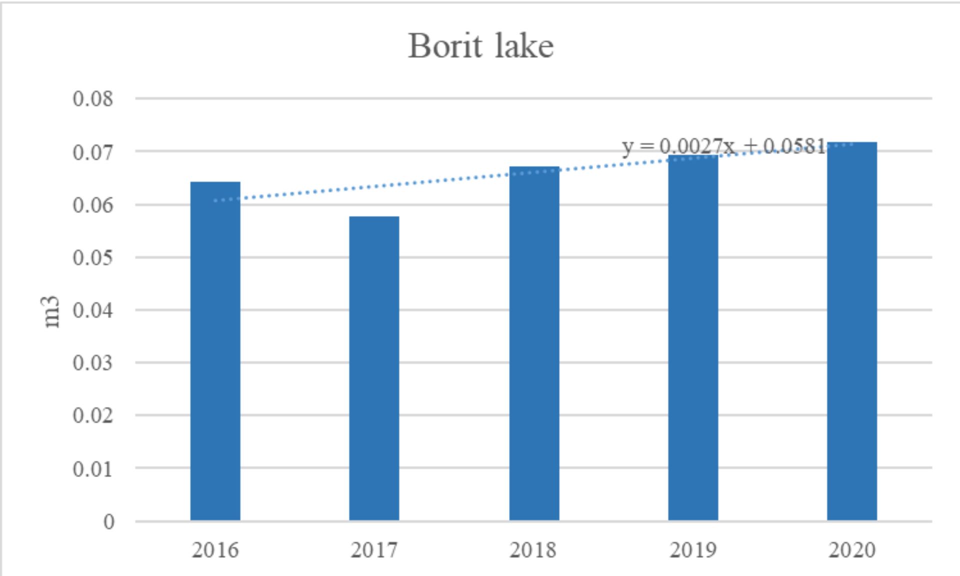

Figure 9. Volume of Borit Lake.

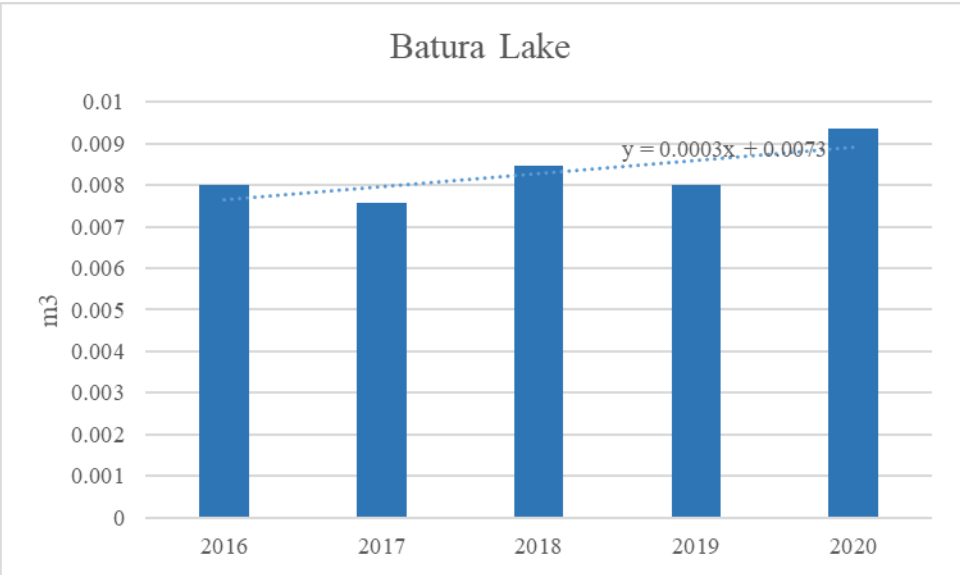

Figure 10. Volume of Batura Lake.

5. Discussion

This study investigated the dynamics of snow cover in Hunza valley and its impact on downstream areas. It has been inferred from the analysis that due to Karakorum anomaly, snow cover is continuously increasing and decreasing at uncertain pace. These phenomena were having an effect on the nearby glacial lakes, which would eventually result in GLOFs in the downstream regions. This study shows the anomalous behavior of glaciers in Karakorum that is urgent to quantify and the impacts on the downstream areas are necessary to be measured.

The results show increase in snow cover in year 2017 and 2019 that can lead to surge in underlying glaciers. Tahir et al., [21] also explained that out of total, almost 13 of the glaciers exhibit rising trends. However, in 2016 and 2018 retreating of glaciers can also be observed and surge-type glaciers are identified in Karakoram region that show short-lived events of surging or retreating [22]. The central and eastern Himalayas', Hindu-Kush's and Karakoram's observed glacier trends are referred to as the "Karakoram Anomaly" [23]. The anomalous behavior shown by these glaciers can be explained by the presence of supra-glacial debris and the lack of mass balance data [24]. The impact of snow cover change results in GLOF risk hazard as explained in this study. The volume of glacial lakes is considerably increasing and the trend of increase in volume is also increasing, extreme risk of GLOFs is observed in the study region [25].

The strength of this study is that for glacier cover mapping and impact analysis, advanced remote sensing techniques like NDSI has been used and validated from other supervised methods as specified by [26]. The limitations of this study are that only snow cover is taken in account, for the extensive study various aspects like glacier ice, debris cover etc. should also be included to quantify Karakoram Anomaly more accurately. Risk assessment for GLOF hazard should be done further.

6. Conclusion

This study concludes that changes in snow cover of Karakoram glaciers were detected using the Normalized Difference Snow Index (NDSI) for the year 2016 – 2020. The results showed the occurrence of Karakoram anomaly, indicating the irregularity in data by increasing and decreasing values of snow cover. As a consequence of glacier surging, the amount of water reaching the glacial lake increases providing the basis for increase in lake volume, thus causing the phenomenon of Glacier Lake Outburst Flooding (GLOF). Four glacier lakes were studied: Batura Lake, Borith Lake and Passu Lake. According to this study, the volume of Batura Lake, Borit Lake, and Passu Lake is increasing.

This study further concludes that GLOF is a phenomenon in which the lake of glacier is filled beyond its capacity and outbursts causing environmental and social hazards. Secondly, glacial retreat is a contributing factor in the rise of the sea level. According to the results, it is noticeable that during the period of 2016 – 2018, the volume of Passu Lake has increased but in the year 2018 – 2020 the volume has been decreased. Though, this decrease in volume is minute yet noticeable but still in the overall year from 2016 – 2020, there is an increase in volume of Passu Lake. The changing volume of these glacial lakes can lead to situation like GLOF, making an unfavorable and ruinous impact on nearby villages, down slope areas, agricultural land, cattle farms, infrastructure including roads and buildings and the Karakoram highway, thus making a huge impact over the region.

7. Recommendations

Karakoram climate is continuously changing and the surging behavior of glaciers alters with climate change. It is necessary to have a detailed study of snow cover change and snow accumulation over the glaciers. There should be more gauging stations in the area for ground observations of climatic variables like precipitation to measure amount of snow seasonally. Downstream areas of glacial lakes are largely affected with GLOFs. Government should take precautionary measures and plan mitigation strategies in the areas that are prone to GLOFs.

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Author contributions

Aiman Nisar: Conceptualization, Methodology, Writing-Original draft preparation. Data curation, Software, Validation. **Shakeel Mahmood:** Writing-Reviewing and Editing. **Mazhar Shakoor:** Writing and Updating

Conflicts of interest

The authors declare no conflicts of interest.

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