Mapping Fluctuations of Hispar Glacier, Karakoram, using Normalized Difference Snow Index (NDSI) and Normalized Difference Principal Component Snow Index (NDSPCSI)

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Abstract, Investigation of the fluctuations in the snow-covered area of the major glaciers of the Karakoram range is essential for proper water resource management in Pakistan, since its glaciers are responding differently to the rising temperatures. The objective of this paper is to map snow covered area of Hispar glacier in Hunza river basin for the years 1990, 2010 and 2018. Two techniques, (NDPCSI) Normalized Difference Principal Component Snow Index and (NDSI) Normalized Difference Snow Index were used. Hispar glacier of the Hunza basin has lost 114 km² of its ice cover area, during the last 28 years, with an alarming annual retreat rate of 1.67 km² of glacier ice from 1990 to 2018. Hunza basin experienced a +1°C rise in both mean minimum and mean maximum temperature during 2007 to 2018. as a result, Karakoram ice reserves have been affected by rising temperature of the region. Due to temperature rise, retreat of snow-covered area of Hispar, Karakoram mountain range shows a shift in the cryospheric hazard zone.

Keywords, GIS, glacial mapping, HKH, NDPCSI, NDSI, water resource management.

Introduction

Upper Indus basin is the core of Pakistan’s fresh water backup (Mazhar et al., 2016). About 80 percent fresh water is contributed to Indus river, depending on the snow melt and glacial composition in the upper Indus basin (Hewitt, et al., 2007). The 11.5% of the total area of this basin is covered with glaciers having perennial snow and ice cover reserves of 20,000 km² (Hewitt, 2011).

Himalayan glaciers are retreating at a more rapid scale than any other part of the world (Cruz, et al., 2007). Hasnain (1999) reported considerable glacial retreat of the eastern and central Himalayas. Glacial retreat has been reported throughout HKH region, with more than 80% of the western China experiencing glacial retreat in the last 50 years (Kehrwald et al., 2008). Kehrwald et al., (2008), concluded that Naimona’ Nyi glacier in Tibet (Himalayas) has not received any net accumulation of ice since 1950.

The cryospheric reserve in the Karakoram range is home to major glaciers which act as freshwater resource, on which Pakistan’s agrarian economy depends heavily. Snow assumes a critical role in impacting worldwide, territorial and local radiation balances alongside heat regimes (Bajracharya et al., 2015). The supply of water downstream is always influenced by the melting of extensive glaciers (Rankl et al., 2014). This influences even the volume and timing of stream-flow, which provides water for irrigation (Bajracharya et al., 2015).

According to IPCC (2007) South Asia is becoming prone to flood events due to glacial melting. As a result, the maximum areal coverage of seasonally frozen land has declined by almost 7% since 1900, which would impact this region’s fresh water supply, hydropower production and quantity of season flows of the rivers. Fowler and Archer (2005) concluded that the 1° C drop of mean summer temperature in UIB is estimated to result in a decrease of almost 20% of the flows of Hunza river, since summer mean temperatures and summer runoff are directly correlated with higher elevation basins of UIB in 2005.

Another significant finding of Fowler and Archer (2006) that the summer temperature of many valley stations of UIB has continued to decrease from 1961 to 2000, while for the same time period, in winter mean minimum and maximum temperatures showed an increasing trend. The reduction of mean summer temperature and positive trend of mean winter precipitation trends are clues of Karakoram glacial expansion (Fowler and Archer, 2005). However, after 2005, the temperature started having a rising trend.

Bocchiola (2011) reported that the Karakoram glaciers had witnessed limited ice thinning and, in some cases, even glacial advancement has been reported for the period 1980-2009. According to Minora et al. (2016) there was general stability during 2011-2010 period,
and a slightly negative trend for the area coverage by glaciers of the region. However, the Karakoram glaciers are mostly advancing, and if retreat is detected in some glaciers, its rate is very slow. This phenomenon is termed as Karakoram anomaly, which is in stark contrast to the rapid retreat of Himalayan glaciers. Qureshi et al. (2017) reported glaciers of Hunza basin to be relatively stable and regarded temperature as a significant factor of climate change that affected the glacial length and coverage in the Hunza basin during 1973-2014 period. Moreover, the appropriate mapping techniques for gauging variations in snow covered area of glaciers in the Hunza basin, and exploring the relation of this variation with temperature fluctuations are lacking. Present study is aimed to map the variations in the snow-covered area of Hispar glacier, using NDSI and NDPCSI, and relating the variations in the snow-covered area with temperature fluctuations of the region.

Study Area

Hispar glacier (49 km long) is located in the part of the Karakoram mountains lying within the Gilgit–Baltistan region of Pakistan. Hispar glacier meets Biafo glacier (63 km long) at an altitude of 5127.95m, at the Hispar La (Pass), creating the world’s largest glacial mass system outside the polar regions (Paul, et al., 2017). Hispar glacier lies in the central Karakoram and drains into the Hunza catchment in Pakistan. It is located at 36° 5′ 0″ N, 75° 16′ 0″ E spatial coordinates. Hunza basin is laid in the westerly influenced zone and has experienced a decrease in the mean annual snow cover (Hasson et al., 2014).

This glacier falls under the category of Mustagh type of glacier and the accumulation area ratio (AAR) of this glacier was reported to be 0.29 with a concentration factor of 5.1 (Dyurgerov and Meier, 2000). Hispar has lost 15% debris covered area out of its main glacier area (Hewitt, 2011). The ice tongues at lower elevation are protected by debris (Fig. 1).

Materials and Methods

To deduct cryospheric changes or fluctuations in Hunza basin, over the past few decades (1990-2018) remotely sensed multi-temporal images of Hispar glacier were acquired from Landsat TM (1990), ETM+ (2010) and Landsat 8 OLI (2018) for the month of October. Autumn imageries were preferred as in this season there is the least cloud cover over study area (Rashid, et al., 2018). Moreover, the perimeter of all three imageries is same for all the three years (1990, 2010, 2018) that was 245 km².

Two techniques Normalized Difference Principal Component Snow Index (NDPCSI) and Normalized Difference Snow Index (NDSI) were used to generate improved glacial mass mapping. In this study NDSI was used to divide the difference in reflectance which is observed in the Landsat 8 short wave infrared band (1.57-1.65μm) and green band (0.53-0.59μm). NDSI is widely used for mapping the snow extent primarily due to its favorable benefit to deal with the topographical effects (Negie et al., 2010; Kour et al., 2016; Mazhar et al., 2018), since it can conceivably outline the snow even in mountain shadows (Kulkarni et al., 2006). According to Kour et al. (2016) green band 3 (0.53 to 0.6μm) and shortwave-infrared band 6 (1.56 to 1.66μm) are used in LAND sat 8, for calculating NDSI in order to find the snow-covered area. A threshold of 0.40 was set for NDSI as its range varies from -1 to +1 (Kour et al., 2016). NDSI is chosen to identify ice or snow in study area. Individual images were geometrically corrected before any calculations were made. NDSI was applied using Equation (1).

\[
NDSI = \frac{\text{Green}_{0.55} - \text{SWIR}_{1.65}}{\text{Green}_{0.55} + \text{SWIR}_{1.65}} \quad \text{Eq. (1)}
\]

The values greater than 0.4 would highlight the presence of snow. As suggested by Kulkarni et al. (2006) and Xiao et al. (2002) to improve NDSI classification accuracy a near-infrared reflectance value (greater than 0.11) was used to mask out water pixels.

Moreover, to classify snow and glacier base on pixels, NDPCSI method is used (Sibandze et al., 2014; Kulkarni et al., 2006). It is the best method to identify the threshold between snow and glacier. To highlight the presence of snow, NDPCSI was then computed because it produced higher classification accuracy, since it combined the principal component imager created by using PCA with commonly used NDSI (Sibandze et al., 2014). These are the best indices to generate improved snow cover mapping. To detect snow, every single principal component was individually analyzed. As shown in the equation 2, NDPCSI was calculated to highlight snow covered area using principal component 1 and 2, illustrated in the equation 2.

\[
\text{NDPCSI} = \frac{\text{PC}_{\text{brightest}} - \text{PC}_{\text{darkest}}}{\text{PC}_{\text{brightest}} + \text{PC}_{\text{darkest}}} \quad \text{Eq. (2)}
\]
These analyses were processed in ERDAS IMAGINE. Geometrically corrected temporal remotely sensed data sets were further improved by classification algorithms and reclassified by using the reclassify tool in ArcGIS 10.5. The resultant snow cover map of Hispar is shown in Figure 2. To deduce Hispar glacial mass fluctuations, four classes were created i.e., ice, wet soil, dry soil, and snow. Pixels that have threshold range from 0.4 to +1 were classified as ice. Similarly, those pixels which have equal to and greater than 0.4 were called snow cover. Threshold values for wet soil class is greater than 0 and less than 0.4 and from 0 to -1 pixels were classified as dry soil. When reclassified the attribute table for each layer was generated which was used to calculate the total amount of snow cover area in square kilometers (Table 1).

Inverse Distance Weighted (IDW) interpolation was used for presenting the 5 yearly mean maximum and mean minimum temperature variations, of the Northern Areas of Pakistan, for the period 1989-2018. The results of IDW interpolation technique performed in Arc GIS version 10.5 took into consideration the mean minimum and mean maximum temperature data for 30 years (1989-2018) of five meteorological stations working in the Gilgit Baltistan region namely Astore, Bunji, Chilas Gilgit and Skardu. In the present study, average of five years has been used for analyzing the climatic variation and it is more favorable to take the average of 5 years for 30-years’ time span. The increase in temperature can be seen from blue (minimum) to red (maximum) (Figs. 7, 8). The mean maximum and minimum monthly temperature data of Hunza meteorological station, where Hispar glacier occurs was available for past ten years only, and thus its variations were graphically presented.

Results and Discussion

Glacial retreat in the form of ice-free area is clearly visibly in the satellite image view, for Hispar glacier (Fig. 2). The comparative multi temporal images of
satellite image view of Hispar glacier shows that it remains the glacier suffering from major ice cover loss from 1990 to 2018 (Fig. 3). Ice covered area is retreating continuously, since Hispar lost 114 km$^2$ of its ice cover in the last 28 years.

Table 1. Comparison in snow covered areas of Hispar glacier for the years 1990, 2010 and 2018.

| Class     | 1990 | 2010 | 2018 |
|-----------|------|------|------|
| Ice       | 184  | 185  | 70   |
| Snow      | 13   | 9    | 81   |
| Wet Soil  | 15   | 24   | 34   |
| Dry Soil  | 33   | 27   | 60   |

Table 2. Comparison in mean annual temperature and rainfall from different metrological stations for the years 1990, 2010 and 2018.

| Metrological stations | Temp °C | Rainfall all mm | Temp °C | Rainfall all mm | Temp °C | Rainfall all mm |
|-----------------------|---------|-----------------|---------|-----------------|---------|-----------------|
| Astore                | 10.09   | 57.21           | 10.51   | 31.72           | 18.81   | 33.22           |
| Bunji                 | 17.96   | 11.58           | 15.08   | 13.35           | 30.93   | 10.85           |
| Gilgit                | 24.95   | 7.42            | 24.13   | 7.58            | 24.60   | 7.83            |
| Skardu                | 13.39   | 24.35           | 11.45   | 41.28           | 21.73   | 8.09            |
| Hisper                | 16.59   | 25.14           | 15.29   | 23.48           | 24.01   | 15.00           |

The mean maximum temperature of Hunza valley which is near the Hispar glacier has increased in the past 10 years. During these 10 years period, a rise of 1°C in the mean maximum temperature of Hunza valley was recorded, which increased from 18.1 °C to 19.1 °C (Fig. 5).

This 1°C rise in mean minimum temperature in 10 years is significant. The mean minimum temperature also increased from 5.30 °C to 6.30 °C and there was a fluctuation in the temperature throughout the time period.

Warmer temperatures cause glaciers to melt faster than they can accumulate new snow. The comparison between rising trends of mean minimum and maximum temperatures and decrease in snow covered area of Hispar glacier support the present study conclusion that western Karakoram glacier Hispar is facing faster retreat due to higher temperature variability (Table 1). The mean minimum temperature of Hunza valley which
is nearest the Hispar glacier has also increased in the past 10 years.

Similar trend (Hispar glacier) can be observed in Urumqi river basin, Tianshan mountain, China, which shortened by 12% between 1962-2003. The pace of the retreat of Hispar glacier is losing its ice-covered area at the rate of 1.67 km² per annum. According to Latief et al. (2016), the zone of Kolahoi glacier, in the northwestern Himalayan region, contracted from 12.21 km² in 1962 to 11.61 km² in 2010. As a result, 0.6 km² (600,000 m²) of the total area has been reduced, while its snout is retreating with a rate of 11.97 m/year.

There was a similar reduction in the clean ice area of Haft Khan glacier in Takht-e-Soleiman region, Iran, since 2010 (Karimi, et al., 2015). As the Hispar glacier is shrinking and experiencing changes and retreat some researchers have likewise anticipated the thinning and shrinking of some glaciers of Hindu Kush Himalayan region (Fujita and Nuimura, 2011; Kargel et al., 2011; Kaser et al., 2006; Scherler et al., 2011; Zemp et al., 2009). During 1989-2018, the mean maximum temperature of northern areas has increased Latief et al. (2016). The normal air temperature has also increased in the Liddar valley north western Himalayas, Pakistan during the time period of 1962-2010. The general
pattern over this study period demonstrated a general increase. Some parts of Himalayas are warming at a higher rate contrasted with the worldwide normal warming (Bajracharya, 2015). While examining the temperature fluctuations in Himalayas, Bhuutiyan et al. (2007) reported a rise of 1.6°C of the temperature during 1901 to 2002. While, Dar et al. (2014) and Romshoo et al. (2015) have likewise anticipated an increase in temperature in Kashmir valley by 6.26 °C (±1.84 °C) in 2098, using Predicting Regional Climates for Impact Studies (PRECIS) model.

According to Ashraf and Rehman (2019), rise in temperature directly affects the surface of glaciers, causing quick increase in its melting process. Qureshi et al. (2017) also reported a steady increase in the maximum and minimum temperatures at Bunji and Chilas meteorological stations near the Hispar glacier. Pakistan experienced 0.76 °C increase in temperature during the last 40 years and the rise in temperature was considerably higher (1.5 °C) during a similar period in mountainous regions that support large number of glaciers (Chaudhry et al., 2009). Amjad et al. (2019) also concluded that Mansehra, located near Northern areas, also experienced maximum temperature increase from 25.82°C in 1988 to 26.739°C in the year 2017.

Conclusion

Hispar glacier of the Hunza basin lying in western Karakoram has lost 114 km² of its ice cover area, with an alarming annual retreat rate of 1.67 km² of ice, in a period of 28 years (1990-2018). It is concluded that warmer temperature is one of the main reasons of the glacial retreat, as temperature rises causes the glaciers to melt faster than they can accumulate new snow. Moreover, the greater temperature variability causes greater snowmelt and thus, faster glacial retreat in Hunza basin has been recorded. The climate change is also leaving its impacts on the Karakoram ice reserves.

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