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Snow cover area change assessment in 2003 and 2013 using MODIS data of the Upper Indus Basin, Pakistan

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Abstract

Snow cover area (SCA) is an important component of the solid water reservoir in the catchment. The study of snow trends is essential for managing water resources and for understanding regional climate change. Changes in the snow budget have socioeconomic and environmental implications for agriculture, water-based industries, environment, land management, water supplies; and many other areas related with snow melt water resources. To date, however, only a few scientific studies are available to analyze the Upper Indus Basin (UIB). The basic objective of this study was to map the change assessment of SCA of UIB in 2003 and 2013. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data were retrieved for the period of 2003 and 2013. Three different digital image processing techniques, including normalized difference snow index (NDSI), satellite image classification and band threshold values were applied to assess the SCA. The results show that snow accumulation typically starts from the beginning of October and continues up to mid of March. From end March, the snow starts melting until it is reduced to a minimum in September. A comparison of snow cover of 2003 and 2013 clearly indicates that the snow accumulation period has shifted and anomaly was observed in the start of November. In 2013, snow cover decreases by almost 49% area during the period 30 Sep to 15 Oct, whereas it increases by 133% area in the first sixteen days of November i.e. 1-16 Nov, as compared to the year 2003. Overall, the correlation between the year 2003 and 2013 SCA is found to be 0.87, which is highly positive correlation.

Keywords: Snow cover; MODIS data; NDSI; Upper Indus Basin; Climate change.

1. Introduction

Seasonal snow cover is a main water resource in arid and semi-arid regions (Gurung et al., 2011). Over one-sixth of world population depends on seasonal snow and glacier melt water for water supply (Barnett et al., 2005). Pakistan is an agriculture based country and its economy is mainly dependent on its agriculture. The agriculture of Pakistan is highly dependent on the Indus irrigation system. The Indus River is one of the major water carriers of South Asia emerging from the Tibetan Plateau and the Himalayas. Tarbela is the first major structure on the Indus River for storage and it supplies the flow to the Indus Irrigation System to irrigate the agricultural lands of Punjab and Sindh provinces of Pakistan, the leading producers of agricultural products in the country.

The dynamic hydrological zone of the UIB lies in the high-altitude Himalaya and Karakoram Ranges (Immerzeel et al., 2009). Many authors (Hewitt et al., 1989; Archer and Fowler, 2004; Hewitt, 2005; Bookhagen and Burbank, 2010) stated that over 65% of the annual flow of the Upper Indus River is contributed by the seasonal and stable snowfields and glacierized areas above 3500 m in elevation (Tahir et al., 2011). Almost 90% of the lowland flow of the Indus River System originates from the Hindu Kush, Karakoram and western Himalayan mountainous areas (Liniger et al., 1998). Hence snow melt is an important source of water supply for Pakistan. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report-2007 summarizes some expected impacts of global warming that can have severe consequences on water resources in Pakistan. This report states that reductions in snow cover over recent decades are projected to accelerate throughout the 21st century, thus reducing water availability, hydropower potential, and changing seasonality of flows in regions supplied by snow and glacier melt water (Reisinger, 2007). The Asian high mountains cover the major volume of ice outside the Polar and Alaskan Regions (Phillips et al., 2000;

Gurung, 2011; Bolch et al., 2011). However, comparatively very sketchy information is available about snow cover variation patterns or snow cover sensitivity to climate changes in this part of the world.

The traditional way to measure seasonal snow is to physically monitor the snow cover in a network (i.e. snow surveys along snow courses) of ground based meteorological stations. Snow survey can provide exact information about seasonal snow cover but the spatial scale of this information is limited. In many parts of the world, the sparse network of meteorological stations cannot deliver sufficient data to produce long-term snow datasets over large areas.

Earth observation by satellites has great potential for assessment of snow dynamics at various levels of scale due to their hostile location and remoteness. Snow is highly reflective in visible bands and moderately absorptive in near-infrared band (Crane and Anderson, 1984; Dozier, 1989; Kaasalainen et al., 2006). At present, a number of optical satellite sensors are available for local to continental scale snow mapping and monitoring, which includes the Advanced Very High Resolution Radiometer (AVHRR) (Ramsay, 1998) and Moderate Resolution Imaging Spectroradiometer (MODIS) (Hall et al., 2001 and 2002).

The recent debates on misleading assessments of Himalayan snow cover meltdown demonstrate the necessity for more robust data from the region (Cogley et al., 2010). Hence MODIS, (Justice et al., 1998) flies on two satellites, Terra since 2000 with a morning Equator crossing, and Aqua since 2002 with an afternoon Equator crossing. The snow products from MODIS have seen growing use in investigations in climate (Dong and Peters-Lidard, 2010) hydrologic modeling (McGuire et al., 2006; Painter et al., 2010; Dozier, 2011) and glaciology (Stroeve et al., 2005).The main objective of the research was to map the change assessment of SCA of UIB in 2003 and 2013.

1.1. Study site

The study area consists of 14 sub-basins of UIB as shown in Figure 1, that lie between the source of Indus river and Tarbela reservoir covering a basin area of about 175,000 km^2 (Tariq and van de Giesen, 2012). Major tributaries of UIB region include Shyok, Gilgit, Hunza, Kabul, Chitral, Swat and Astore rivers. The UIB constitutes a major part of Hindu Kush- Karakorum-Himalaya (HKH) region.

The water flow in streams of the study area is characterized by seasonal snowmelt and melting of glacier ice, which is obviously increased during summer because of higher temperature. Snow and glacier melt is estimated to contribute more than 50% of the total flow to the Indus river system (Bajracharya, 2012). Some 80 % of total stream flow occurs in only 6-10 weeks during the whole year. Almost 80-90 % area of UIB is snow covered with occasional exception of 60 % in winter season. The UIB lacks major lakes and large forests; and about one quarter of the area is occupied by glaciers. Also in 2011, Bajracharya and Shrestha mapped a total 21,192.67 km^2 glacier area in Indus basin with an overall area of 1,116,086 km^2, and an estimated 2,696.05 km^3 of ice reserves.

The UIB region is dominated by large glaciers as listed in Table 1 and there is a 5 to 10 times increase in precipitation from glacier termini (~ 2500 m) to accumulation zones above 4800 m. Maximum precipitation occurs between 5000 and 6000 m (Shroder, 1993). Whereas the elevation range of clean ice glaciers is 2,723 and 8,566 as minimum and maximum respectively and for debris covered glaciers the elevation range is 2,409 and 5,913 as minimum and maximum respectively (Bajracharya and Shrestha, 2011).

2. Materials and methods

In this study, the MODIS data with the resolution of 250 m was used along with its products including MOD10A1V5 (MODIS/Terra Snow Cover Daily L3 Global 500m Grid) and MOD10A2V5 (MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid). These products were constructed from the middle infrared, near infrared and red channels; further resampled at 250 m spatial resolution. Index was generated from the raw MODIS spectral bands including short-wave infrared (SWIR) and visible, to improve the mapping capabilities of snow cover.

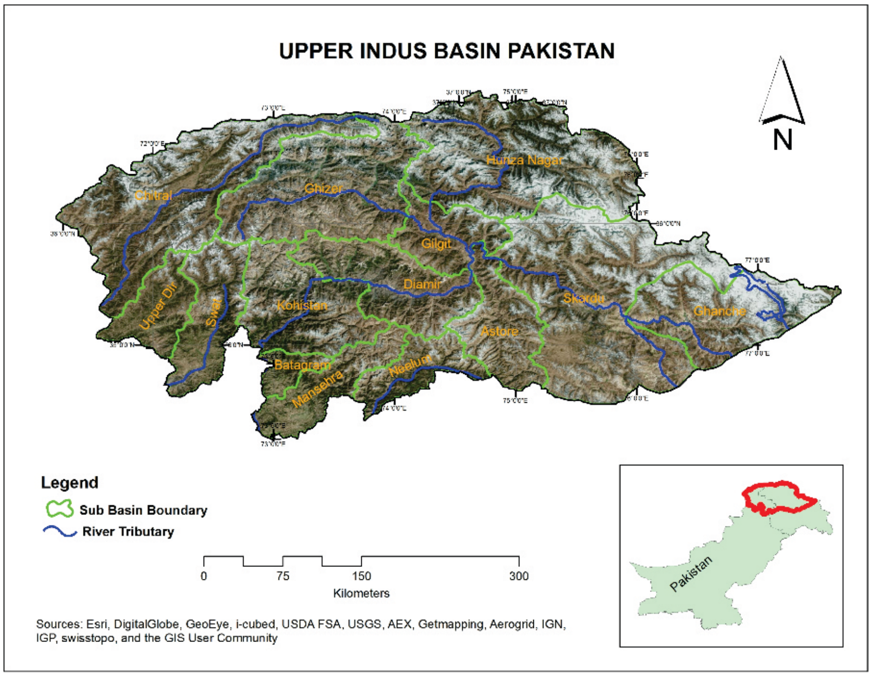


Fig. 1. Sub-basins of the Upper Indus Basin in Pakistan.

Table 1. Dimensions of some large glaciers in the UIB region (McGuire et al., 2006).

Glacier	Length (Km)	Area (Km^2)
Siachen	75.0	1181
Baltoro	62.1	756.3
Biafo	67.9	626.8
Hispar	53.1	621.6
Rimo	45.1	510.2
Skamri	41.0	427.4
Panmah	43.9	1515.1
Te Rong	27.4	295.3
Batura	59.6	285
Khurdopin	41.0	280
Sarpo Laggo	32.0	230.5
Braldu	35.1	202
Virjerab	36.1	189
Kero Lungma	20.9	150.2
Yazghil	30.2	145
Barpu	33.7	136
Malangutti	23	105
Yashkuk Y	24	125
Bualtar	21.5	105
Pasu	20.5	115
Ghulkin	18	55
Hassanabad	17	60
Minapin	16	58

2.1. Methodological framework

The detailed methodology is illustrated in Figure 2.

Grouped criterion technique was incorporated to efficiently map the SCA from the MODIS data i.e. NDSI, image classification and band threshold value. The purpose to use different techniques was to achieve highly accurate SCA. We took benefit from different softwares (Table 2) to efficiently run the SCA extraction algorithms and various raster and vector based analysis techniques. Erdas Imagine 2013 software was used for raster based analysis and ArcGIS 10.2.2 for the areal estimation.

2.2. Normalized difference snow index

The MODIS snow mapping algorithm NDSI was applied. This Index (equation 1) helps to exploit the spectral variations between snow using Band 4 (from 0.545 to 0.565 μm) and Band 6 (from 1.628 to 1.652 μm) to identify snow versus other land features in the imagery.

$$\text{NDSI} = \frac{\text{Band 4 (Visible) - Band 6 (SWIR)}}{\text{Band 4 (Visible) +Band 6 (SWIR)}} \quad (1)$$

Band 4: from 0.545 to 0.565 μm (visible)

Band 6: from 1.628 to 1.652 μm (short-wave infrared)

This index value NDSI value ranged from -1 to +1 as shown in Figure 3. NDSI value of ≥0.1 was applied to delineate the SCA from other landcover features. The constraint was used with the value ranges between 0.1 and 1.0.

After using ≥ 0.1 as NDSI value, some pixels of dense coniferous forests and water bodies are also categorized as snow, as shown in Figure 4. To overcome these misclassified pixels, a more fine threshold value of 0.4 was applied for NDSI i.e. the NDSI pixels with equal to or greater than 0.4 were classified as snow pixels (Tait et al., 2001; Klein and Barnett, 2003).

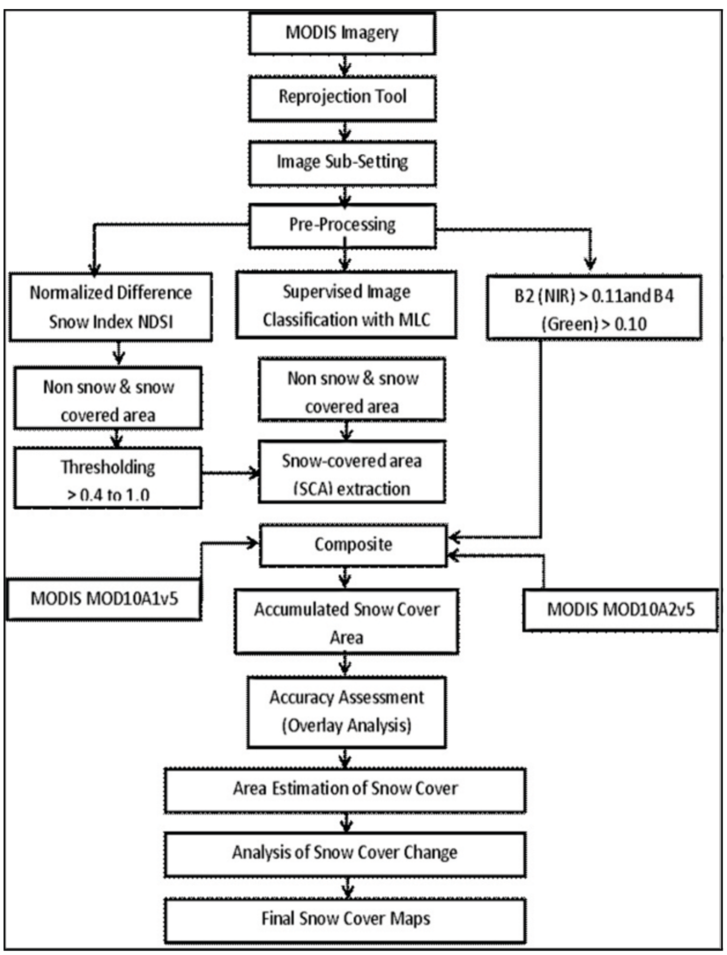


Fig. 2. Detailed flow chart of methodology.

Table 2. Data and software used in the process of snow cover area assessment.

Data/Software	Specifications
Satellite Imagery	MODIS Raw Imagery MOD10A1V5 (250 m) MOD10A2V5 (250 m)
ArcMap 10.2.2	To collect, organize, manage and analyze the snow cover
Sigma plot	A proprietary software package for scientific graphing and data analysis
Erdas Imagine 2013	Raster based analysis

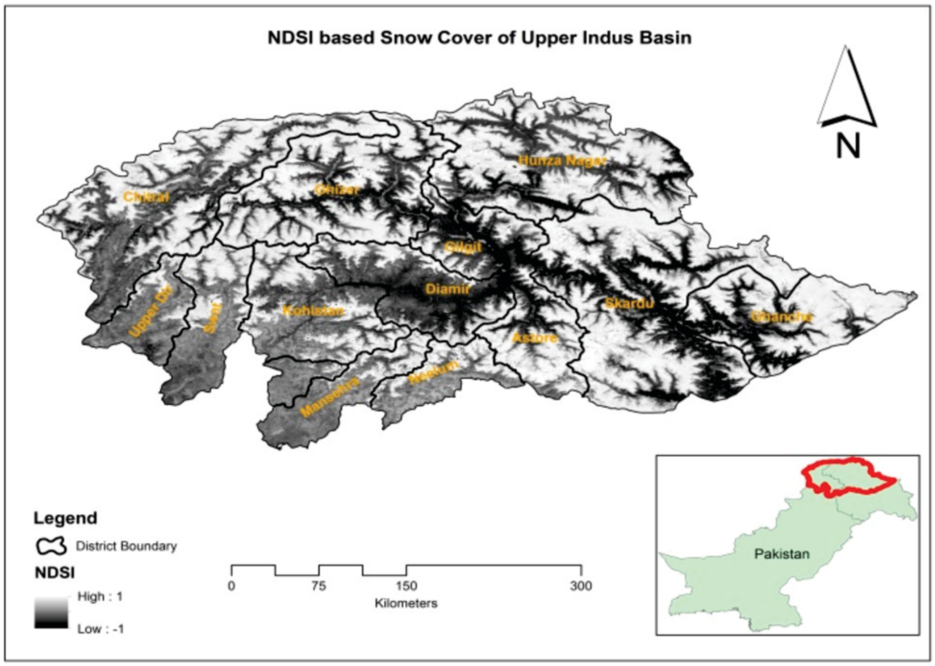


Fig. 3. Normalized difference snow index (NDSI) result.

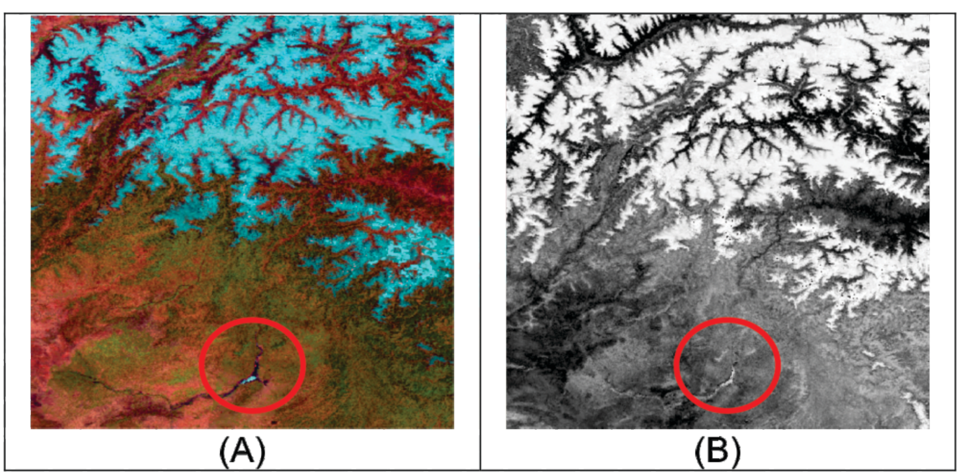


Fig. 4. Water pixels of Tarbela reservoir (shown in red circle) in false color composite (A) is misclassified as snow cover area (B).

The advantage to use constraints on NDSI was that it excludes the influence of features other than snow-covered area and only captures those where snow was observed.

2.3. Satellite image classification

Satellite image classification is a well-established technique for the interpretation of satellite images. Many well-developed software packages, are available that provide a range of sophisticated tools for the whole process of image-processing. They include Geomatica, ENVI & IDL, ER Mapper, ERDAS Imagine, Msphinx, Image Processing Workbench etc. In this study, we used ERDAS Imagine 2013 because of its strong handling of satellite data. Basically, the supervised classification uses the spectral signatures obtained from training samples to classify an image. This research used the supervised classification method to map snow cover from the MODIS satellite images. The extensively preferable maximum likelihood classifier (MLC) was selected to achieve the required objective.

Based on the ground knowledge of land cover type distribution in the study area, MODIS data was mainly classified into two classes, SCA and non-SCA. Snow covered class was further sub-classified into three categories, snow under shadow, snow mixed ice and snow mixed debris. Non-SCA class included the land features other than snow like water, vegetation, debris, etc.

2.4. Band thresholding

For the better mapping of SCA in dense vegetated land cover, shadow and low illumination conditions, an additional technique was incorporated by applying constraints to the MODIS spectral bands, reflectance values > 0.11 for band 2 and > 0.10 reflectance values for band 4.

A pixel was identified as snow where the NDSI values that exist within the range of ≥ 0.4 to 1.0 additionally the band thresholding criteria of MODIS band-2 (> 0.11) and band-4 (> 0.10) also achieved.

Standard MODIS snow-cover products were utilized on daily basis and snow cover composite with the temporal resolution of eight days, which is based on the algorithm to pick the highest snow value within a specific temporal window. Composite snow map was acquired by combining the snow-covered area from all the three techniques i.e. the NDSI, MODIS snow product and SCA extracted through classification. Accumulated SCA was derived with the temporal resolution of fifteen days for the years 2003 and 2013. SCA was estimated to evaluate the snow cover trend in the UIB using the software ArcMap 10.2.2. The SCA maps were generated for the years 2003 and 2013 on bi-weekly basis. Finally, to analyze the snow covered trend, a graph on decade basis was produced using the software Sigma plot 12.3.

2.5. Integration of snow cover

The SCA derived from each technique were combined together to get an accumulated snow cover of the UIB. Finally, area of each image was calculated and different statistical and spatial analyses were performed.

2.6. Accuracy assessment

The accuracy of a classification is usually assessed by comparing the classification with some reference data that is believed to accurately reflect the true land-cover. Sources of reference data include ground truth, higher resolution satellite images, and maps derived from aerial photo interpretation. In this research, the accuracy of the SCA was assessed using high spatial resolution Landsat imagery. A random 268 points were generated using random sampling technique and then the SCAs were assessed. The overall accuracy for the year 2003 was 93% whereas it was 88% for year 2013.

3. Results and discussion

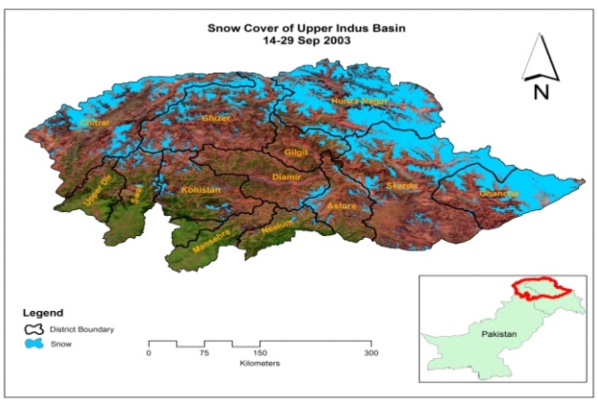
To evaluate the spatial pattern of the snow cover over the UIB, the region is divided into North East (NE), South East (SE), North West (NW), and South West (SW). Further, the maps which were generated at the interval of fifteen days for the year 2003 and 2013 were segregated on the basis of seasonal weather.

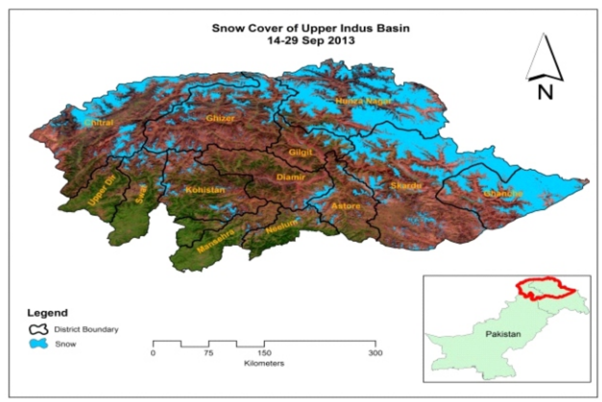
The climate of UIB is altered by the factors like high maximum temperature and less solid precipitation. According to Rasul et al. (2011) at global level it was predicted that 0.6°C temperature would increase for the time period of 2001 to 2010. But in actual it ended up with 0.93°C and particularly for Northern area of Pakistan it got intense up with increase of 1.3°C. This caused the receding of the glaciers and snow melting in HKH region. Mainly the Western disturbance and monsoon are the reasons, which changed the weather of UIB.

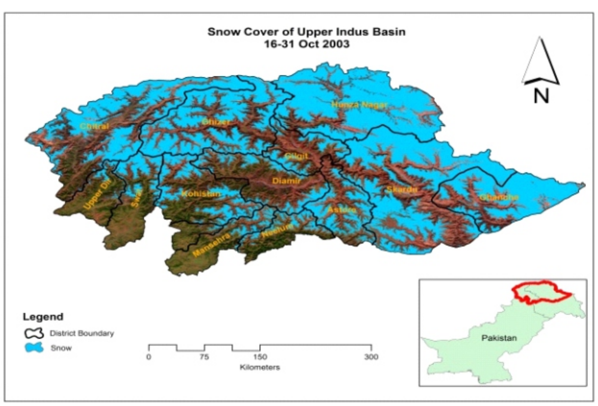
Maps depicted that from the start of March up to the end of September, the snow melted. High temperature during this period caused the depletion of snow cover especially at the low elevation (3000–5000 m) of HKH covering the SW and SE extent; but at the high altitude in UIB, particularly at NE extent, the presence of snow covered throughout the year where exist the renowned glaciers Baltoro, Biafo, Siachen Glaciers etc. According to Moody et al. (2007), the glacier retreat will be highest in Pakistan and Afghanistan in coming 10 to 15 years unless there is an increase in rainfall due to high oceanic evaporation.

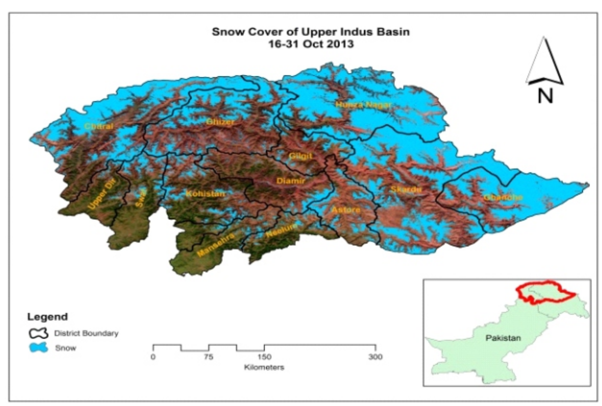
The snow accumulation started in the beginning of October and continued up to the end of February covering the NE and NW extent due to the westerlies.

As we studied the maps, the anomaly was observed in the start of November: the snow cover was much high in 2003 as compared to 2013. From this study, the snow cover estimations demonstrated the retreat in area for the whole year of 2013 instead of few months: November, January and February as compared to the SCA trend in 2003 shown in Figure 5. Meteorologist Amin reported that the snowfall season now has reduced and is limited to only two months a year i.e. January and February, which was previously five months a year from November to March.









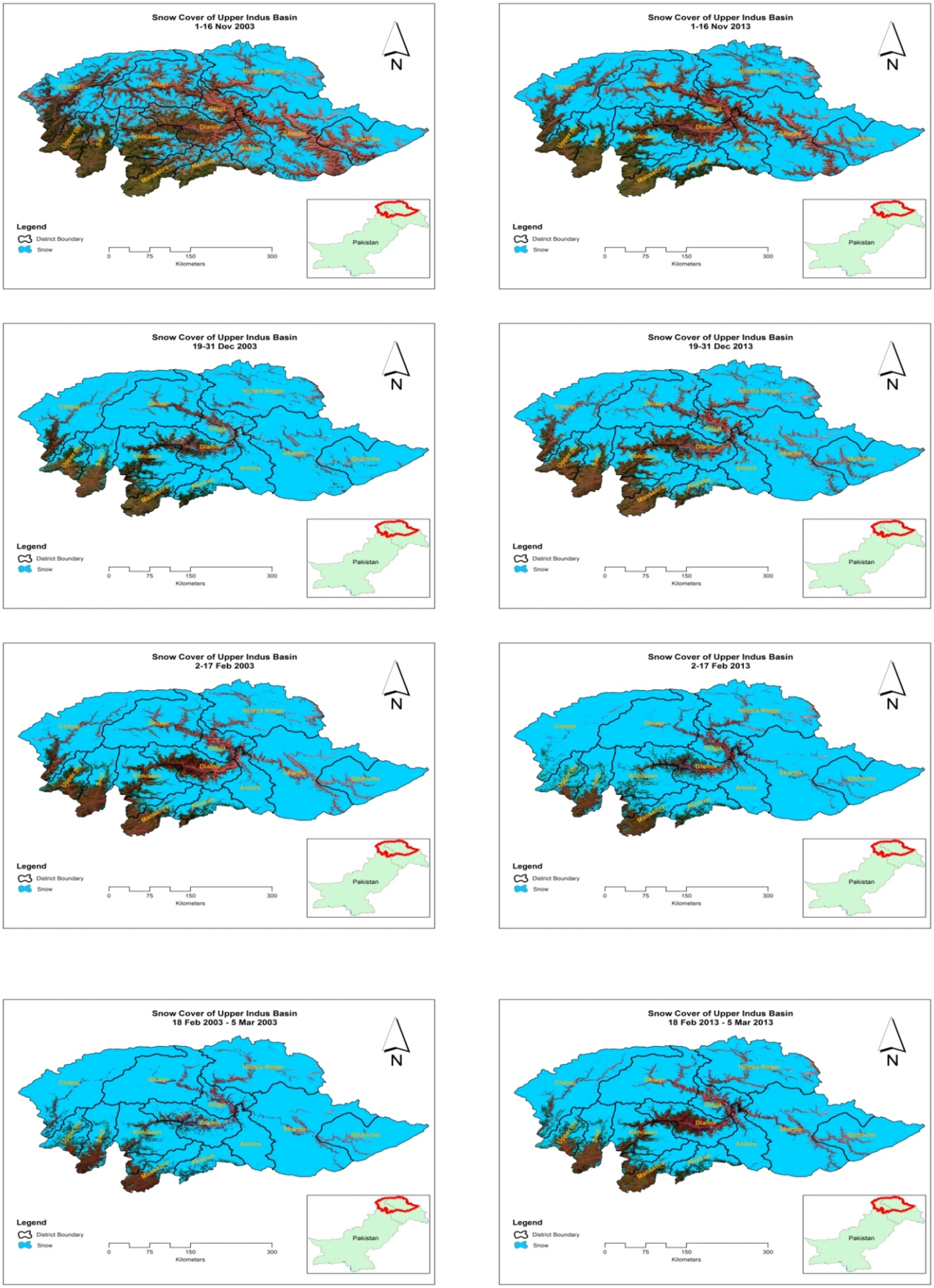


Fig. 5. Snow cover area of Upper Indus Basin Pakistan for year 2003 (first column) and 2013 (second column).

Table 2. Accumulated snow cover area estimated from MODIS data.

Date	Snow cover area 2003 (km^2)	Snow cover area 2013 (km^2)
1-16 Jan	100281	111014
17 Jan - 1 Feb	103440	112044
2-17 Feb	107468	118904
18 Feb - 5 Mar	122817	113121
6-21 Mar	113498	110867
22 Mar - 6 Apr	111819	104076
7-22 Apr	105263	96799
23 Apr - 8 May	100540	95756
9-24 May	92559	85832
25 May - 9 Jun	79944	73749
10-25 Jun	64722	57854
26 Jun - 11 Jul	51235	46944
12-27 Jul	41484	38346
28 Jul - 12 Aug	36013	34345
13-28 Aug	35742	34653
29 Aug - 13 Sep	37630	34851
14-29 Sep	37799	36558
30 Sep - 15 Oct	72360	35258
16-31 Oct	66293	52562
1-16 Nov	68712	91110
17 Nov - 2 Dec	94045	84626
3-18 Dec	98109	90230
19-31 Dec	112203	103529

As shown in Figure 6, the snow accumulation starts from the beginning of October and continues up to mid of March. The snow starts melting from end March and is reduced to a minimum in September. Also, the areal difference of snow cover in 2003 and 2013 has been analyzed as shown in Figure 7. The major change in snow cover trend occured in first fifteen days of October (from September 30 to October 15 both in 2003 and 2013); and after that in first sixteen days of November (from Novermber 1 to 16 both in 2003 and 2013).

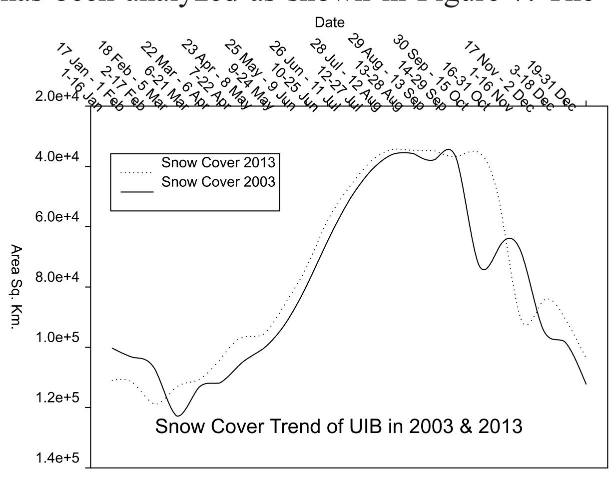


Fig. 6. The snow cover trend of upper Indus basin in 2003 and 2013.

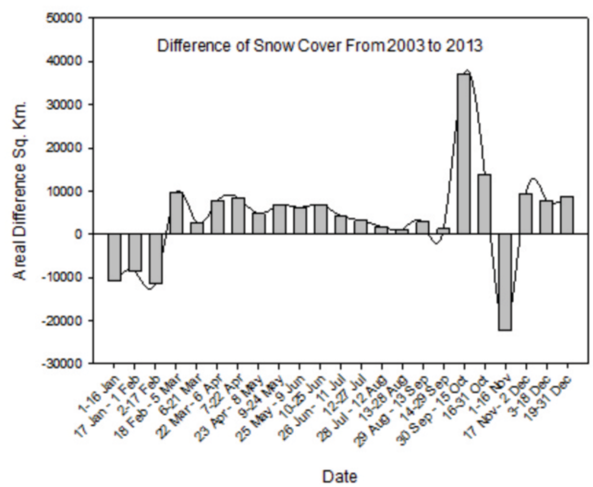


Fig. 7. The difference of snow cover area in 2003 and 2013.

Overall the correlation between the year 2003 and 2013 snow cover area is found to be ~0.9 which is highly significant and positively correlated as shown in Figure 8.

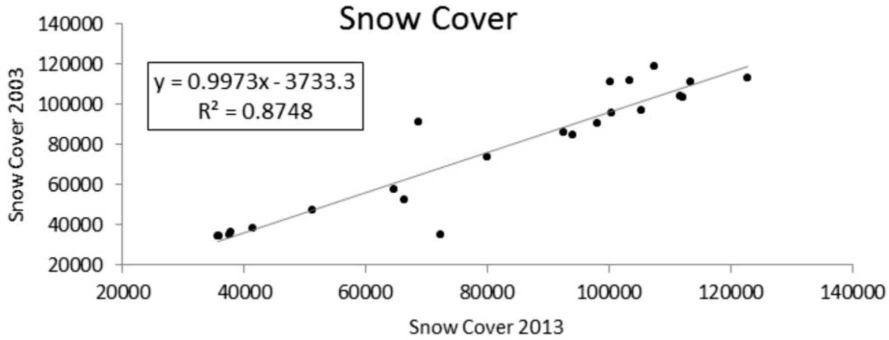


Fig. 8. The correlation between snow cover area of 2003 and 2013.

4. Conclusions

With the advancement in space technology, an extensive range of satellite sensors and data products with different characteristics is now available to the scientific community for mapping and monitoring of natural resources. But the accessibility of large numbers of satellite images is still a challenge; and so is the choice for the most suitable image. Estimation of SCA through remote sensing and GIS is quite effective. All the techniques were found suitable but satellite image classification is less reliable because of the presence of shadowed regions in the high mountainous regions. Our study found no significant changes in SCA of UIB based on the analyses of 10 years' MODIS snow-cover data, from 2003 and 2013. Many previous studies on SCA estimation in UIB region were based on low temporal resolution data whose quality needs to be further examined. Our future study will continue to resolve these issues and will expand our analyses to sub basin level of UIB.

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Conflicts of Interest

"The authors declare no conflict of interest".

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