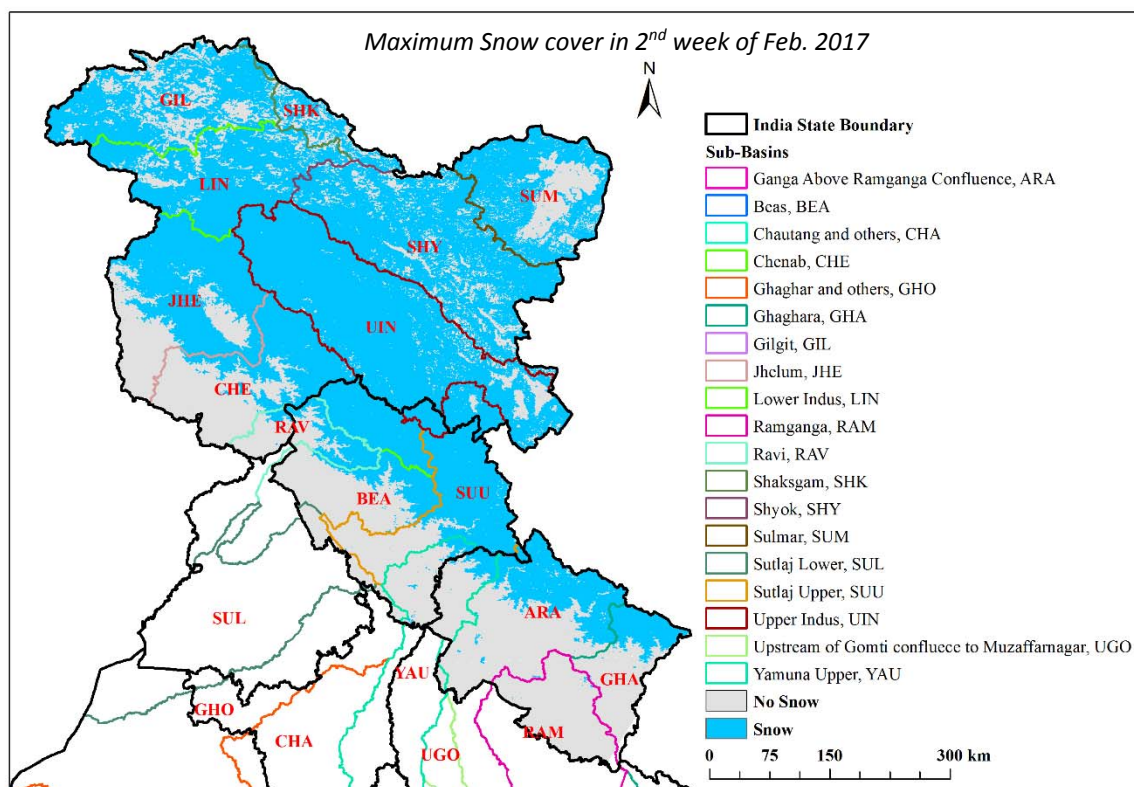


**A Preliminary Assessment Report**  
**on**  
**Assessment of Long-Term and Current Status**  
**(2016-17) of Snow Cover Area in North Western**  
**Himalayan River Basins using Remote Sensing**



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15.	Abstract (with keywords)	<p>Large areas of North West Himalaya (NWH) receives precipitation in terms of snowfall due to low temperatures in winters and high altitude mountains. Snow cover area (SCA) in NWH varies seasonally as well as annually. During winter season of 2016-17 heavy snowfall has been recorded in many part of NWH. As per the reports appearing in various national and local agencies and media that high snowfall in early spring season in entire NWH has broken last 30 years records at many places. This triggered the present study of assessing the status of SCA in NWH region and comparing it with last 15 years records. In the present study 8-day SCA product from MODIS and 15-daily snow cover fraction product from AWiFS were used to analyse the current and past 15 years SCA status at sub-basin scale in the NWH region.</p> <p>Keywords: Snow Cover Area(SCA), North Western Himalaya (NWH), MODIS, Temporal SCA analysis</p>			

## Summary

1. During winter season of 2016-17 heavy snowfall has been recorded in many part of NWH. As per the reports appearing in various national and local agencies and media, the unusually low temperature and **high snowfall in early spring season in entire NWH has broken last 30 years records at many places**. This triggered the present study of assessing the status of SCA in NWH region and comparing it with last 15 years records.
2. Space based remote sensing has proven capability of mapping and monitoring SCA with high temporal and spatial resolution. Hence, in the present study 8-day SCA product from MODIS and 15-daily snow cover fraction product from AWiFS were used to analyse the current and past 15 years **SCA status at sub-basin scale** in the NWH region.
3. **Main Highlights of this study:**
  - Long-term (2001-2017) temporal SCA of all the NWH sub-basins has been generated and analysed
  - SCA of year 2016-17 has been compared with long-term mean SCA of each basin for respective time period.
  - Maximum SCA as percentage of total basin area for Upper Indus, Lower Indus, Gilgit, Sulmar, Jhelum, Chenab, Shyok, Shaksgam, and upper part of Sutlaj, Beas and Ganga sub-basins estimated to be in the range of 75 to 95% during winter season of 2016-17.
  - Maximum SCA in Upper Ganga, Beas, Chenab and Jhelum sub-basins is observed in 2<sup>nd</sup> week of January 2017. However, in the sub-basins located in higher latitudes *viz.* Upper Sutlaj, Lower Indus, Shyok, Sulmar sub-basins maximum SCA is observed in 2<sup>nd</sup> week of February 2017 and Gilgit & Shaksgam sub-basins in 3<sup>rd</sup> week of February 2017.
  - The maximum SCA observed for year 2017 in all these sub-basins is approximately 10 to 50 % higher as compared to SCA of same time period in 2016.
  - NWH region has also received one of the highest snowfall in early March of 2017 with average 8 % higher SCA as compared to previous year.
  - The ground observed data from field instruments installed by IIRS in Beas basin reveals increase in snow depth at these locations in the order of 1 to 1.5 m during January to March of 2017 as compared to same time period of year 2016.

#### 4. Possible Implications & Further study areas

It is expected that, the increased SCA, snow depth will produce higher snow melt/discharge during upcoming spring and summer season in these sub-basins.

- **On the benefits:** Enhanced Hydro-power generation, reservoir storage and irrigation projects - possibilities with a proper planning.
- **On the Concerns:** Hydrological disasters due to heavy snowfall leading to higher SCA in spring season increases the probability of flash floods, landslide, sudden increase in river flow and associated hazards.
- **Further study:** These aspects can be studied in detail with the help of suitable hydrological models if hydro-meteorological data, snow depth, snow water equivalent, snow density, baseline topographical data, location of water resources projects, etc., of NWH region are made available.

# 1. Introduction

## 1.1. Snow Cover and Its Mapping

Snow cover presents one of the most important land surface parameters in global water and energy cycle as it controls the global and regional radiation feedback and stores and releases freshwater in hydrological cycle. On a regional scale, snow cover is important for local water availability, river run-off and groundwater recharge, especially in middle and high latitudes (Jain et al., 2008). Large areas of North West Himalayan (NWH) receives precipitation in terms of snow due to low temperatures in winters and high altitude mountains. The melt water from snow and glacier provides major contribution to discharge in all major rivers of NWH and its annual contribution to river flow varies from 70% for Chenab upto Akhnoor, 60 % from Satluj upto Bhakra dam and 30 % for Ganga river upto Devprayag (Singh and Singh, 2001). These rivers are major source of hydropower in Northern India, hence, snow cover/melt also plays a relevant role in energy supply. In this context, exact knowledge of the snow-covered area (SCA) is essential for water resource management (Butt and Bilal 2011). The hydrological models also use SCA along with hydro-meteorological data to simulate snowmelt runoff (Ramamoorthi, 1986; Aggarwal et al., 2013). Regular mapping and monitoring of this seasonal snow cover by traditional means is very difficult due scanty snow gauges, inaccessible terrain during peak winters, rugged and high altitude topography and remoteness of these mountains. Space based remote sensing satellites has proven capability of mapping and monitoring snow cover, glacier extents and high altitude lakes in these area with high temporal and spatial resolution (Aggarwal et al., 2013).

One of most commonly used method for operational and research oriented snow cover mapping using optical remote sensing is, Normalised Difference Snow Index (NDSI), which is defined in terms of the green and SWIR spectral bands of EMR as (Dozier, 1984, 1989; Dozier and Marks, 1987):

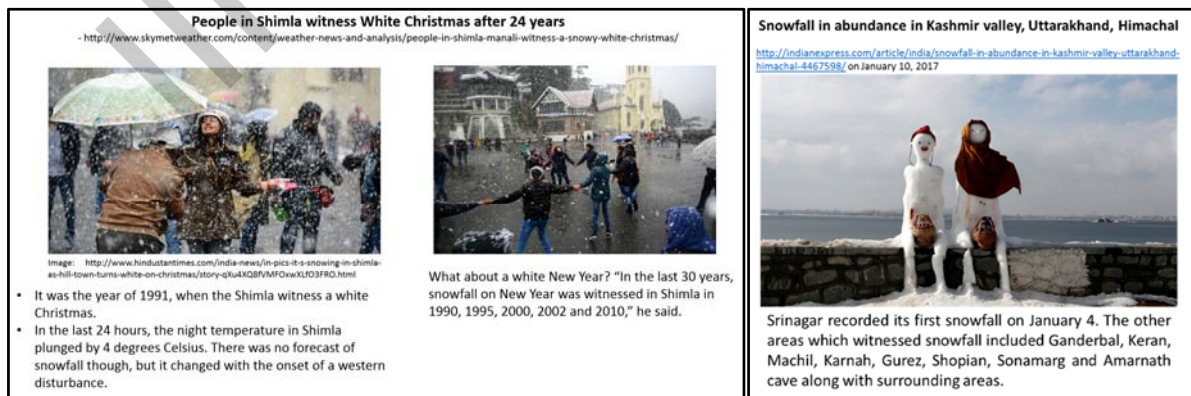
$$NDSI = (R_G - R_{SWIR}) / (R_G + R_{SWIR}) \quad (1)$$

Where,  $R_G$  and  $R_{SWIR}$  are the reflectance's in Green and SWIR bands, respectively. Snow is normally assumed to be present if the NDSI exceeds a value of 0.4 (Dozier, 1984, 2009; Kulkarni et. al., 2006), and recent studies have shown that the optimum value of the threshold can varies seasonally (Vogel, 2002). Similarly, presence of forest cover, cloud cover, and water

bodies can cause errors in final reported SCA, if only NDSI is used for SCA mapping. To overcome these limitations, a rule based algorithm was proposed and implemented by Hall et al., (2002) for operational mapping of SCA using moderate-resolution imaging spectroradiometer (MODIS) sensor on-board Terra (EOS AM) and Aqua (EOS PM) satellites, which provides daily, 8-daily and 16-daily SCA products from 2000 onwards. MOD10A2 product with 500m grid size at 8-day maximum snow cover product of (Dorothy et al., 2001) has been used in this study to map and monitor SCA from 2000 to 2017. In addition, Resourcesat 1/2 based AWIFS sensor has been used by (Subramaniam and Suresh Babu, 2014) from NRSC, to provide 15 day 3 minute spatial resolution snow fraction grids for Himalayas from 2014 onwards. This data was also used for SCA mapping of NWH during 2014-2017.

## 1.2. Why This Study Is Done?

All the major rivers of NWH have catchment area in middle and higher altitudes, which receives snowfall during winter time period. Therefore, the sub-basin covered under NWH region are selected as study area in the present analysis as shown in Figs. 1. Seasonal variations in the snow cover area in this region affects the fresh water storage in terms of standing snow and contribution to glaciers during winter time, however, their melt during spring and summer time provides important contribution to river flow. In year 2015-16, the annual snowfall and associated SCA was less as compared to usual trend, whereas, 2016-17 season has experienced heavy spells of snowfall since December 2016 till March 2017. The month of February 2017 has experienced unusual high temperature across India and less snowfall in NWH. As per the reports appearing in various national and local agencies and media, the unusually low temperature and high snowfall in month of March in entire NWH has broken last 30 years records at many places. Few of the snapshots of media reports are given below;



chandigarhmetro.com March 15, 2017



**Snowfall in Shimla Leads to Coldest March in 3 Decades**

- The minimum temperature recorded was  $-0.9^{\circ}\text{C}$  in the last 24 hours. On Saturday, Shimla recorded  $-0.2^{\circ}\text{C}$ . Keylong was recorded coldest in the state at  $-8.6^{\circ}\text{C}$ . Tourist town Manali was recorded minimum with  $-3.8^{\circ}\text{C}$ , Kalpa in Kinnaur with  $-7^{\circ}\text{C}$ , Chamba  $2.7^{\circ}\text{C}$  and Sundernagar  $1^{\circ}\text{C}$ .
- In last 3 days, Shimla has recorded around 17 cm of snowfall, Kufri over 20cm, Narkanda 25cm, Kharapathar 25cm and Kalpa 30cm. In last 24 hours, Shimla has recorded 7 cm of snowfall.

chandigarhmetro.com March 15, 2017



**Mussoorie Receives Snowfall on Holi After 19 Years & it's a Delight to Watch**

- The areas located near to Mussoorie witnessed approximately 6 cm of snow.
- It is after 19 years that Mussoorie has witnessed snow in the month of March.

**India experienced 4th hottest Feb since 1901 despite El Nino absence**  
<http://timesofindia.indiatimes.com/city/pune/india-experienced-4th-hottest-feb-since-1901-despite-el-nino-absence/articleshow/57677074.cms>

- The freakishly warm February this year broke at least 113 past temperature records for the month, according to the India Meteorological Department (IMD). Last month was also 1.3 degree C warmer than the 20th century February average.
- High altitude winds blowing from west to east bring these disturbances to India from the western world. "During the winter months of November-December 2016 and February 2017, western disturbances were more active in parts of Middle East, Iran and Afghanistan because of these high altitude winds blowing over these regions. But over India, there was a notable deflection of these winds, which in turn repelled the western disturbances,"

**Avalanche threat in parts of HP; snowfall in mid, higher hills**  
<http://www.newindianexpress.com/nation/2017/mar/12/avalanche-threat-in-parts-of-hp-snowfall-in-mid-higher-hills-1580561.html> on 12th March 2017

- Shimla received 14.8 cm of snow since yesterday, followed by Kalpa 14.2 cm and Manali 2 cm
- Solan was the wettest in the state with 26.3 mm of rains followed by Kangra 22.4 mm, Manali 15 mm, Dharamshala 10.2 mm, Sundernagar 3.2 mm and Bhuntar 2.6 mm. Keylong in tribal Lahaul and Spiti district was the coldest recording a low of minus 5.1 degrees Celsius followed by Kalpa minus 4.0 degrees Celsius while Manali, Shimla and Dharamshala recorded minimum temperatures of 0.6 degrees Celsius, 0.4 degrees Celsius and 6.6 degrees Celsius respectively.

Heavy snowfall in early spring can cause avalanche, landslides and flash floods in downstream low-lying areas due to sudden increase in day time air temperature resulting high snowmelt. Although, the increased SCA is also seen as good indicator for increased river flow due to melt during spring and summer which will lead to increase in hydropower generation and reservoir storage. However, for better management and efficient utilization of this additional water available in form of snow/snow melt, the proper assessment of SCA and its variations with time and space is pre-requisite. These variations in SCA can be easily monitor and mapped using space based remote sensing data. Hence, in the present study an attempt has been done to map and analyse long-term SCA of all the NWH sub-basins using MODIS and AWiFS derived snow cover products. The comparison of SCA of winter season 2016-17 with long-term mean SCA of respective periods and SCA of winter season 2015-16 has been done to highlight the unusually high SCA in NWH region during early spring season.

## 2.Data Used

Weekly maximum snow cover maps generated using NDSI approach over daily MODIS data on-board NOAA Terra are available in public domain from 2000 to till date, same have been used to map and assess the status and variations in SCA in NWH. In the present analysis the winter seasonal (November –March) months MODIS snow cover products (MOD10A2, <https://nsidc.org/data/MOD10A2>) has been analysed using automated SCA extraction tool developed in-house and standard geo-spatial tools. Weekly maximum snow cover data, starting from Julian day 361 (01 November) to Julian day 89 (30 March) of each winter season has been analysed and statistics for each NWH sub-basin has been calculated and compared. The bi-monthly snow cover fraction maps derived using AWiFS data, available on Bhuvan, has also been used in the present study to estimate total area under snow in each sub-basin in recent years. Figures 2 show the sample snow cover area derived from MODIS. The list of MODIS snow cover data and AWiFS snow cover fraction data analysed in the present study is give in Tables 1 a

**Table 1a:** List of MODIS (MOD10A2) maximum snow cover data used in the present study

Julian Day →	1	9	17	25	33	41	49	57	65	73	81	89	305	313	321	329	337	345	353	361
2000	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2001	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2002	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2003	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2004	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2005	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2013	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2014	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2015	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2016	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2017	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-

**Table 1b** : List of AWiFS snow cover fraction data used in the present study

	1to15 Jan	16to31 Jan	1to15 Feb	16to28 Feb	1to15 Mar	16to31 Mar	1to15 Nov	16to31 Nov	1to15 Dec	16to31 Dec
2014	-	-	-	-	✓	✓	✓	✓	✓	✓
2015	✓	-	-	✓	✓	✓	✓	✓	✓	✓
2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2017	✓	✓	✓	-	-	-	-	-	-	-

The basin boundaries of all the NWH basins has been referred from India Water Resources Information System (IWRIS). The sub-basin receiving snowfall during winter season in NWH region are considered in the present analysis.

### 3. Methodology

#### 3.1. Snow Cover Area Extraction

The MOD10A2 products used in the study gives 8-day composite of the snow cover area and also the 8-day maximum snow extent (Hall et al., 2006). One tile of MOD10A2 consists of 2400 by 2400 rows and columns with 500 m pixel resolution and is available in sinusoidal map projection. These datasets are usually coded according to each land cover, e. g. snow covered area is represented by the code 200, lake ice by 100, cloud by 50, etc. Since, the pixel value for the snow covered pixels is a constant value, the process of the extraction of the snow cover area can be very easily automated. The process of snow cover mapping becomes difficult in the case of existence of cloud over the snow covered areas for longer duration (week or more) in such cases the area will be coded as cloud mask (code:50) in MODIS snow cover product, however, the underlying areas may still be covered with snow. Manually rectification of snow under cloud is very difficult due to the dependence on available geo-statistical tools in GIS software used usually. To overcome this problem an automated snow cover mapping tool has been developed using Interactive Data Language (IDL) and used in the present study. The tool initially generates a permanent snow cover map based on analysis of all the long-term snow cover datasets available. In the second run the tool analysis three subsequent time period snow cover products. The pixel in input dataset (of time period t) designated by code 200 will be marked as snow pixel and other ambiguous pixel with cloud cover (code-50) are analysed with reference to permanent snow cover map generated in first step and snow cover products

of previous (t-1) and subsequent time period (t+1). Elevation mask of 1500 m has been used in the tool to avoid misclassification of pixels below 1500 m elevation in to snow cover area. The snow cover area on fortnight basis has also been estimated using snow cover fraction products derived from AWiFS available at 3'×3' spatial resolution.

### **3.2. Sub-Basin wise SCA Analysis**

The sub-basin wise temporal SCA has been derived using histogram extraction tool of Arc GIS. Long-term SCA of each sub-basin for each time step has been analysed and mean, maximum and minimum SCA of each time step (week) for every sub-basin has been identified. It is to be noted that the SCA data of winter 2016-17 (November 2016 to February 2017) has not been considered in calculation of mean, maximum and minimum SCA. The SCA of each time step (week) of winter season 2016-17 has been compared with long-term mean SCA (2000-01 to 2015-16) of respective sub-basin and time step. The comparison has also been done with SCA of winter season 2015-16. Observations are made on the basis of sub-basin wise statistics and spatial SCA maps. The maximum SCA (max. SCA) in winter season of 2016-17 has been identified for each sub-basin along with the time of occurrence of the max. SCA. The SCA on same dates in previous winter season were used to highlight the difference (increase) in SCA during winter 2016-17. The SCA at sub-basin level has been reported in terms of fractional area (i.e. SCA/Sub-basin area) for better representation. Additionally, to analysis the status of SCA in early spring season of 2017, the comparison of fractional SCA between 1<sup>st</sup> Week of March 2016 and 2017 was also carried out. Weekly SCA plots of each sub-basin along with long-term mean SCA of respective periods were generated and analysed. The field observed data (snow depth, snow water equivalent) from instruments installed by IIRS at Dhundi, Manali (Beas sub-basin) was used to validate the observation regarding SCA in NWH.

## 4. Results and Observations

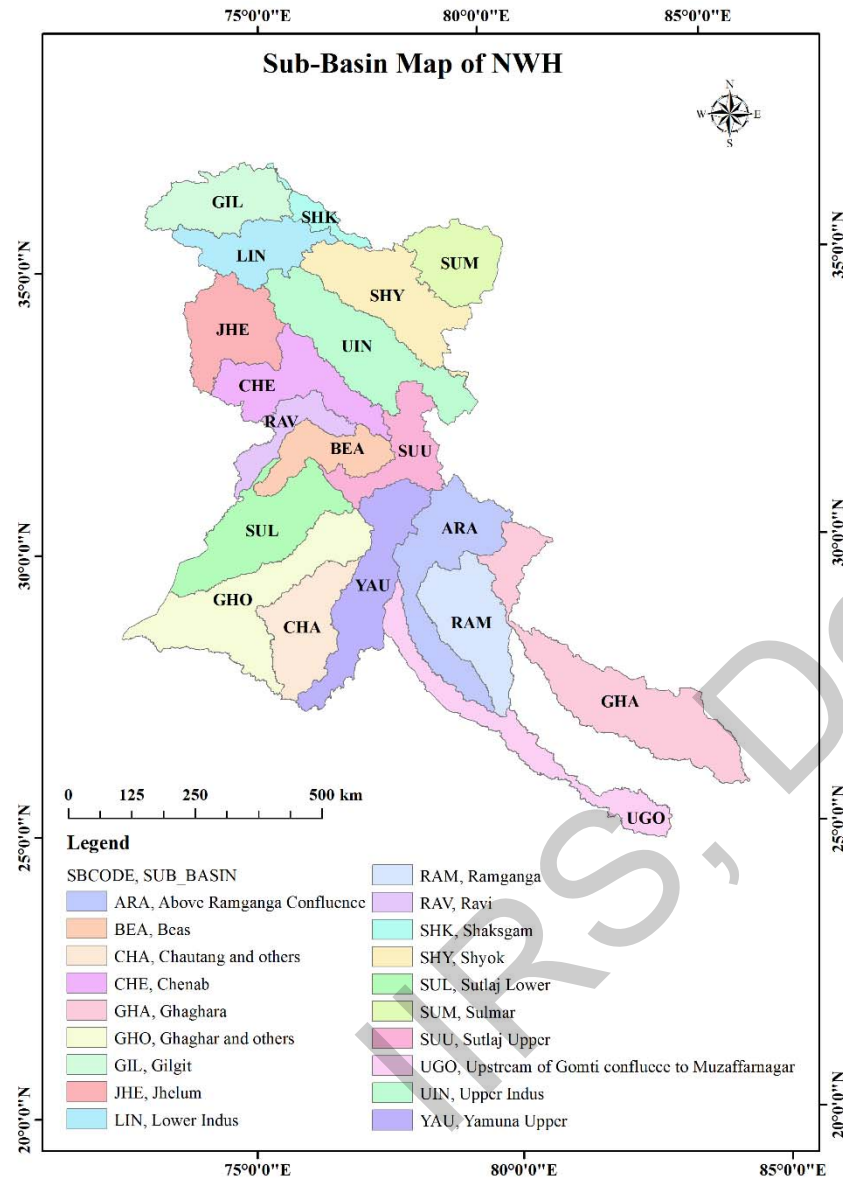
The sub-basin wise analysis of SCA from 2001-2017 has been done for entire NWH. Figure 1 shows location of all sub-basins of NWH (source: IWRIS) and Fig. 2 highlights the 8-day maximum SCA during 2<sup>nd</sup> week of February 2017 having around 64% of total area under snow. The detailed analysis of fractional SCA (refer Fig. 3) has revealed around 20% increase in SCA during winter season of 2016-17 especially in the months of January to March 2017 as compared to previous year. The temporal increase in SCA in NWH region from November 2016 to February 2017 can be visualise in the representative SCA maps shown in Fig. 5 (a-c). Further to validate the increase in snowfall/snow cover observed data from field instrument (Snow Pack Analyser) installed at Dhundi, Manali (falls in Beas Sub-basin) for measuring snow properties has been analysed as shown in Fig. 4. The figure shows significant increase in snow depth (1 to 1.5 m) during 1<sup>st</sup> week of January, 2<sup>nd</sup> week of February and 1<sup>st</sup> week of March 2017; resulting in significant increase in SCA of NWH region in subsequent weeks as observed in SCA results and maps shown in Figs. 3 & 5.

Figure 6 depicts the sub-basin wise maximum SCA of winter 2016-17 and the period of occurrence of maximum SCA in each sub-basin. It was observed that maximum SCA occurred on 2<sup>nd</sup> week of January, 2<sup>nd</sup> and 3<sup>rd</sup> weeks of February. The maximum fractional SCA values in Upper Ganga, Beas, Chenab and Jhelum sub-basins has occurred during 2<sup>nd</sup> week of January and it varies from 0.3 to 0.76. However, in Upper Sutlaj, Lower Indus, Shyok, Sulmar sub-basins maximum SCA was observed in 2<sup>nd</sup> week of February 2017, ranging from 0.73 to 0.95. Whereas, the max SCA in Gilgit & Shaksgam sub-basins was noticed in 3<sup>rd</sup> week of February 2017, with value varies from 0.75 to 0.84. Figure 7 shows SCA of these sub-basins in same time period in 2015-16. The maximum SCA observed for year 2017 in all these sub-basins is approximately 10 to 50 % higher as compared to SCA of same time period in 2016.

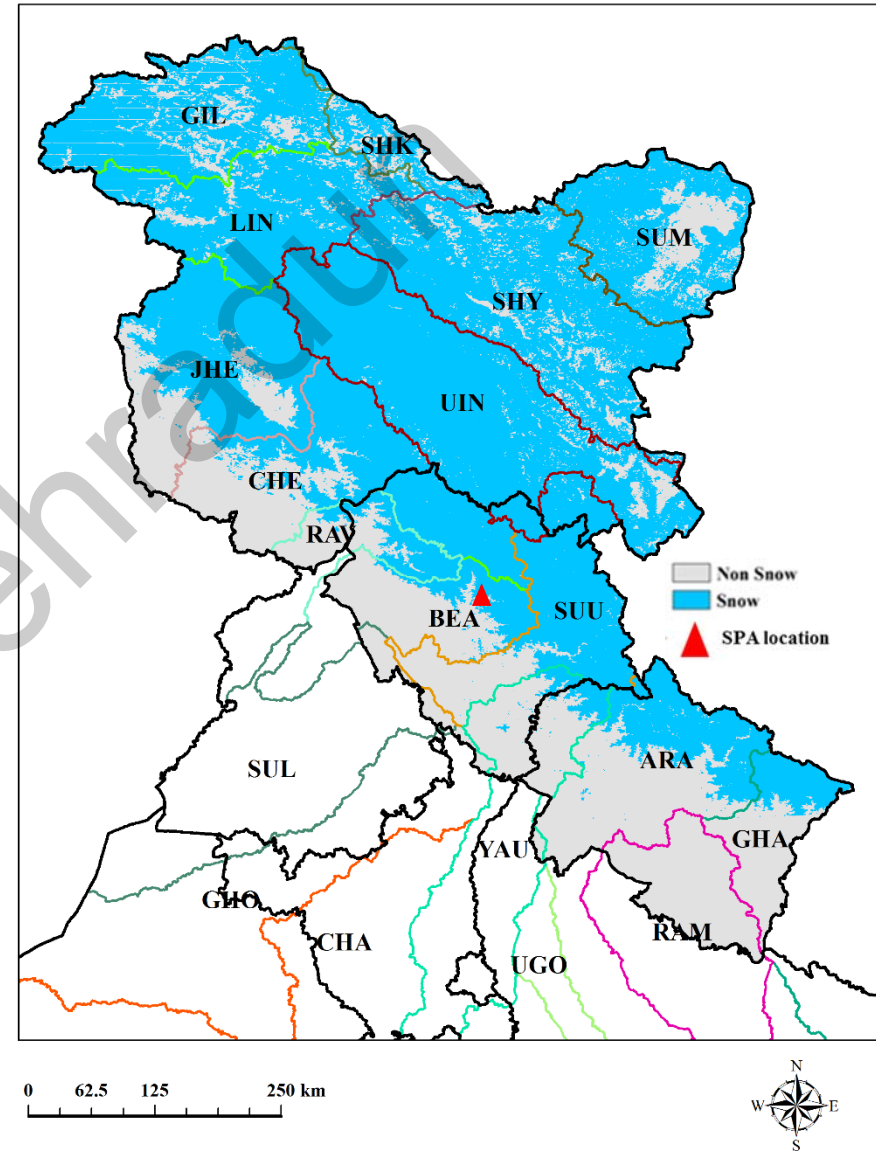
Heavy snowfall has been recorded in the month March 2017, with some of the location receiving highest snowfall for this duration in last 30 years. Figures 8, 9, 10 & 11 shows the comparative SCA maps of NWH highlighting increased SCA even in lower altitude regions. The sub-basin wise fractional SCA for 1<sup>st</sup> week of March 2017 and 2016 are also depicted in Figure 12 & 13, respectively. The average increase of 08% (approx.) was observed in SCA

during 1<sup>st</sup> week of March 2017 as compared to 2016. (refer Appendix-1 for detailed information and maps)

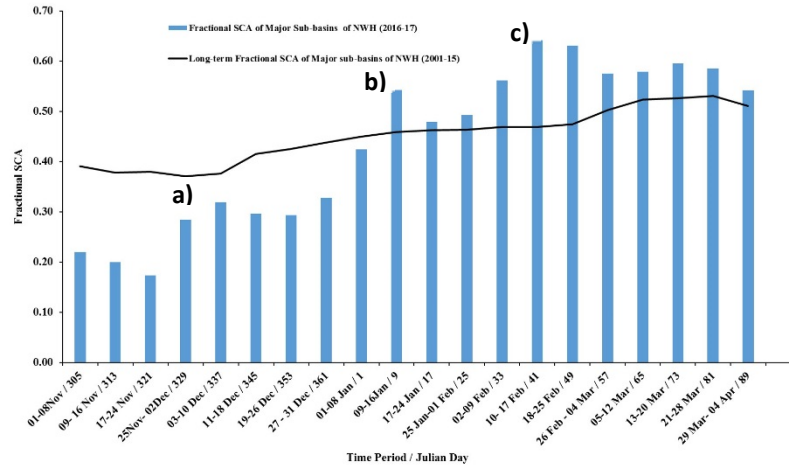
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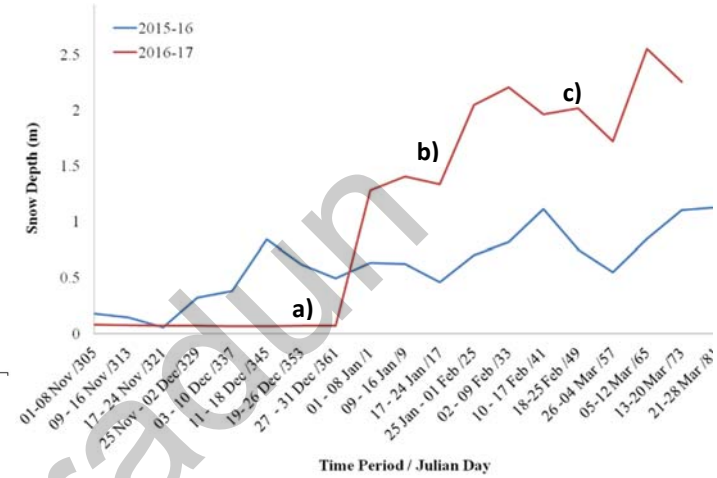
**Fig 1.** Sub-basin map of NWH



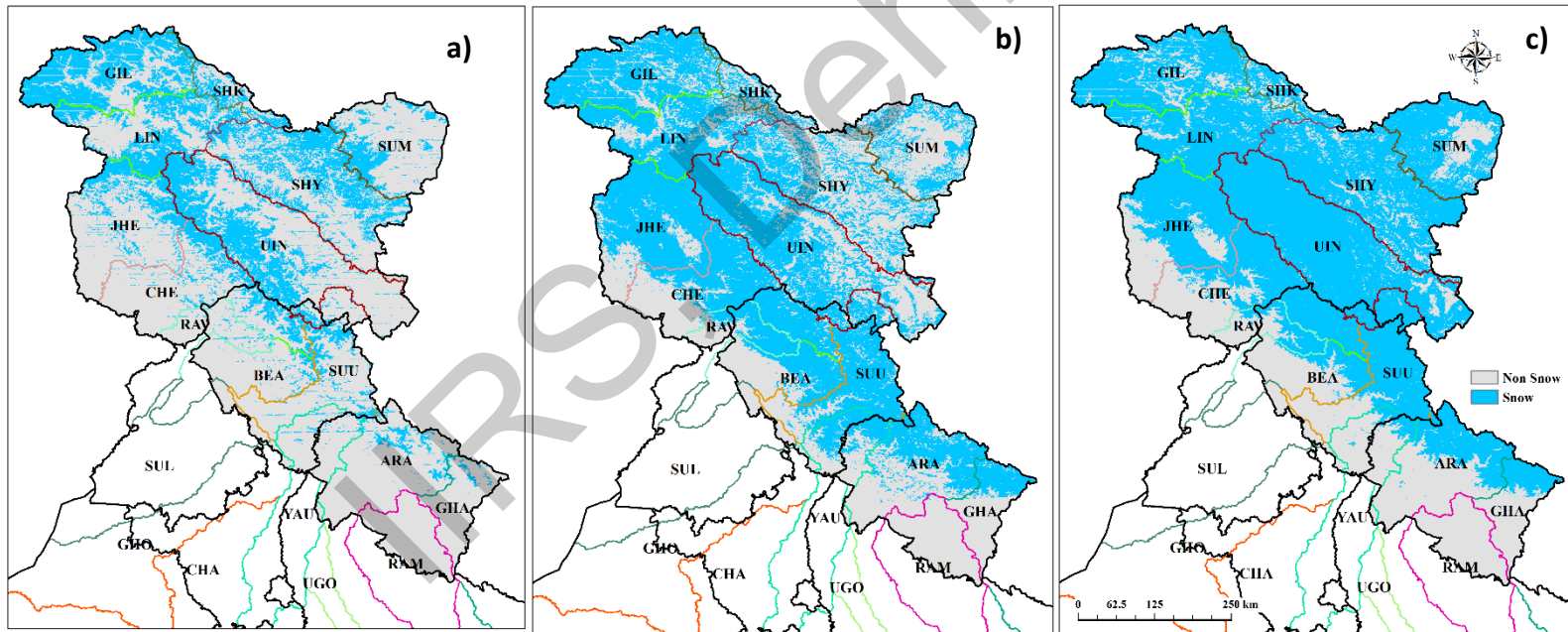
**Fig. 2.** Eight day maximum SCA in 2<sup>nd</sup> week of February 2017 derived from MOD10A2 product.



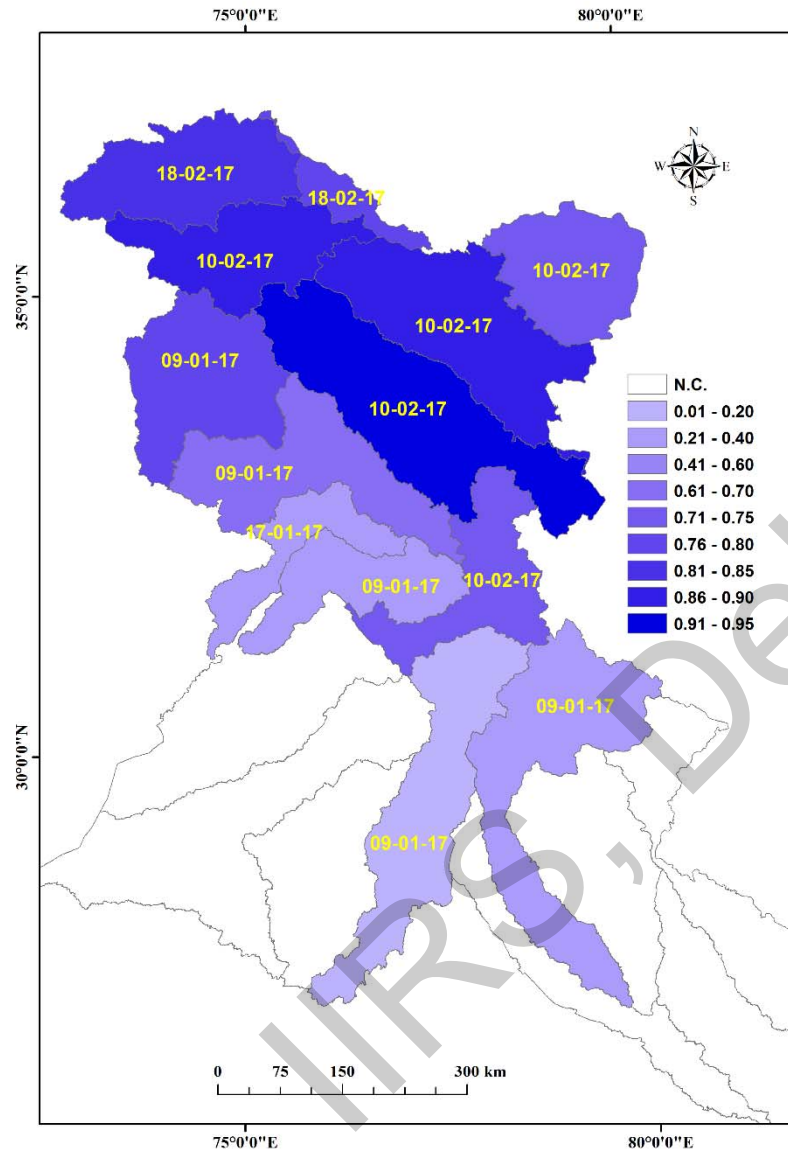
**Fig. 3.** Comparison of fractional snow cover in NWH



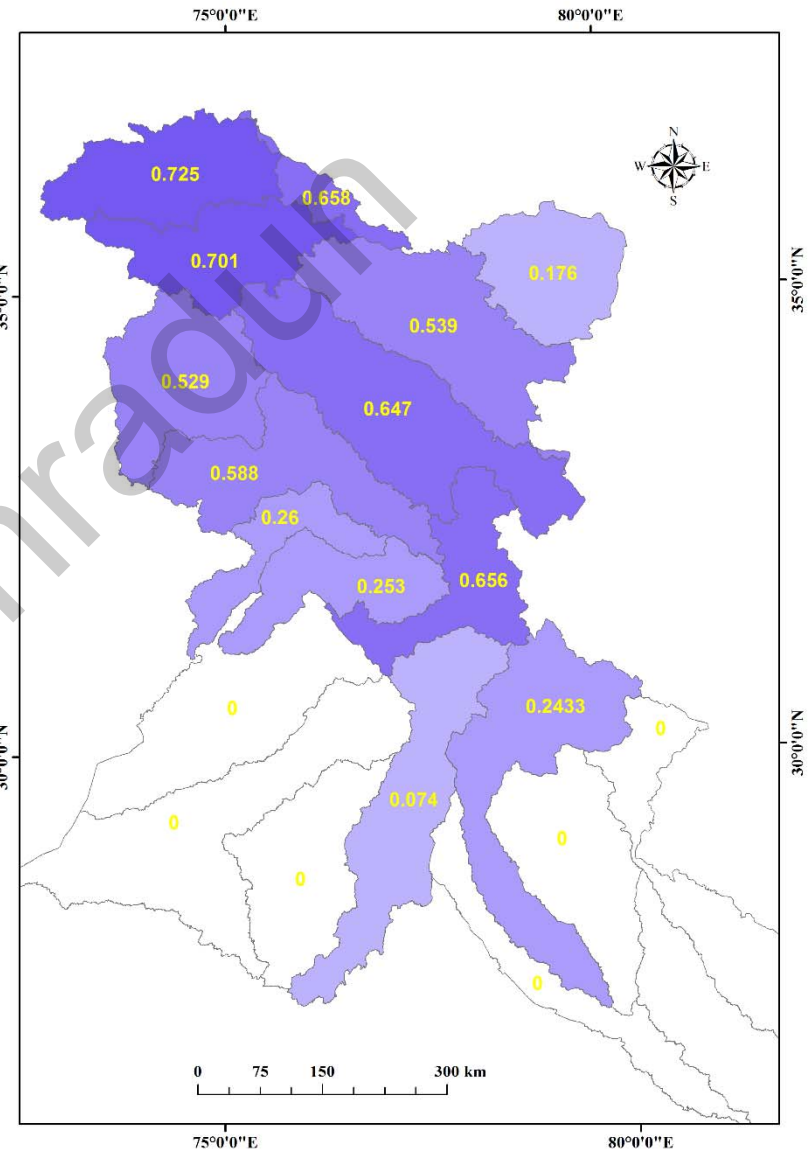
**Fig. 4.** Observed Snow depths at Dhundi, Manali (Beas sub-basin)



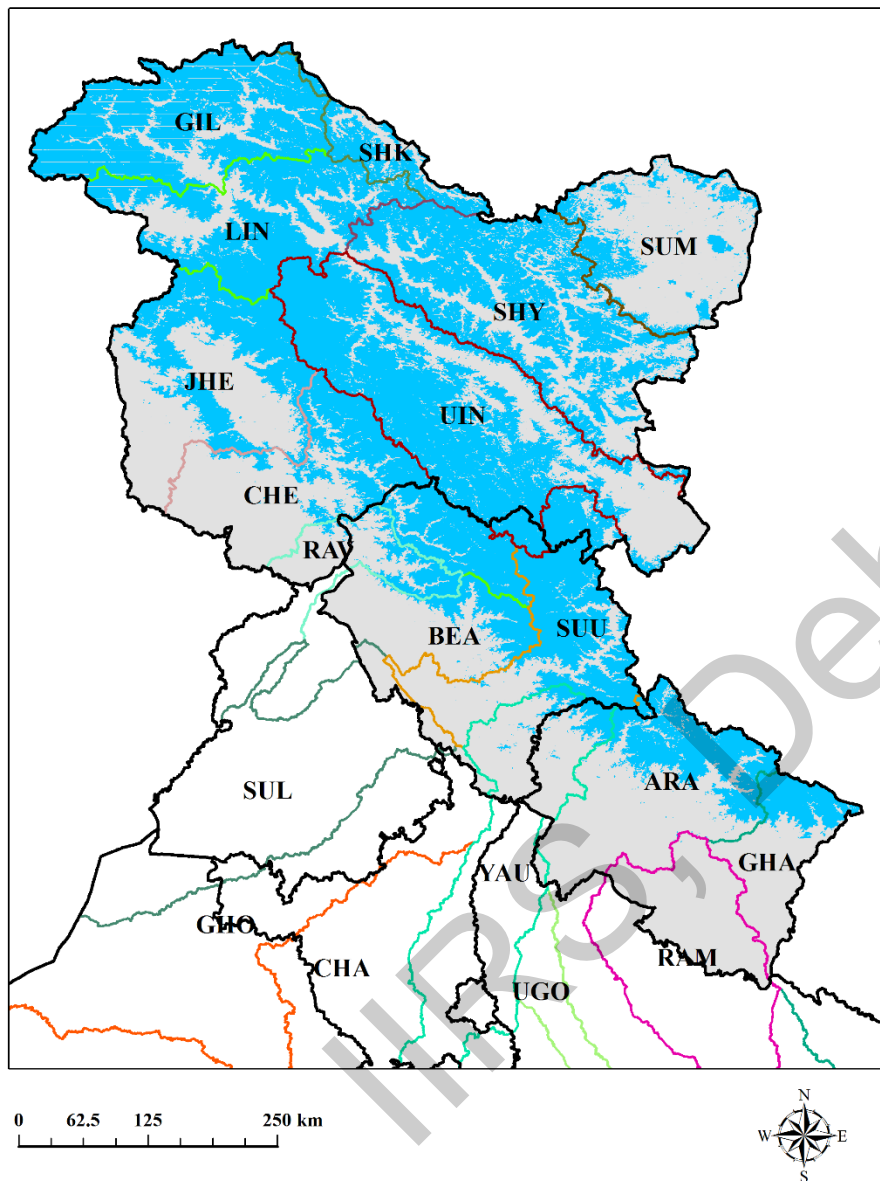
**Fig. 5.** Temporal change in SCA during winter 2016-17 a) 25 Nov-02 Dec. 2016, b) 09-16 Jan. 2017, c) 10-17 Feb 2017



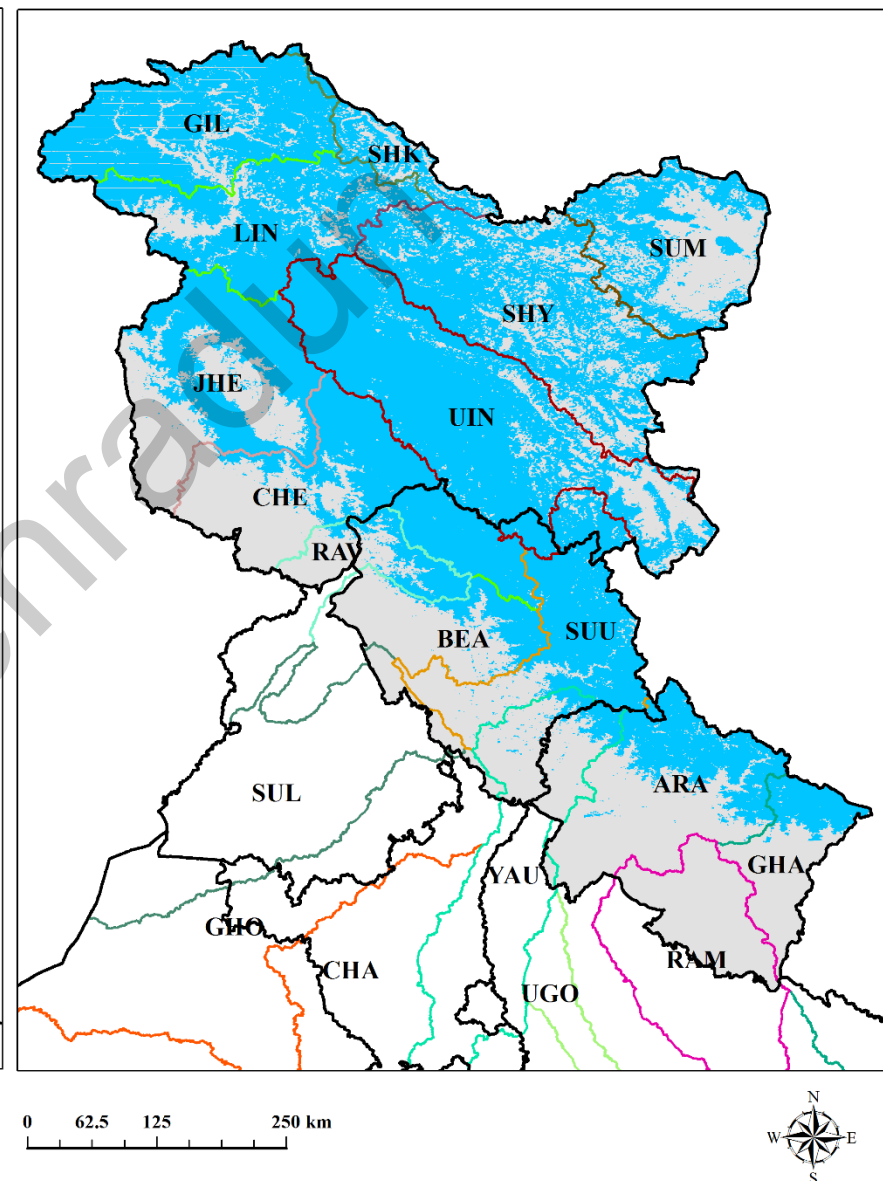
**Fig. 6.** Maximum SCA fraction in each sub-basin and the date of occurrence of Max. SCA in winter season of



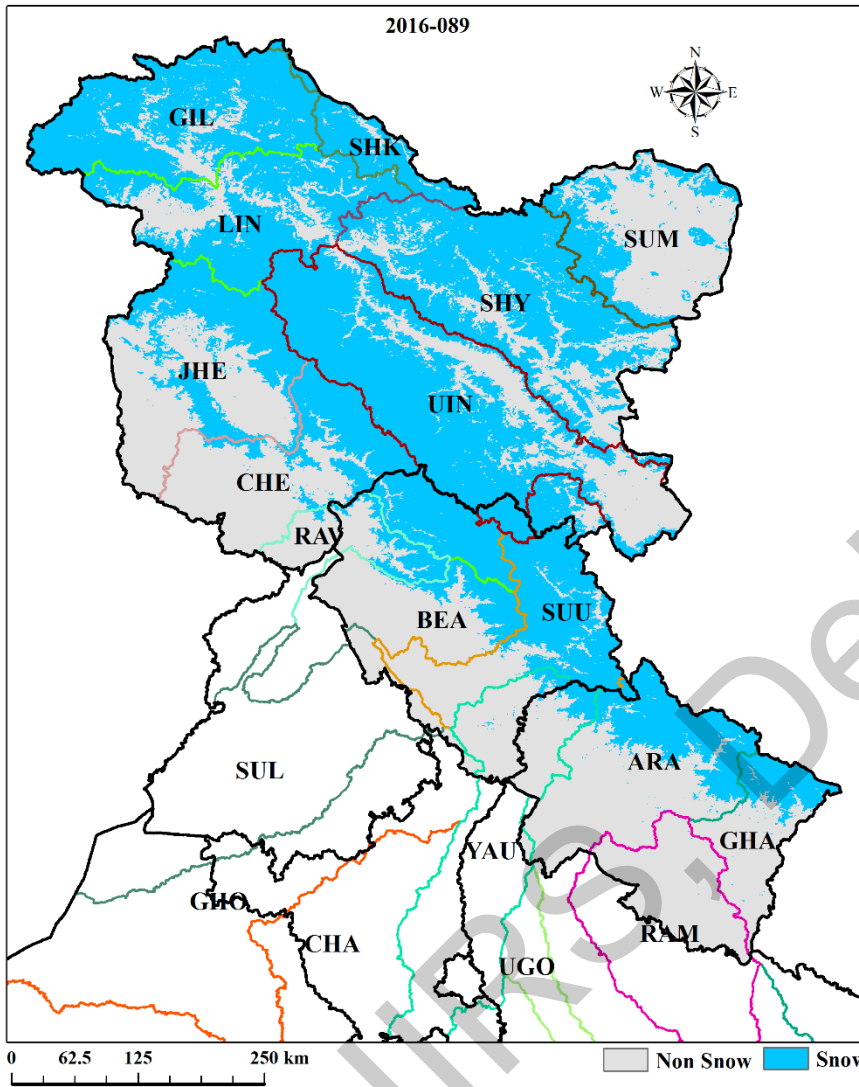
**Fig. 7.** SCA fraction in each sub-basin in winter season of 2015-16 on same dates on which Max. SCA occurred in winter seasons of 2016-17



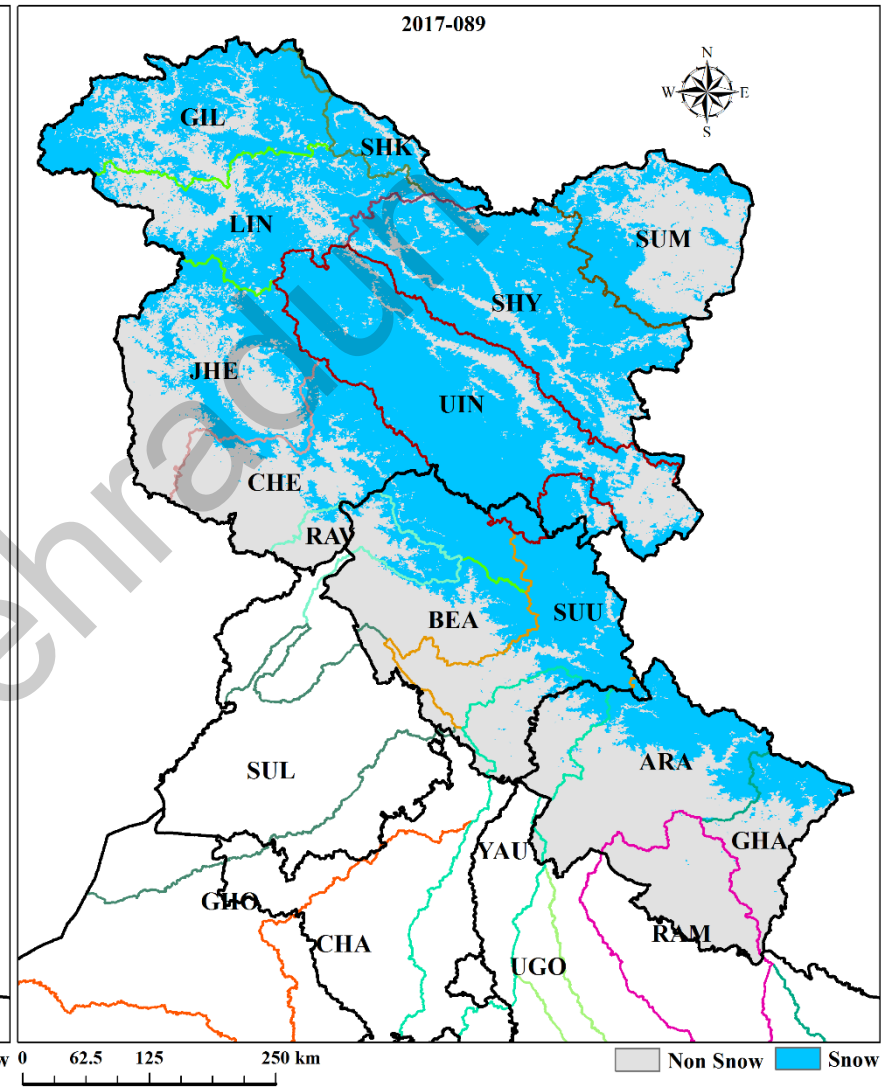
**Fig. 8.** SCA in 1<sup>st</sup> Week of March 2016



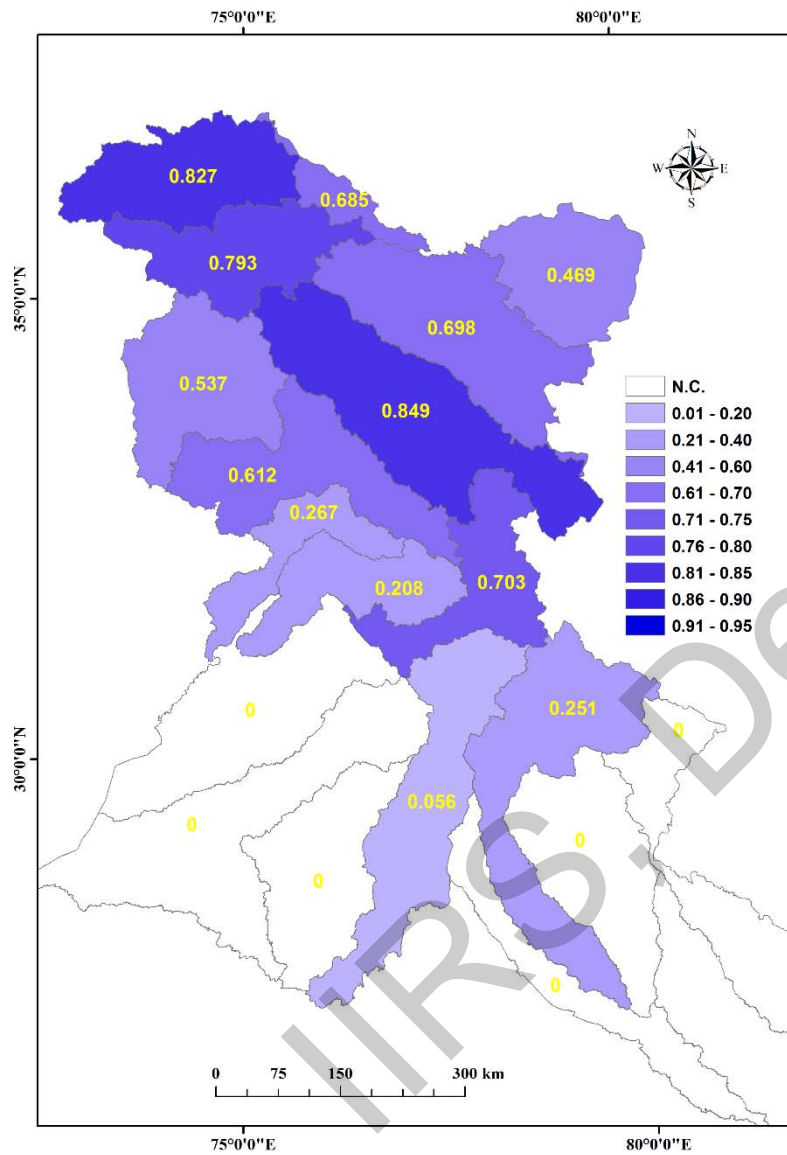
**Fig. 9.** SCA in First Week of March 2017 (average 10% increase in SCA has been observed in NWH)



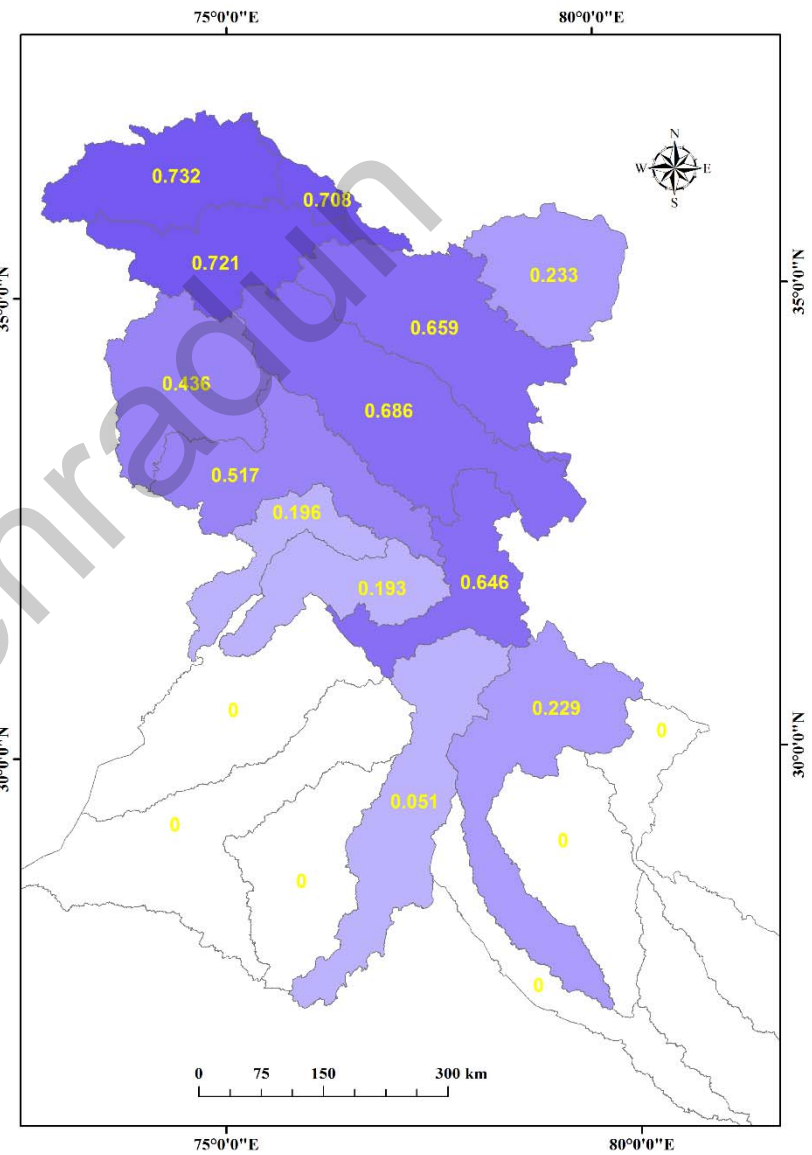
**Fig. 10.** SCA in 1<sup>st</sup> Week of April 2016



**Fig. 11.** SCA in First Week of April 2017



**Fig. 12.** Status of SCA fraction in each sub-basin in 1<sup>st</sup> week of March 2017



**Fig. 13.** Status of SCA fraction in each sub-basin 1<sup>st</sup> week of March 2016

### **Further Scope of Work**

This work will be continued for entire NWH with MODIS and AWIFS data and new SCA products from Suomi-NPP (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) snow cover algorithm (Hall et al 2015) will be used to improve SCA estimates mainly in spatial due to its higher (365 m as compared to 500m for MODIS). Additionally, Synthetic Aperture Radar (SAR) data can provide SCA especially during wet snow time (Thakur et al, 2012, 2016). Therefore, SAR data from RISAT-1 and Sentinel-1/2 can be used to map SCA in areas affected by persistent cloud cover and during melt season.

## **5. Implications of High SCA**

Heavy snowfall in NWH leading to higher SCA in spring season increases the probability of flash floods, landslide, sudden increase in river flow and associated hazards in the region. It is expected that, the increased SCA, snow depth will produce higher snow melt/discharge during upcoming spring and summer season in these sub-basins. This will require proper planning including hydrologic forecast will lead to increase in hydropower generation, reservoir storage and other associated activities. These aspects can be studied in detail with the help of suitable hydrological models if hydro-meteorological data, snow depth, snow water equivalent, snow density, baseline topographical data, location of water resources projects, etc., of NWH region are made available.

It is therefore, suggested that the administrator, policy planner and local government must initiate local scale studies especially as hydropower and reservoir operations are planned using ten day river flow forecast.

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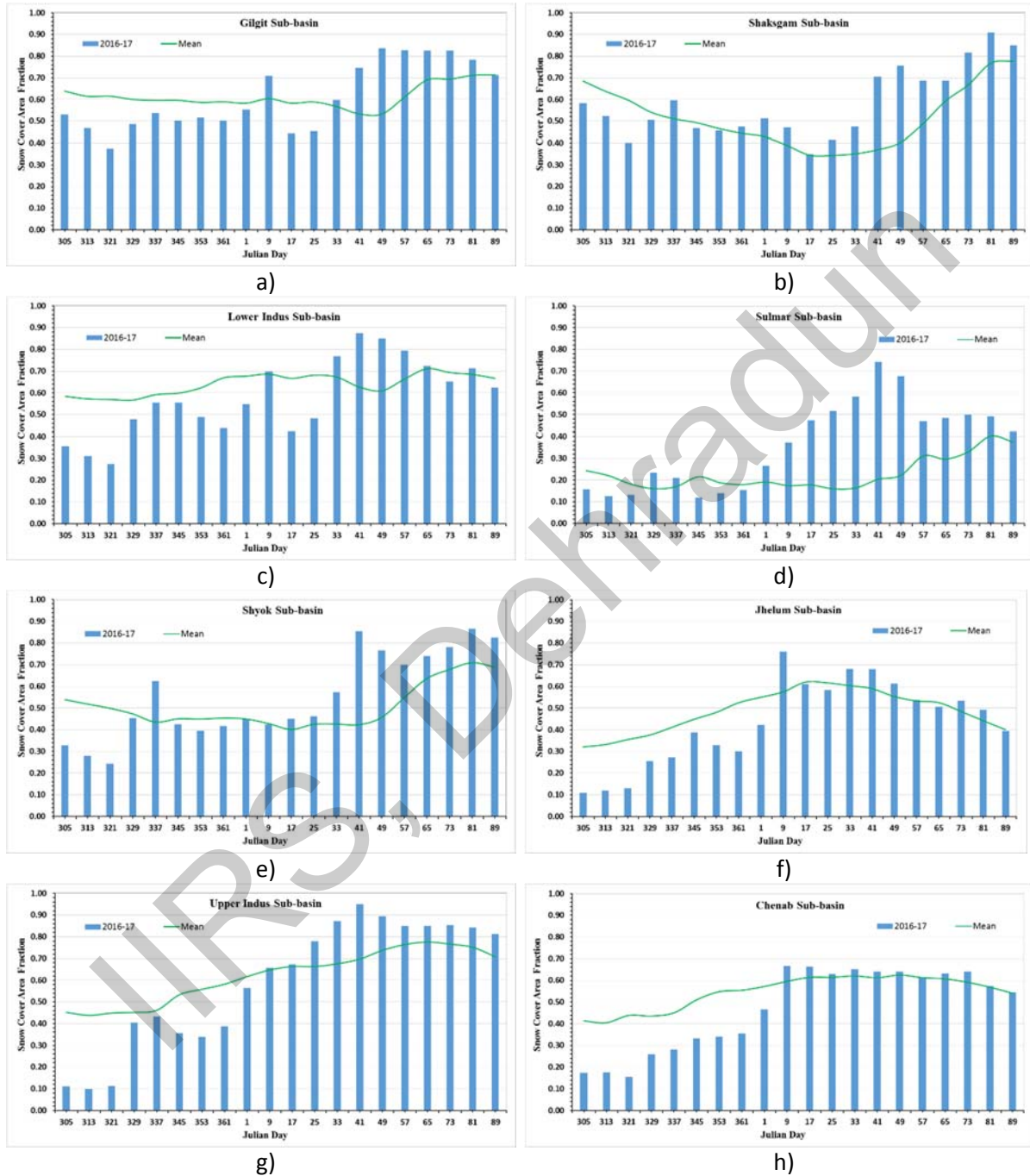
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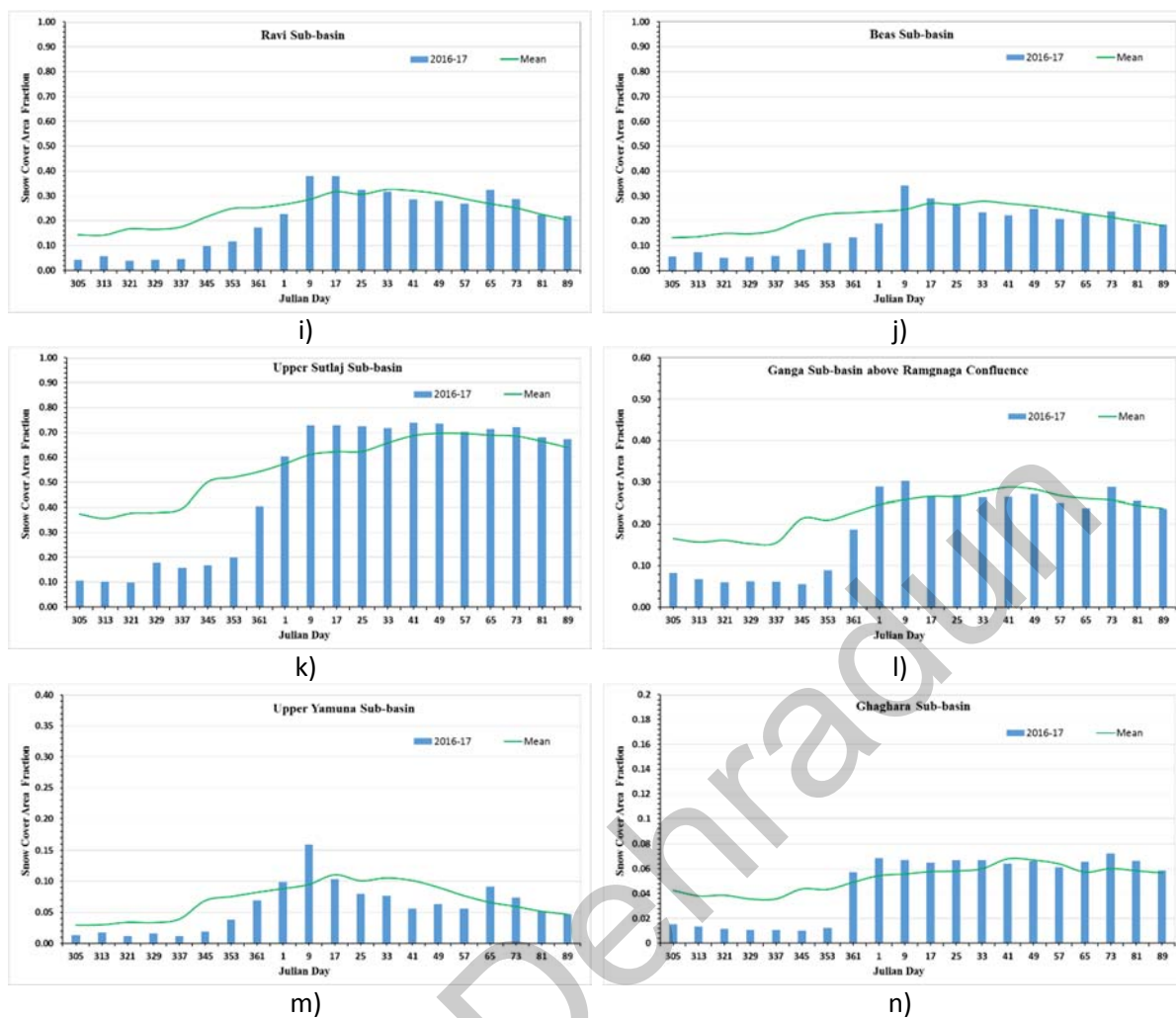
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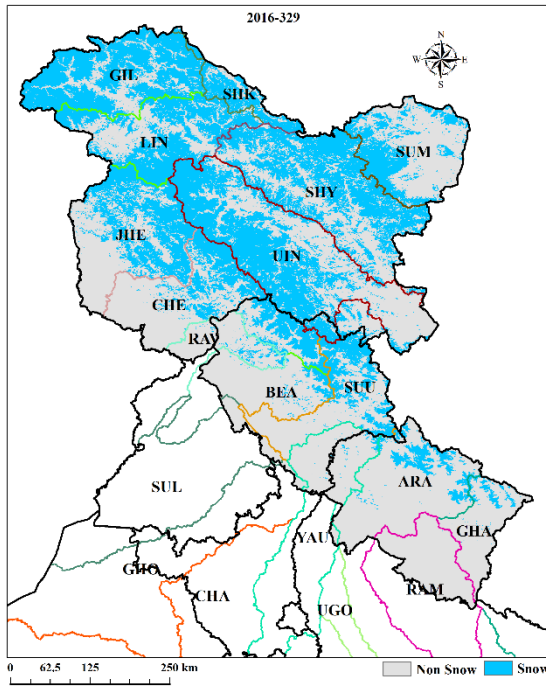
## Appendix – I

Weekly maximum fractional snow cover area in all the major sub-basins of NWH compared against the long-term mean fractional SCA of same week.

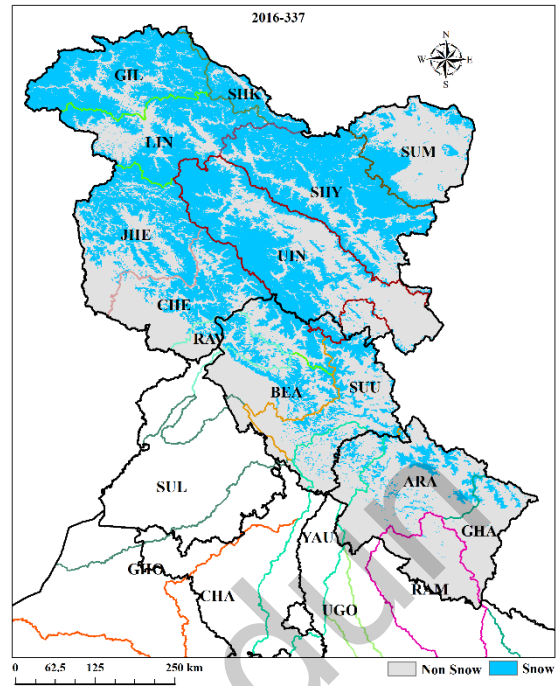




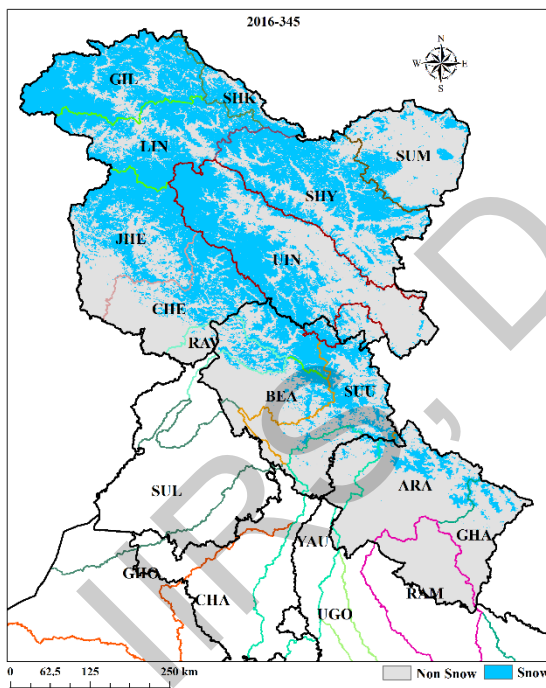
**Figure A1 :** Snow cover area (SCA) of different sub-basin in the winter season of 2016-17 compared with long-term mean SCA and SCA of winter season of 2015-16



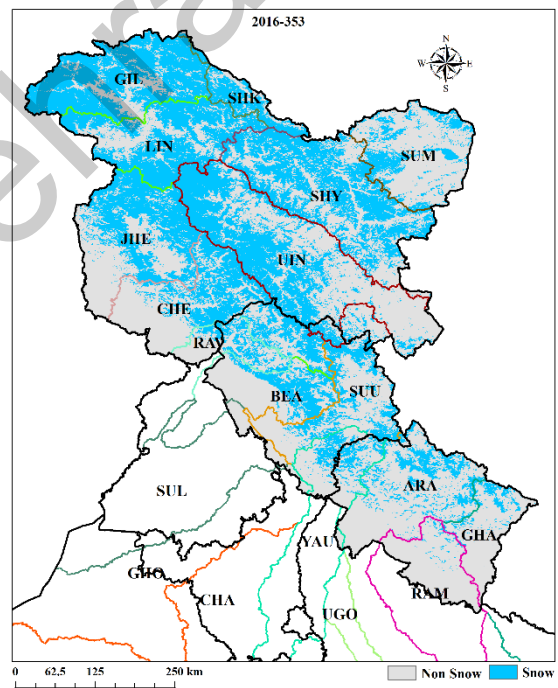
Max. SCA during Nov. 25–Dec. 02, 2016



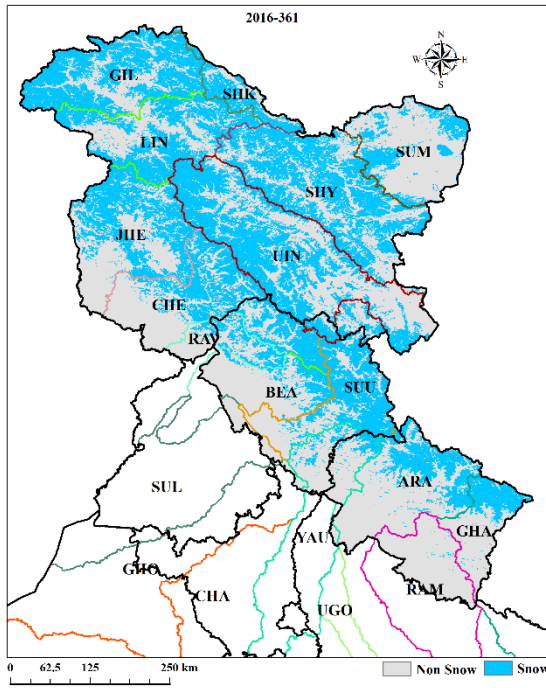
Max. SCA during Dec. 03–10, 2016



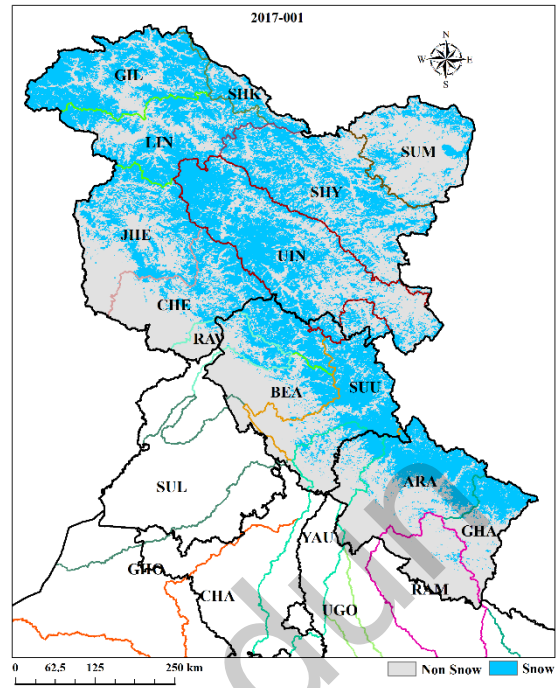
Max. SCA during Dec. 11–18, 2016



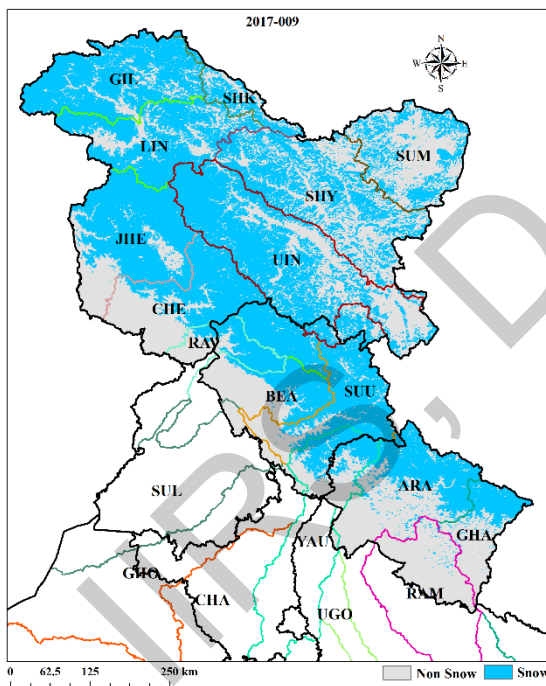
Max. SCA during Dec. 19–26, 2016



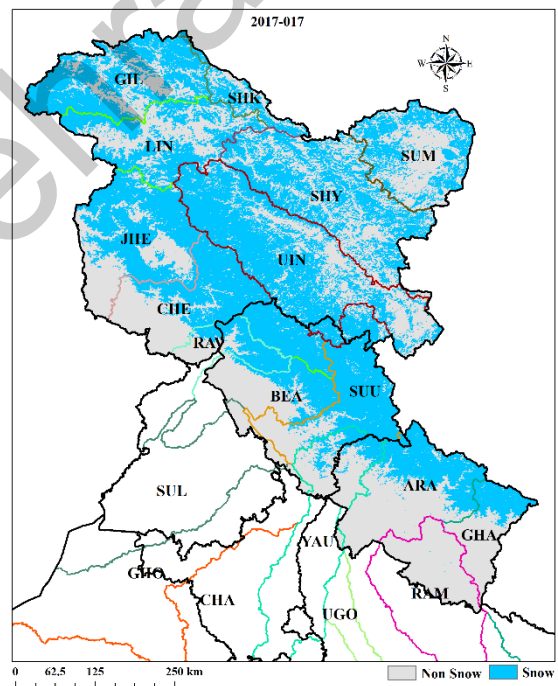
Max. SCA during Dec. 27-31, 2016



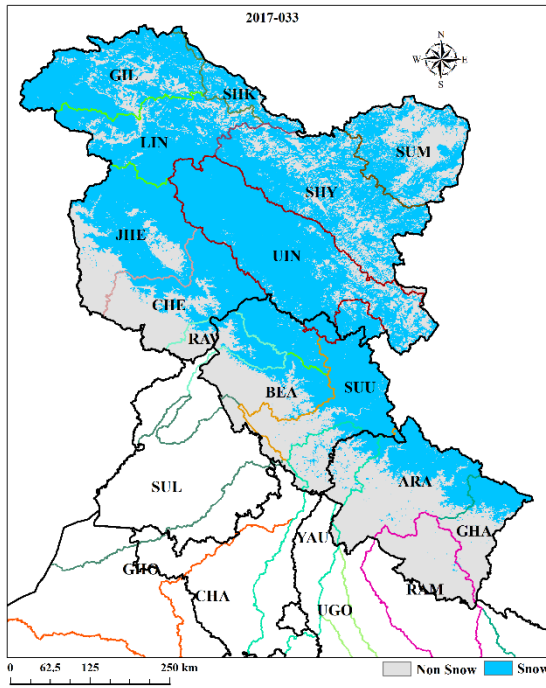
Max. SCA during Jan. 01-08, 2017



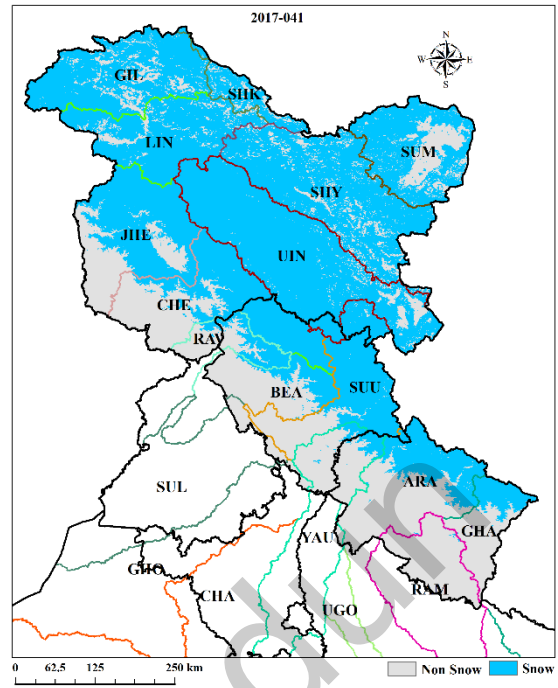
Max. SCA during Jan. 09-16, 2017



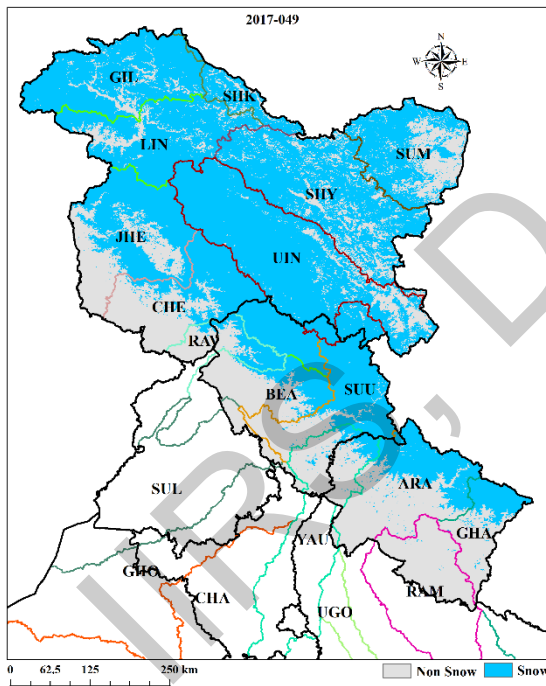
Max. SCA during Jan. 17-24, 2017



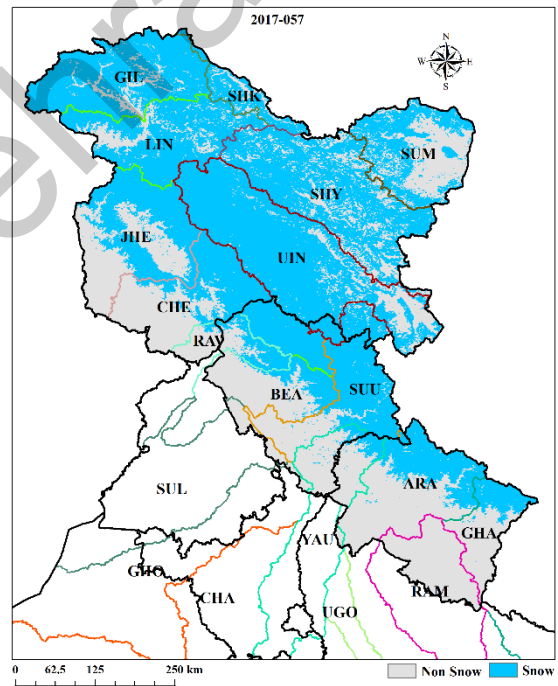
Max. SCA during Feb. 02-09, 2017



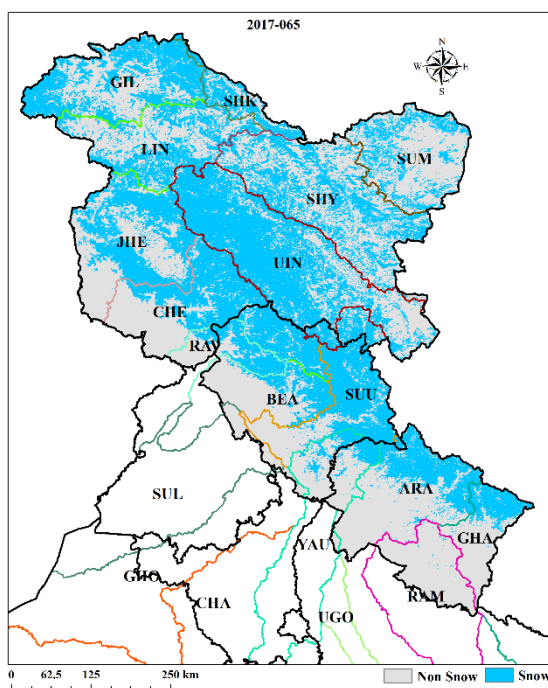
Max. SCA during Feb. 10-17, 2017



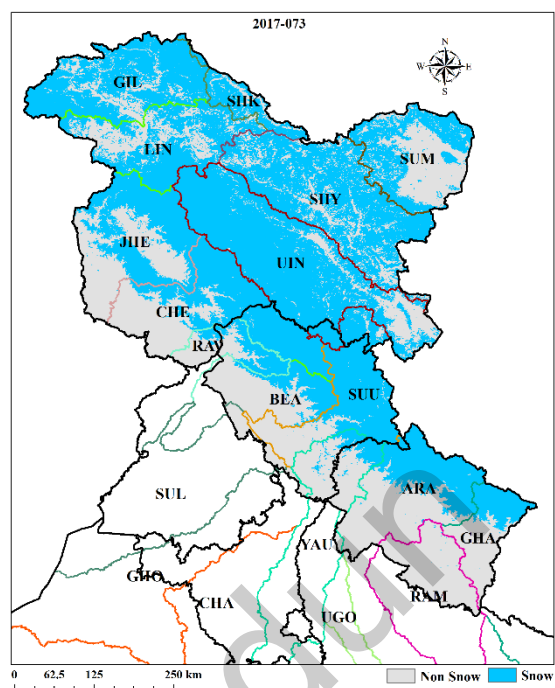
Max. SCA during Feb 18-25, 2017



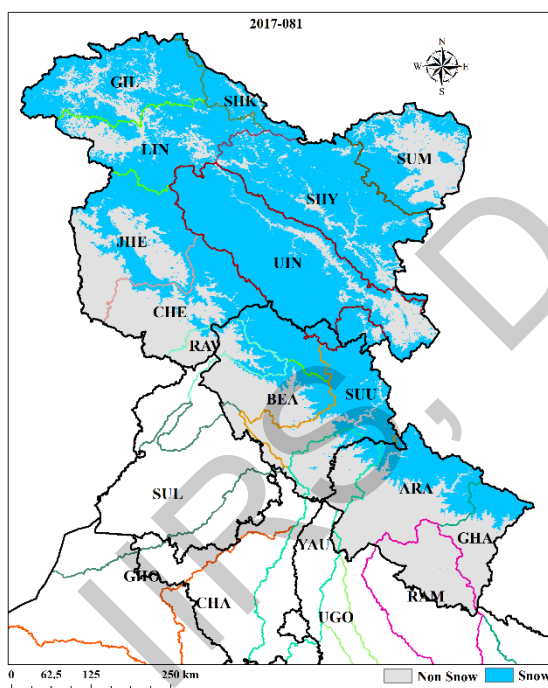
Max. SCA during Feb 26 - March 04, 2017



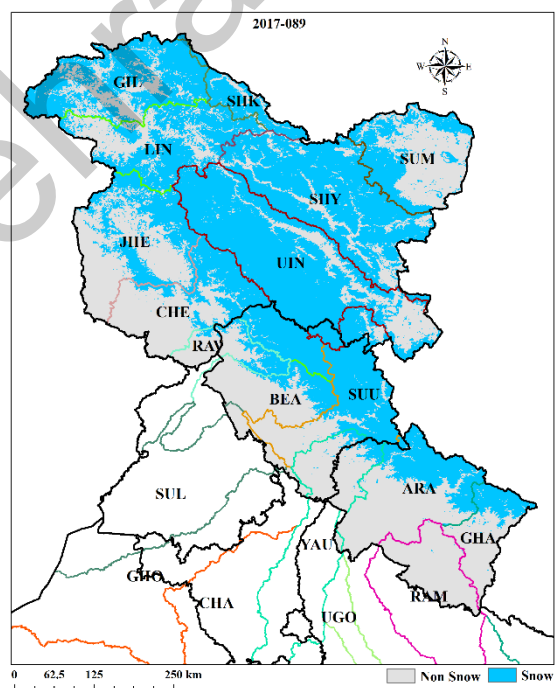
Max. SCA during March 05-12, 2017



Max. SCA during March 13-20, 2017



Max. SCA during March 21-28, 2017



Max. SCA during March 29- April 04, 2017

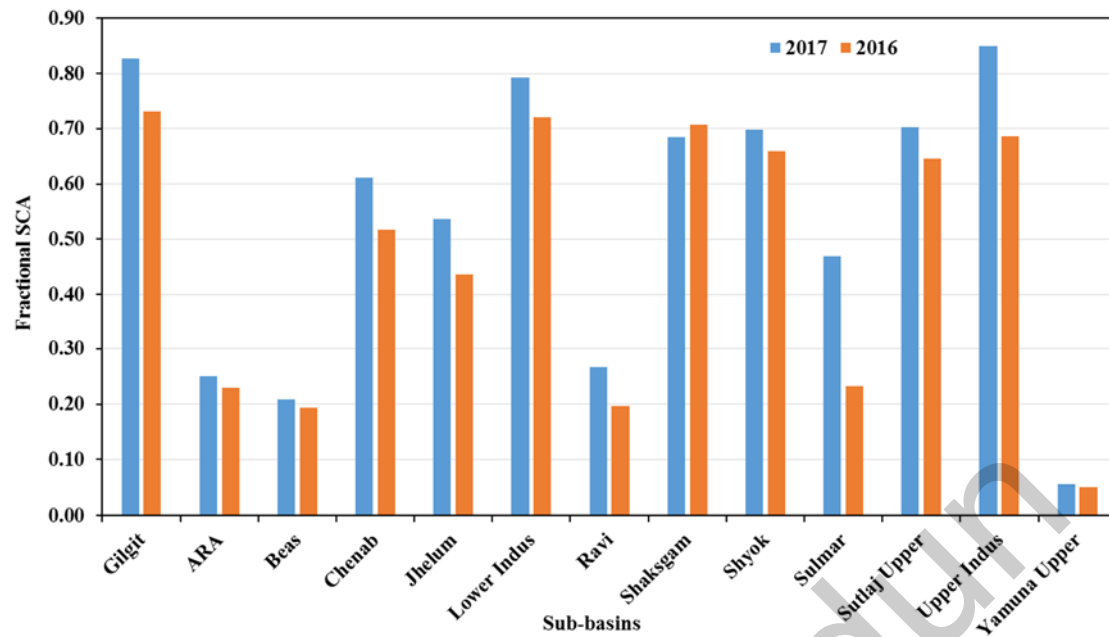
**Figure A2 :** Snow cover area (SCA) in NWH mapped using MODIS data for the winter season of 2016-17

**Table A1:** Maximum SCA fraction occurred in majority sub-basins using winter season of 2016-17 along with data of occurrence of maximum SCA

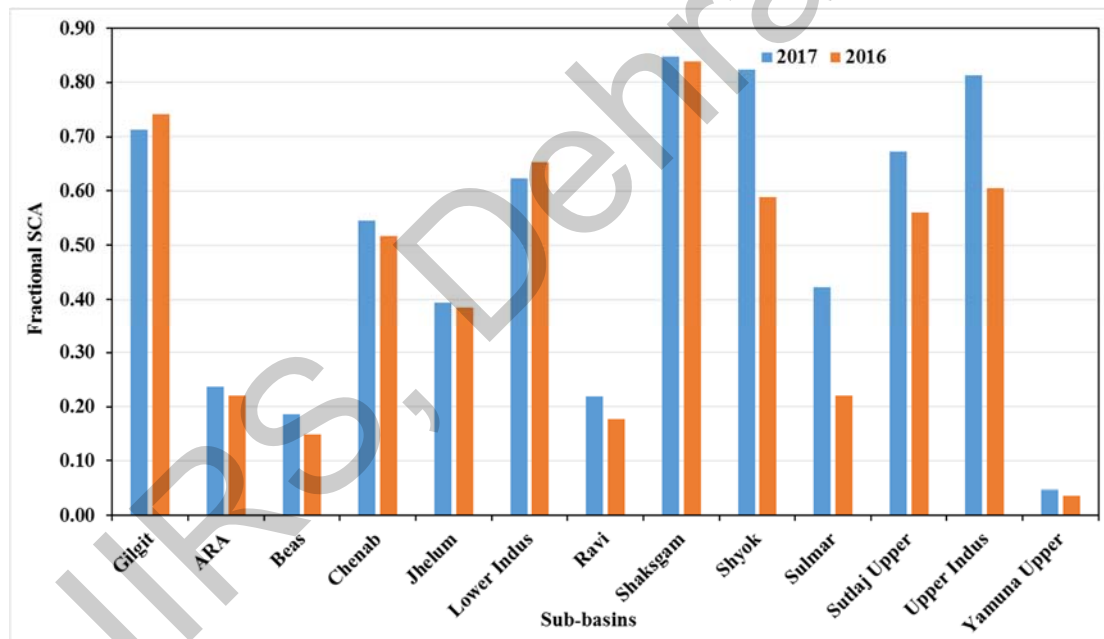
Basin Name	Date of Max SCA	Max. SCA Fraction in winter 2016-17	SCA on same date in 2015-16	Percent difference between a & b
		(a)	(b)	
<b>Gilgit</b>	18-02-17	0.836	0.725	11.11
<b>ARA</b>	09-01-17	0.304	0.2433	6.07
<b>Beas</b>	09-01-17	0.343	0.253	9
<b>Chenab</b>	09-01-17	0.667	0.588	7.9
<b>Jhelum</b>	09-01-17	0.762	0.529	23.3
<b>Lower Indus</b>	10-02-17	0.875	0.701	17.4
<b>Ravi</b>	17-01-17	0.38	0.26	12
<b>Shaksgam</b>	18-02-17	0.755	0.658	9.7
<b>Shyok</b>	10-02-17	0.853	0.539	31.4
<b>Sulmar</b>	10-02-17	0.742	0.176	56.6
<b>Sutlaj Upper</b>	10-02-17	0.738	0.656	8.2
<b>Upper Indus</b>	10-02-17	0.95	0.647	30.3
<b>Yamuna Upper</b>	09-01-17	0.159	0.074	8.5

**Table A2:** Maximum SCA fraction occurred in majority sub-basins using winter season of 2016-17 along with data of occurrence of maximum SCA

Basin Name	SCA Status in first week of March in year		Percent increase in SCA in early spring season in year 2017 with reference to 2016
	2017	2016	
<b>Gilgit</b>	0.827	0.732	9.5
<b>ARA</b>	0.251	0.229	2.2
<b>Beas</b>	0.208	0.193	1.5
<b>Chenab</b>	0.612	0.517	9.5
<b>Jhelum</b>	0.537	0.436	10.1
<b>Lower Indus</b>	0.793	0.721	7.2
<b>Ravi</b>	0.267	0.196	7.1
<b>Shaksgam</b>	0.685	0.708	-2.3
<b>Shyok</b>	0.698	0.659	3.9
<b>Sulmar</b>	0.469	0.233	23.6
<b>Sutlaj Upper</b>	0.703	0.646	5.7
<b>Upper Indus</b>	0.849	0.686	16.3



**Figure A3 a).** Status of SCA in early spring season of 2017 (1<sup>st</sup> week of March) compared with SCA fraction of same time period in year 2016.



**Figure A3 b).** Status of SCA in 1<sup>st</sup> week of April 2017 compared with SCA fraction of same time period in year 2016.