MAPPING OF LONG-TERM SNOW COVER AREA VARIABILITY AND ITS CURRENT STATUS (2016-17) IN NORTH WESTERN HIMALAYAN RIVER BASINS USING REMOTE SENSING

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ABSTRACT: Snow cover is one of the most important land surface parameters in global water and energy cycle. Large area of North West Himalaya (NWH) receives precipitation mostly in form of snow. The major share of discharge in rivers of NWH comes from snow and glacier melt. The hydrological models used to quantify this runoff contribution uses snow covered area (SCA) along with hydro-meteorological data as essential inputs. In this context, information about SCA is essential for water resource management in NWH region. Regular mapping and monitoring of snow cover by traditional means is very difficult due to scanty snow gauges, inaccessible terrain. Remote sensing has proven its capability of mapping and monitoring snow cover and glacier extents in those area with high spatial and temporal resolution. In this study, 8-day snow cover products from MODIS, and 15-daily snow cover fraction product from AWiFS were used to generate long term SCA maps (2000-2017) for entire NWH region. The variability of 8-daily SCA and its current status has been analysed. The problem of persistent cloud cover in the snow cover products of MODIS was resolved using an innovative two tier Geo-Spatial-Temporal approach (GSTA). The SCA mapped through GSTA has been validated using AWiFS derived SCA. The current status analysis of SCA has indicated that the SCA of 2016-17 has broken all the past records of extent of snow cover in most of the river basins of NWH. In 2nd week of February 2017, around 67% of NWH region was snow covered. The comparison of SCA during 1st week of March and April in year 2016-17 against 2015-16 indicate 7.3% and 6.5%, increased SCA in current year. This increased SCA may increase the snow melt contribution to the basins in early- and mid-spring, which may also lead to increased risk of hydro-meteorological disasters.

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 Himalaya (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; Li et al., 2017; Nikam et al., 2017b; Shukla et al., 2017).

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 in Green and SWIR bands, respectively. Snow is normally assumed to be present if the NDSI exceeds a value of 0.4 (Dozier, 1984, Dozier and Frew, 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 data from 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. MODIS 8-day maximum snow cover product, MOD10A2 (Dorothy et al., 2001) has been used in this study to map and monitor SCA in entire NWH region for the period from 2000 to 2017. In addition, 15 daily 3 Arc minute spatial resolution fractional snow cover product (Subramaniam and Suresh Babu, 2014), generated by National Remote Sensing Centre (NRSC), using multi-spectral and temporal data from AWiFS sensor on-board Resourcesat 1/2, has been used in the present study for SCA mapping of NWH during 2014-2017 and validation of MODIS derived SCA.

1.2. Impetus

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, as shown in Figs. 1, are selected as study area in the present study. Seasonal variations in the SCA 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.

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 easily be monitor and mapped using space based remote sensing data. Hence, in the present study an attempt has been made to map and analyse long-term SCA of all the sub-basins of NWH using MODIS and AWiFS derived snow cover products. The comparison of SCA of winter season 2016-17 with long-term 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 study, the long-term MODIS snow cover products (MOD10A2, https://nsidc.org/data/MOD10A2) has been analysed using automated SCA extraction tool developed in-house based on an innovative two tier Geo-Spatial-Temporal approach (GSTA). 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* (*https://bhuvan.nrsc.gov.in*), have also been used in the present study to estimate total area under snow in each sub-basin in recent years (March 2014 to February 2017) and to validate the MODIS derived SCA results. The basin boundaries of all the NWH basins have been referred from India Water Resources Information System (IWRIS, *http://www.india-wris.nrsc.gov.in/wris.html*). Only 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., 2002). 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 snow covered pixels are denoted by a constant value (200), 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. Manual rectification of snow-covered area 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, based on an innovative two tier Geo-Spatial-Temporal approach (GSTA), using Interactive Data Language (IDL). The developed tool has been implemented in the present study to generate temporal SCA maps of NWH region using long-term MODIS maximum snow cover products (MOD10A2). The tool works on two tier Geo-Spatial-Temporal approach in which it initially generates a permanent snow cover map based on frequency analysis of the pixel as snow covered considering all the long-term snow cover datasets available. In the second run the tool analyses 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) (Nikam et al., 2017 a, b). Elevation mask of 1500 m has been used in this approach/tool, based on standard literature (Jain et al., 2008; Sharma et al., 2014), 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 and the results are used to validate the MODIS derived SCA.

3.2. Sub-Basin wise SCA Analysis

The sub-basin wise temporal SCA has been derived using histogram extraction tool developed in house using Interactive Data Language (Nikam et al., 2017 a, b). The sub-basin boundaries of NWH region have been taken from IWRIS demarcated by Central Water Commission (CWC), as shown in Figure 1. The SCA has been reported in terms of fractional area (SCA/basin area) for better representation and are discussed at weekly time scale. 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 (SCA_{max}) in winter season of 2016-17 has been identified for each sub-basin along with the time of occurrence of the SCA_{max}. The SCA on same dates in previous winter season were used to highlight the difference (increase) in SCA during winter 2016-17. Additionally, to analysis the status of SCA in early spring season of 2017, the comparison of fractional SCA between 1st 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.

3.3. 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, 2013, 2016). Therefore, SAR data from RISAT-1 and Sentinal-1/2 can be used to map SCA in areas affected by persistent cloud cover and during melt season.

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 Figure 2 highlights the 8-day maximum SCA during 2nd week of February 2017 having around 64% of total area under snow. To validate the SCA mapped using MODIS data products, the SCA derived from AWiFS products and MOD10A2 products for the period of January 2017 to March 2017 were compared and 0.9 coefficient of determination was achieved in this comparison (Nikam et al., 2017b). The detailed analysis of fractional SCA (Figure. 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 Figure 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 Figure 4. The figure shows significant increase in snow depth (1 to 1.5 m) during 1st week of January, 2nd week of February and 1st 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 Figures 3 & 5.

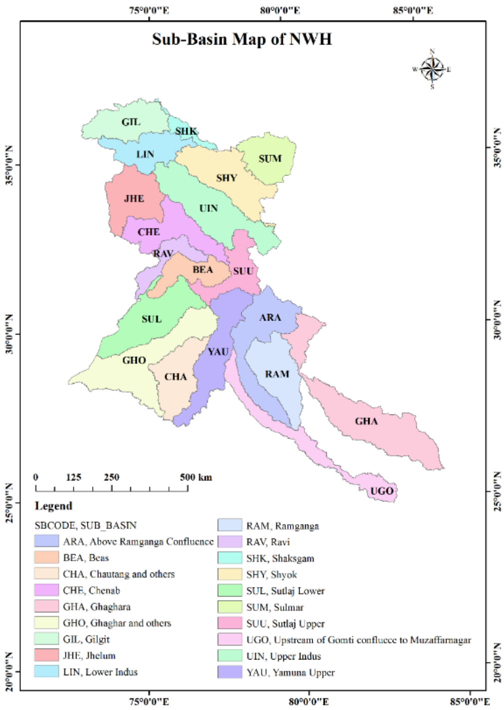

Figure 1. Sub-basin map of NWH

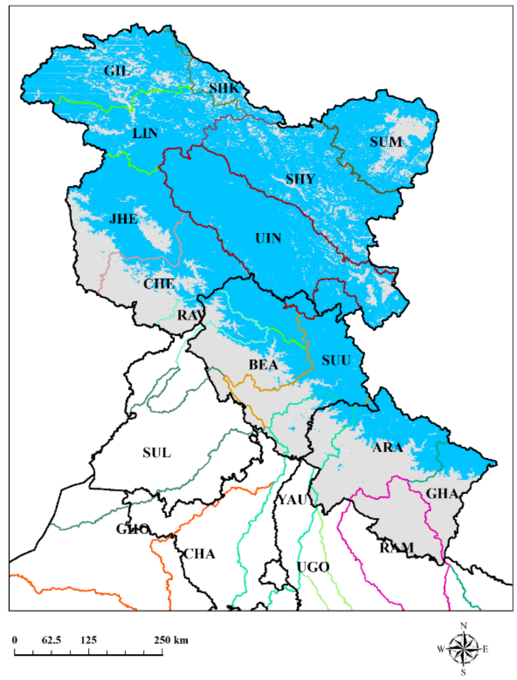

Figure 2. Eight day maximum SCA in 2nd week of February 2017 derived from MOD10A2

Table 1 highlights 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 2nd week of January, 2nd and 3rd weeks of February. The maximum fractional SCA values in Upper Ganga, Beas, Chenab and Jhelum sub-basins has occurred during 2nd 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 2nd week of February 2017, ranging from 0.73 to 0.95. Whereas, the max SCA in Gilgit & Shaksgam sub-basins was noticed in 3rd week of February 2017, with value varies from 0.75 to 0.84. The SCA of these sub-basins in same time period in 2015-16 is also given in Table 1. 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 6 & 7 shows the comparative SCA maps of NWH highlighting increased SCA even in lower altitude regions. The sub-basin wise fractional SCA for 1st week of March 2017 and 2016 are also depicted in Figure 8 & 9, respectively. The average increase of 08% (approx.) was observed in SCA during 1st week of March 2017 as compared to 2016. Further details of this analysis and all the Basin wise SCA maps can be found at Nikam et al. (2017 a) (*https://iirs.gov.in/content/sca-mapping-activity*).

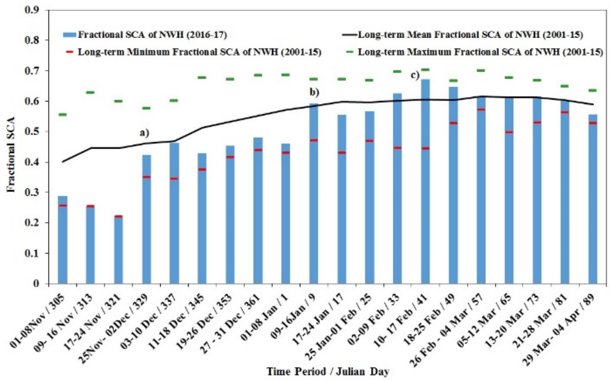

Figure 3. Comparison of fractional snow cover in NWH (source: Nikam et al., 2017 b)

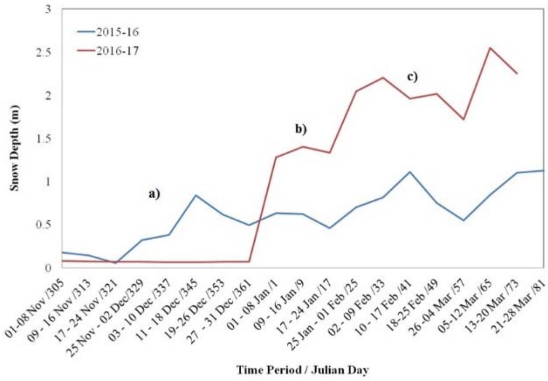

Figure 4. Observed Snow depths at Dhundi, Manali (source: Nikam et al.,

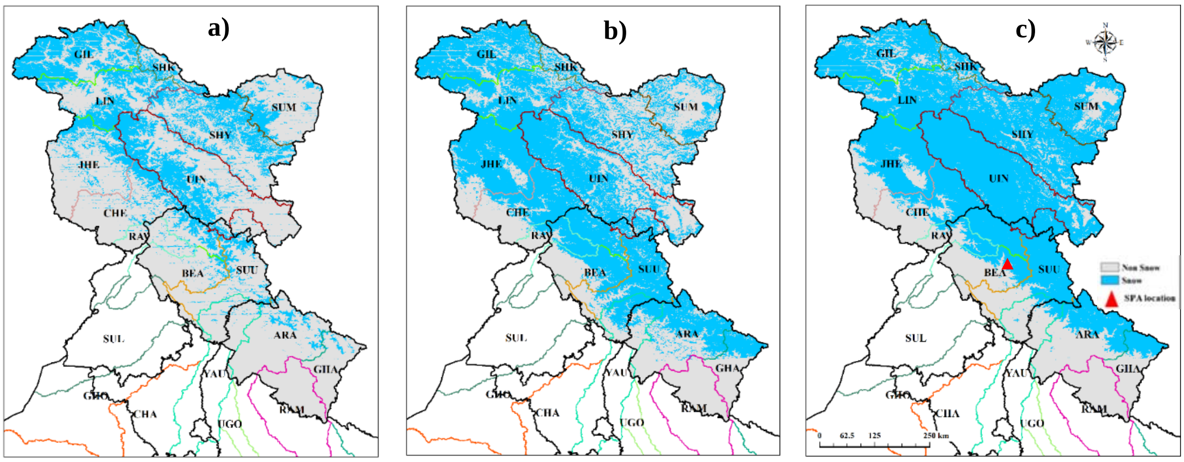

Figure 5. Temporal change in SCA during winter 2016-17 **a)** 25 Nov.- 02Dec. 2016, **b)** 09-16 Jan. 2017, **c)**10-17 Feb. 2017

Table 1: 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 (a)**	**SCA on same date in 2015-16 (b)**	**Percent difference between a & b**
Gilgit	18-02-17	0.836	0.725	11.11
ARA	09-01-17	0.304	0.2433	6.07
Beas	09-01-17	0.343	0.253	9
Chenab	09-01-17	0.667	0.588	7.9
Jhelum	09-01-17	0.762	0.529	23.3
Lower Indus	10-02-17	0.875	0.701	17.4
Ravi	17-01-17	0.38	0.26	12
Shaksgam	18-02-17	0.755	0.658	9.7
Shyok	10-02-17	0.853	0.539	31.4
Sulmar	10-02-17	0.742	0.176	56.6
Sutlaj Upper	10-02-17	0.738	0.656	8.2
Upper Indus	10-02-17	0.95	0.647	30.3
Yamuna Upper	09-01-17	0.159	0.074	8.5

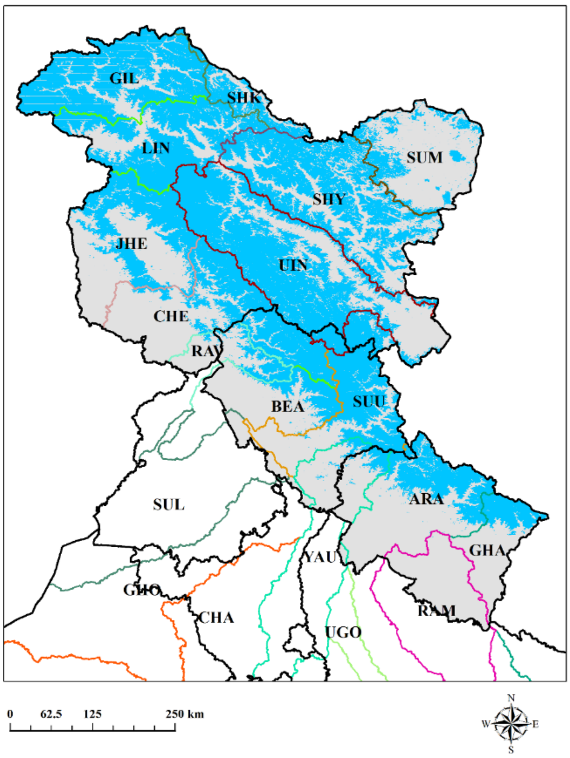

Figure 6. SCA in 1st Week of March 2016

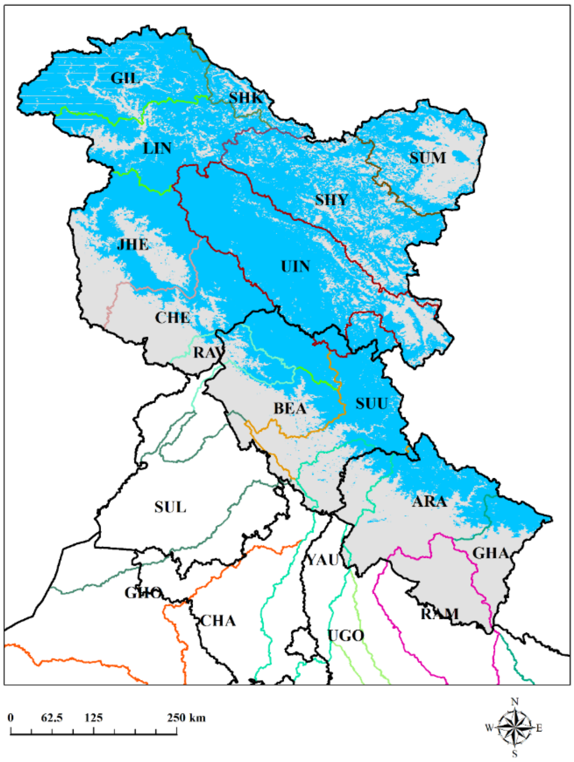

Figure 7. SCA in 1st Week of March 2017 (average 10% increase in SCA has been observed in NWH)

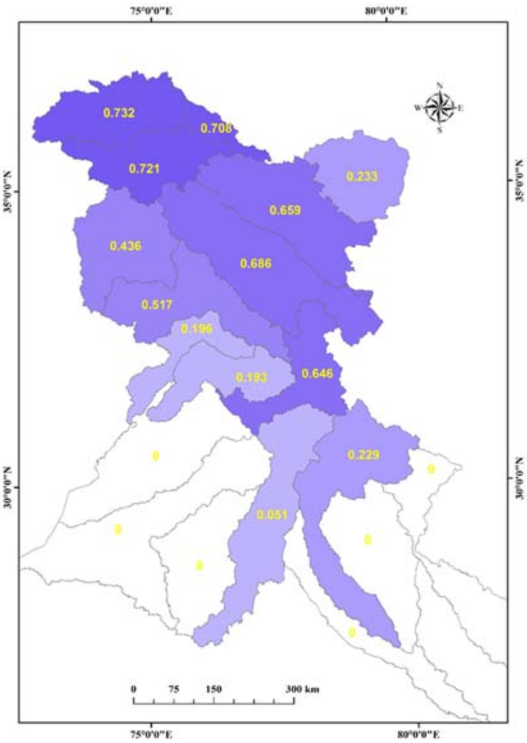

Figure 8. Status of SCA fraction in each sub-basin 1st week of March 2016

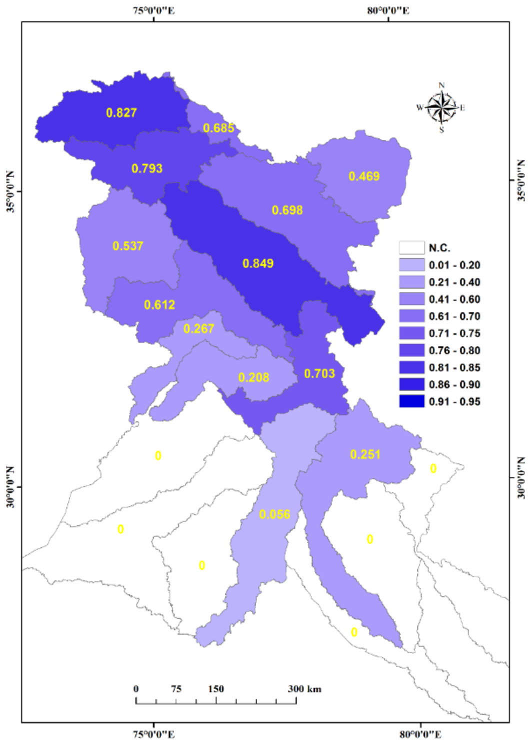

Figure 9. Status of SCA fraction in each sub-basin in 1st week of March 2017

5. CONCLUSIONS

The present study was dedicated towards development of an operational system for continuous snow cover area maps for entire North Western Himalayan region. Eight day maximum snow cover product of MODIS (MOD10A2) and fraction snow cover products of AWiFS have been used in the present study to map weekly snow cover area in all the sub-basin of NWH. The problem of cloud cover has been eliminated using two tier Geo-Spatial-Temporal approach (GSTA). An interactive tool has been developed for processing long-term MODIS data products to derive SCA maps. The SCA results derived from MODIS data were validated using fractional snow cover estimates for AWiFS products and 0.9 coefficient of determination was achieved in this comparison. The long-term spatial statistics of SCA in each sub-basin has been analysed. At NWH scale 20% increase in SCA during winter season of 2016-17 has been observed, especially in the months of January to April 2017 as compared to previous year. Further, comparison of SCA during 1st week of March and April in year 2016-17 against 2015-16 indicate 7.3% and 6.5%, increased SCA in year 2016-17.

6. 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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