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# Snow Cover and Snowline Variation in Relation to Land Surface Temperature in Spiti Valley, Himachal Pradesh, India

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## ABSTRACT

Spiti Valley, a cold desert mountain is located in the Trans Himalaya region where snow cover is a dominant type of land cover. Characterized, as a rain shadow area where precipitation occurs in the form of snowfall and almost negligible rainfall. Snow/glacier melt water is a single source of freshwater which is used in agricultural and household activities by mountain dwellers. The objective of the study is to determine the effects of Land Surface Temperature (LST) on snow cover and snow line position in Spiti Valley. The study is based on geospatial techniques in which Landsat imagery is the main source of data for snow cover, snow line position, and Land Surface Temperature (LST) analysis. It includes Operational Land Imager/Thermal Infrared Sensor (OLI / TIRS) and Thematic Mapper (TM) scenes of all the twelve months (January to December) of 1990 and 2015. Snow cover was extracted from January to December; using Normalised Difference Snow Index (NDSI). As per the result, the average snow cover was 4, 68,998.50 ha (61.68%) in 1990 and 3, 69,676.4 ha (48.71%) in 2015. Approximately 98,422.08 ha (0.51%) of snow cover was converted into a non-snow cover area at an average rate of 3,937 ha/year. Analysis of the altitudinal position of the snow line indicates that it moved 445.11 m upwards in Spiti Valley during the study period. In 1990, the snow line was visible at the height of 5,159.37 m at the end of the summer, but reached at 5,604.48 m height in 2015, marking the loss of snow accumulation in the lower heights. In addition, Land Surface Temperature (LST) was calculated to examine the impact on snow cover where the mean LST of snow cover was -3°C in 1990 and -2°C in 2015, indicating that the temperature increased by 1°C in the last 25 years. The Karl Pearson correlation method was used to establish the relationship between LST and NDSI. It shows a negative relationship with strong correlation coefficients of $R^2$ 0.9,416 and 0.9,684 in 1990 and 2015. It indicates that LST and snow cover have a negative relationship with respect to the physical changes in the soil, emissivity of the land surface and the albedo of the region. The impact of declining snow cover can be easily understood by a simple cause-and-effect relationship where most of the people are engaged in the primary sector such as farming, growing orchards, and animal husbandry. As per the primary survey, most of the people felt that the availability of water in the study area decreases in the late summer season which leads to water scarcity.

**Key words**: Landsat, Snow cover, NDSI, Snowline, Spiti valley

## INTRODUCTION

Snow cover is a characteristic feature of high altitude region, especially in the Himalayan mountain ranges, which is least accessible to human beings owing to its rugged terrain. It is one of the most important type of land cover, which acts as an important source of freshwater for streams and rivers (Kulkarni 2007). It is an essential part of the cryosphere. The spatial and temporal variability of snow cover over the greater Himalayan region is important for climate change study, regional and global energy balances, aquatic cycles, and resource management etc. Snow is involved in many types of hydrological processes which are treated differently, even in the form of precipitation when it falls to the surface and flows in the form of water and feeds the groundwater. Accumulated snow begins to melt after the end of winter, resulting in a longer melting period. There is generally little or no snowmelt during the accumulation period. Precipitation falls as snow is temporarily stored in the snowpack until the beginning of the melt season (Engman and Gurney 1991).

The western Himalaya is known for higher snow cover because of higher average elevation combined with the influence of winter westerly winds (Bookhangen and Burbank 2010). The timing of the snow cover peak varies due to the influence of different weather systems (Kriplani et al. 2003). The maximum snow cover in the Kashmir valley is recorded in February (Negi et al. 2009), while in the Bapsa basin in Himachal Pradesh, it is identical to that observed at the end of March. The variation in seasonal snow cover also significantly affects the height of the snow line position. The extent and duration of snow cover determines the length of the growing season for shrubs and lichens and influences the availability of water for agriculture and plants later in the summer.

According to Kulkarni et al. (2007), snow cover of the Himalaya has a direct impact on the socio-economic development of the states of northern India and its society. It also controls the thermal regime of the soil and snowmelt dominates the hydrological regime of the northern rivers (Koster 1991).

Land Surface Temperature (LST) is radiative skin temperature of the land surface, obtained from top-of-atmosphere brightness temperatures from infrared spectral channels of a constellation of geostationary satellites. LST is emerging as one of the powerful tools for monitoring temporal change in heat of the earth surface. It has become a serious environmental issue (Sahoo et al. 2016). It is related to the physical process of surface energy and depending upon different Land Use and Land Cover (LULC).

The main objective of the study is to determine the effects of LST on snow cover and snow line position in Spiti Valley. Where LST has direct/indirect effects on snow cover, an increase in LST enhanced snowmelt rate by releasing stored heat from the earth's surface. As per the study, snow cover has declined in significant proportion during the study period which leads to an upward shift in snowline position.

Spiti Valley is made by sedimentary rocks which are susceptible to rainfall, where precipitation occurs in the form of snowfall and rainfall is almost negligible. Nowadays, precipitation has started occurring in the form of rainfall due to a change in regional climatic condition and an increase in the vegetation cover (Pankaj et al. 2018). In the short run, increasing vegetation cover would be a good sign for the valley because it provides fodder and fuelwood for mountain dwellers. But in the long run, it creates a major problem, if precipitation takes place in the form of rain on a large scale huge disaster will occur in the future due to an increase in landslides incidents.

This study will help in monitoring the change in snow cover and height of snowline position in relation to LST in the future, which is an essential study for the livelihood security of people living in the valley, where the local people are dependent on the snow and glacier melt water for agricultural and household activities. Thus, the continuous monitoring of snow cover has become essential for the sustainability of Spiti Valley.

## STUDY AREA

Spiti Valley is situated in the Trans Himalayan region of the northeastern part of Himachal Pradesh in India. The meaning of Spiti is "Middle Land" the land between India and Tibet (Pankaj et al. 2018). It covers an area of 7,589 km² and lies between latitudes 31° 42' and 33° 41' N, longitudes 77° 37' and 78° 35' E. It is bordered by Ladakh in the north, Kinnaur and Kullu to the south, Tibet to the east, and Lahaul to the west (Fig. 1). Due to the absence of rainfall and a minimum altitude of more than 3,000 meters, the leeward side of the great Himalayan range gives Spiti a dark and impressive terrain, apparently devoid of vegetation cover and one of the most the harshest climates in the world (Bajpai 1987). Life-sustaining resources are low in the Spiti Valley due to harsh climatic conditions and rugged topography.

Spiti Valley has only two seasons: a short summer and a long extreme winter. Snowfall often starts from September and continuo tills the end of April. During

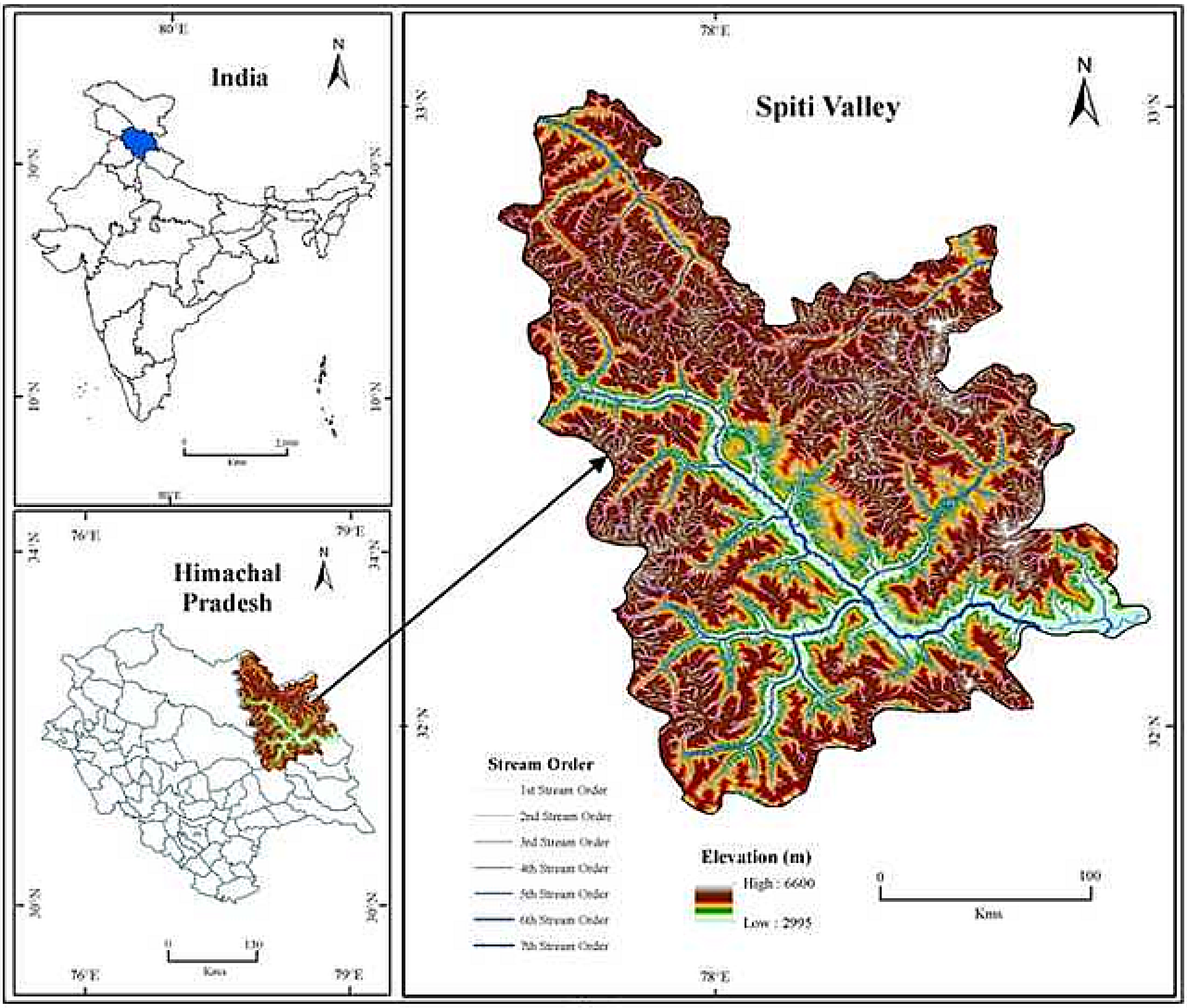

Figure 1. Study area

the peak winter season, the temperature dips down to -20°C. During heavy snowfall, the recorded temperature was -30°C. The surface of the snow becomes very hard and when walking, the feet do not go down into the snow. These factors have a great influence on the population distribution in the region. The population is highly concentrated in a few pockets confined to villages situated on the bank of Spiti River which is generally small and contains a small population.

## METHODOLOGY

Landsat images were the main source of data for the study of snow cover variations, including Operational Land Imagery (OLI) and Thematic Mapper (TM) scenes of all the twelve months of 1990 and 2015. Remote sensing data with less than 20% Cloud cover was included in this study (Table 1). These datasets were acquired from the National Aeronautics and Administration (NASA) via their USGS (Earth Explorer) Data Gateway. The satellite data were re-projected in the 44 N zone of the Universal Transverse Mercator (UTM) projection system and in the World Geodetic System 84 (WGS 84) datum, thus ensuring the consistency of the datasets during analysis (Pankaj et al. 2018).

Haze reduction and histogram equalization tools were run over Landsat Imagery, given in ERDAS Imagine 2014. Further, Geometric and radiometric corrections were made to enhance the accuracy of the data. The snow cover was extracted for the years 1990 and 2015 from January to December using the ratio:

Table 1. List of remote sensing data set use

| **Dataset type** | **Acquisition months** | **Pixel resolution / Scale** | **Repeated period** |
|---|---|---|---|
| Landsat TM 5 Band 2 | January, February, March, April, May, June, July, August,September, October, November, December, 1990 | 30 m | 16 days |
| Landsat TM 5 Band 5 | January, February, March, April, May, June, July, August,September, October, November, December, 1990 | 30 m | 16 days |
| Landsat 8 OLI/TIRS Band 2 | January, February, March, April, May, June, July, August,September, October, November, December, 2015 | 30 m | 16 days |
| Landsat 8 OLI/TIRS Band 5 | January, February, March, April, May, June, July, August,September, October, November, December, 2015 | 30 m | 16 days |

**Source:** Earth Explorer, United States Geological Survey (USGS)

$NDSI_{TM}$ = Band 2 – Band 5/Band 2 + Band 5
Where,
Band 2 = Green (Wavelength 0.52-0.60µm)
Band 5 = SWIR (Wavelength 1.55-1.75µm)

$NDSI_{OLI}$ = Band 3 – Band 6/Band 3 + Band 6
Where,
Band 3 = Green (Wavelength 0.52–0.60µm)
Band 6 = SWIR (Wavelength 1.56–1.66 µm)

In order to differentiate the water masses in the snow cover pixel, the NDSI criterion > 0.40 was incorporated (Dozier 1989).

Further, Landsat images of the same dates (September 24, 1990, and 2015) were used to analyze the height of the snow line in Spiti Valley. Other secondary forms of data related to precipitation (snowfall and rainfall) were collected from the sub-division office of Kaza. The mean altitudes were used to calculate the height of the snowline position, which varies with altitude in response to global climate change.

In the present study, the mean elevation of the snow line position was calculated by averaging all the pixels taken as the sample, extracted from Advanced Spaceborne Thermal Emission and Reflection (ASTER) - Digital Elevation Model (DEM). To validate the result of snow cover obtained from Landsat images, snowfall data of all twelve months were analyzed. The mean monthly snowfall was calculated to examine the differences in the pattern of snowfall between months of accumulation and ablation during the study period (Fig. 2). No Significant variation was found in the pattern of snowfall and it remained similar for both the reference years.

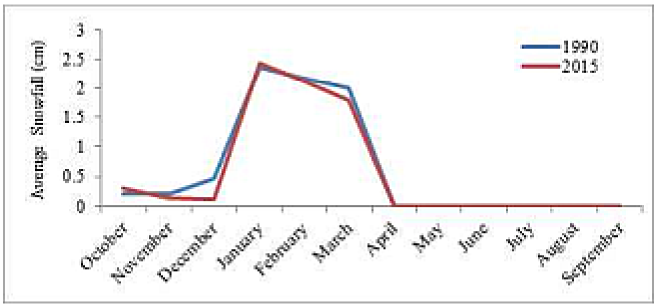

Figure 2. Mean monthly snowfall in Spiti Valley

Primary data related to the impacts of snow cover change were collected using a purposive sampling technique, in which information was collected from respondents over 50 years of age. Further, LST was calculated to examine its impact on snow cover area by applying the established formula based on (Liqin et al. 2018), in which two-step processes are followed to derive the luminosity temperature of the thermal band extracted from the Landsat Images. The methodology includes the following steps:

Digital number (DN) was converted into spectral radiance (L) by using the ratio

$$L (ë) = (L_{MAX} - L_{MIN}) / 255 * DN + L_{MIN}$$

Where,
L (ë) = Spectral radiance
$L_{MIN}$ = Spectral radiance of the Digital number
$L_{MAX}$ = Spectral radiance of the Digital number
DN = Digital number

Spectral radiance was converted into temperature (in Kelvin)

$T = K_2 / \ln (K_1 / R) + 1$
Where,
$K_1$ = Calibration Constant 1
$K_2$ = Calibration Constant 2
R = Radiation Values W/m$^2$ SR ìm T = Surface Temperature (in Kelvin)

Land Surface Emissivity (LSE) is calculated on the basis of NDVI values (Sobrino and Raissouni, 2001) by using the equation:
$LSE = 1.0094 + 0.047 * \ln (NDVI)$
and the final step, LST (in Kelvin) was converted to Celsius by the formula:

$BT = T – 273$
Where,
BT = Top of atmosphere brightness temperature

## RESULTS AND DISCUSSION

### Snow cover dynamics

Snow cover is an essential element of land cover and the most active natural component on the earth surface. In winter, snow cover in the northern hemisphere occupies more than 34% area of the Earth's surface (Pulliainen 2006). It has a considerable impact on climate change, energy balance, surface albedo, and hydrological circulation system, with social, economic and ecological consequences (Wulder et al. 2007). Landsat snow products are extracted from the visible and near-infrared part of the electromagnetic radiation. It is particularly helpful for mapping the characteristics of snow due to their ability to differentiate snow from other features like clouds cover (Andreadis et al. 2006, Tekeli et al. 2005). These products have an important role in the monitoring of snow cover and data assimilation. The monthly data represent overall change in snow cover during the year in which spatial distribution maps of snow cover of all the twelve months were prepared.

These maps have considerable potential for local water resources, the livestock industry, agriculture, and disaster management. The graphical representation of the snow cover indicates that the ablation period starts in April and continues until the end of September, while the accumulation period begins in October and ends until the end of April (Fig. 3). Snow cover begins to accumulate in the upper Himalayas in the beginning of October, where these areas begin to receive snowfall due to disturbances from the west (Singh et al. 2018). There are complex interactions between the regional variability of early snow cover in the fall and that of subsequent winter accumulation due to the complex interaction of temperature and precipitation anomalies.

### Snow accumulation and ablation 1990 and 2015

The monthly variations in snow cover from January

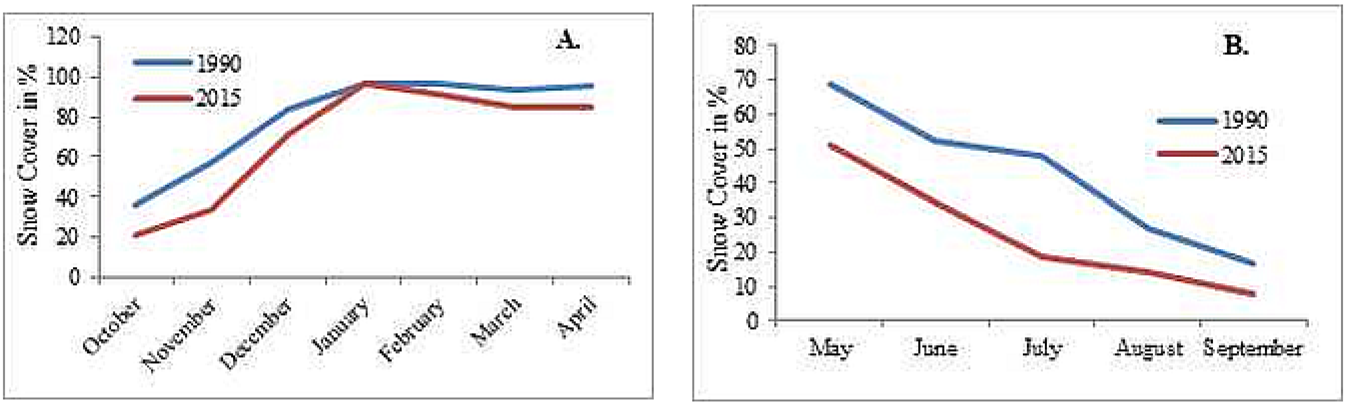

Figure 3. (A) Variations in snow cover during accumulation and (B) ablation period
**Source:** Lal Kitab, Kuliyat Tehsil Spiti, (Kaza Tehsil office)

to December were analyzed for better understanding of accumulation and ablation periods (Fig. 3). No significant changes were observed in the accumulation and ablation periods, but the extent and duration of snow cover availability have changed in the last 25 years.

In 1990, the accumulation period lies between October and April where snow cover was 2,64,018 ha. (36.26%) in October, 4,15,570 ha. (57.08%) in November, 6,09,308 ha. (83.69%) in December, 7,05,618 (97.00%) in January, 70,050 (96.25%) in February, 6,80,656 ha. (93.49%) in March and 6,92,404 ha. (95.10%) in April (Table 2). The study found that almost the entire valley was covered with snow in January and February. Peak snow cover was observed in January where only 2, 2,405 ha. (3%) area was devoid of snow in Spiti Valley. The average snow cover was 5, 81,189.14 ha. during the accumulation period in 1990. The study conducted by Singh et al. 2018, also confirms that the least snow cover was observed in August/September and maximum in January/February. The period of ablation lies between May and September because snow cover begins to decline in these months (Fig. 3).

The snow cover area during the ablation period was 5.02,206 ha (68.98%) in May, 3.79,903 ha (52.18%) in June, 3 50 129 ha (48.09%) in July, 1 977 271 ha (27.09%) in August and 1 19 349 ha (16.39%) in September (Table 2). The average snow cover was 3, 09, 771.6 ha during the ablation period and the minimum was observed in September where only 16.39% of the total area of Spiti Valley was covered with snow.

In 2015, the accumulation period lies between October and April, same as in 1990. The snow cover during the months of accumulation was 1,51,612 ha (20.82%) in October, 2,50,182 ha (34.36%) in November, 5,16,584 ha (70.95%) in December, 7,02,771 (96.53%) in January, 6,67,021 (91.62%) in February, 6,15,377 ha (84.52%) in March and 6,17,752 ha (84.85%) in April. The maximum snow cover was observed in January, where only 2,5,252 ha (3.46%) of the total area of Spiti Valley devoid of snow. The average snow cover during the accumulation period was 5, 03,042.7 ha. The period of ablation lies between May and September, where snow begins to decrease in these months. The snow-

Table 2. Snow cover variations during accumulation and ablation periods

| | **1990** | | **2015** | |
|---|---|---|---|---|
| | **Snow Cover (ha)** | **% of Total Area** | **Snow Cover(ha)** | **% of Total Area** |
| Accumulation Period | | | | |
| October | 2,64,018 | 36.26 | 1,51,612 | 20.82 |
| November | 4,15,570 | 57.08 | 2,50,182 | 34.36 |
| December | 6,09,308 | 83.69 | 5,16,584 | 70.95 |
| January | 7,05,618 | 97.00 | 7,02,771 | 96.53 |
| February | 7,00,750 | 96.25 | 6,67,021 | 91.62 |
| March | 6,80,656 | 93.49 | 6,15,377 | 84.52 |
| April | 6,92,404 | 95.10 | 6,17,752 | 84.85 |
| Total | 40,68,324 | - | 35,21,299 | - |
| Average | 5,81,189.14 | - | 5,03,042.7 | - |
| Ablation Period | | | | |
| May | 5,02,206 | 68.98 | 3,70,180 | 50.84 |
| June | 3,79,903 | 52.18 | 2,52,531 | 34.68 |
| July | 3,50,129 | 48.09 | 1,33,562 | 18.34 |
| August | 1,97,271 | 27.09 | 1,01,776 | 13.97 |
| September | 1,19,349 | 16.39 | 5,6,769 | 07.79 |
| Total | 15,48,858 | - | 9,14,818 | - |
| Average | 3,09,771.6 | - | 1,82,963.6 | - |

covered area was 3,70,180 ha (50.84%) in May, 2,52,531 ha (34.68%) in June, 1.33,562 ha (18.34%) in July, 1.01,776 ha (13.97%) in August and 5.6,769 ha (7.79%) in September (Table 2). The average snow cover was 1,82,963.6 ha, while the minimum was observed in September with 5,6,769 ha (7.79%) of the total area of Spiti Valley.

### Snow Cover Change in Accumulation and Ablation Periods

Analysis of snow cover extracted from Landsat images indicates that the extent of snow cover is decreasing in both the accumulation and ablation periods. The decrease in snow cover from October to April was observed as -1,12406 ha (15.43%) in October, -1,65,388 ha (-22.71%) in November, -9,2,724 ha (-12.73%) in December, -2,847 ha (-0.46%) in January, -3,3729 ha (-4.62%) in February, -6,5,279 ha (-8.96%) in March and -7,4,652 ha (-10.24%) in April.

It has decreased during ablation period by -1,32,026 ha (-18.13%) in May, -12,7,372 ha (-17.49%) in June,-2,16,567 ha (-29.74%) in July, -9,5,495 ha (-13.11%) in August,-6,2,580 ha (-8.59%) in September (Table 3). The maximum and minimum variation in the extent of snow cover was observed in July and January, with the reduction of 29.74 and 0.46% of the existing snow cover in 1990. As per the analysis, in both the period's accumulation and ablation decrease in the extent of snow cover is much more widespread and visible in summer than winter. In 1990, the average snow cover was 5,81,189.14 ha and 3,09,771.6 ha both in accumulation and ablation periods, while 5,03,042.7 ha and 1,82,963.6 ha in 2015 (Table 2). The result indicates that the snow cover has decreased by 78, 14, 644 ha in accumulation and 1,26,808 ha in ablation periods.

The maximum and minimum rate of declining snow cover was observed in May and September as 26.12% and 10.7% in 1990, while 34.02% and 6.18% in 2015 of the existing snow cover of the previous months.

### Declining Pattern of Snow Cover and Altitudinal Shift in Snowline Position

Snow cover has decreased in significant proportion during the study period in Spiti Valley. It has declined at its maximum level in November and July amongst all the months of the accumulation and ablation periods (Fig. 6). The NDSI result revealed that the average snow cover was 4,689,098.5 ha (61.68%) in 1990 and 3,69,696.4 ha (48.71%) in 2015. Approximately 98,422.08 ha (0.51%) of the snow cover was converted to a non-snow cover area at an average rate of 3,937. ha/year (Table 4). Several authors (Singh et al. 2018, Sharma et al. 2014, Muntán et al. 2009, Jain et al. 2008, Lemke et al. 2007) have also observed a trend towards declining snow cover area in the Himalayan region.

Table 3. The change in snow cover during accumulation and ablation periods

| | 1990-2015 | |
|---|---|---|
| | Snow Cover (ha) | Snow Cover in % of total geographical area |
| Accumulation Period | | |
| October | -1,12,406 | -15.43 |
| November | -1,65,388 | -22.71 |
| December | -92,724 | -12.73 |
| January | -2,847 | -0.46 |
| February | -33,729 | -4.62 |
| March | -65,279 | -8.96 |
| April | -74,652 | -10.24 |
| Ablation Period | | |
| May | -1,32,026 | -18.13 |
| June | -1,27,372 | -17.49 |
| July | -2,16,567 | -29.74 |
| August | -95,495 | -13.11 |
| September | -62,580 | -8.59 |

Table 4. The status of snow in the Spiti valley (1990 – 2015)

| **Year** | **Snow Cover Status** | |
|---|---|---|
| | **ha** | **% of geographical area** |
| 1990 | 4,68,098.5 | 61.68 |
| 2015 | 3,69,676.4 | 48.71 |
| 1990-2015 | -98,422.08 | 0.51 |

Snowline is a lower limit of snow cover above which permanent snow cover is found, which is an irregular line along the land surface where snow accumulation is equivalent to ablation. The average altitude of snowline was taken to establish a snow

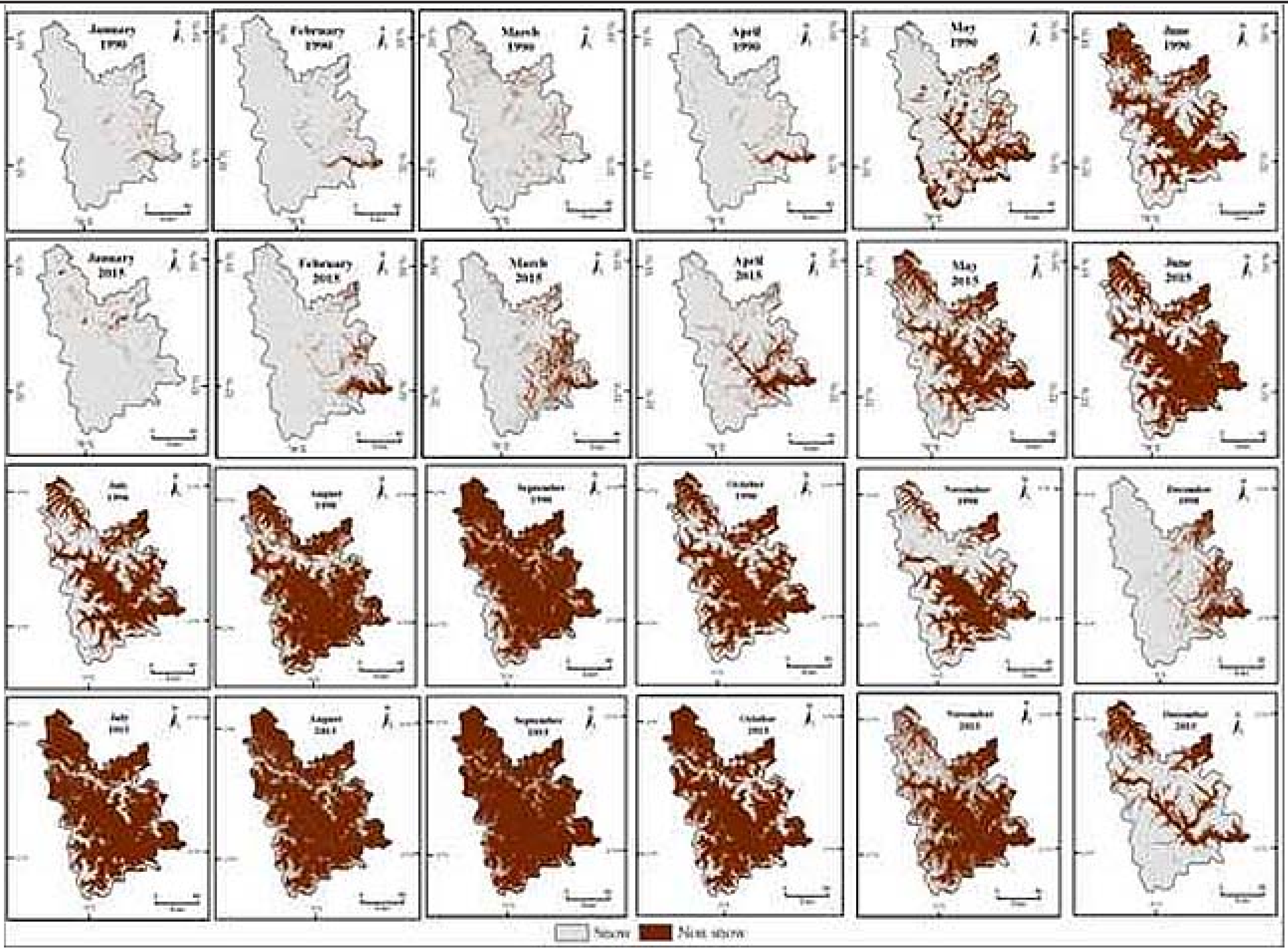

Figure 4. Monthly variation in snow cover

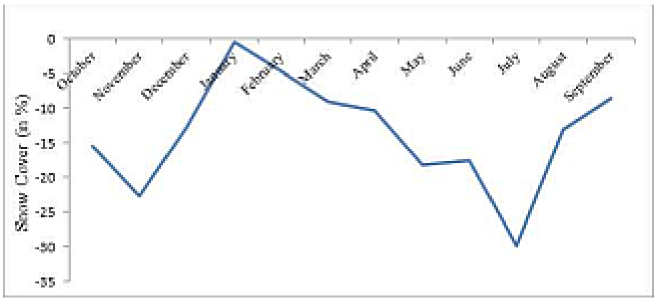

Figure 5. The pattern of declining snow cover during accumulation and ablation period

line position in Spiti Valley, which falls or rises in the altitude in response to global climate change.

The altitude of snow line was determined using the Advanced Digital Elevation Emission and Reflection (ASTER) - Digital Elevation Model (DEM). Landsat images of the same dates (September 24, 1990 and 2015) were used to reduce the seasonal variability where September was chosen to determine the altitudinal position of snow line because the upper limit of snow cover was clearly visible (Fig. 4). As per the analysis of the snowline position for both the reference years (1990 and 2015), it has shifted upwards by 445.11 m in Spiti Valley in the last 25 years. In 1990, it was visible at the height of 5,159.37 m at the end of the summer season but it moved up to the height of 5,604.48 m in 2015 marking the loss of snow accumulation in the lower heights (Table 5). This shift took place in the higher altitudinal zone of Himalaya due to a decrease in snow cover area in the lower altitudinal zone. This result is similar to Bhilangana watershed where snowline has shifted upward by 87 m at an average rate of 4.35 m/yr during research span from 1990 to 2000 (Kumar and Kumar 2016).

## Snow Cover and Snowline Variation in Relation to LST

The temperature of the land surface is the temperature of the earth's skin that has a direct impact on snow cover. If LST increases, the rate of snowmelt will automatically increase, and snow will not be available for longer duration in Spiti Valley. The trend

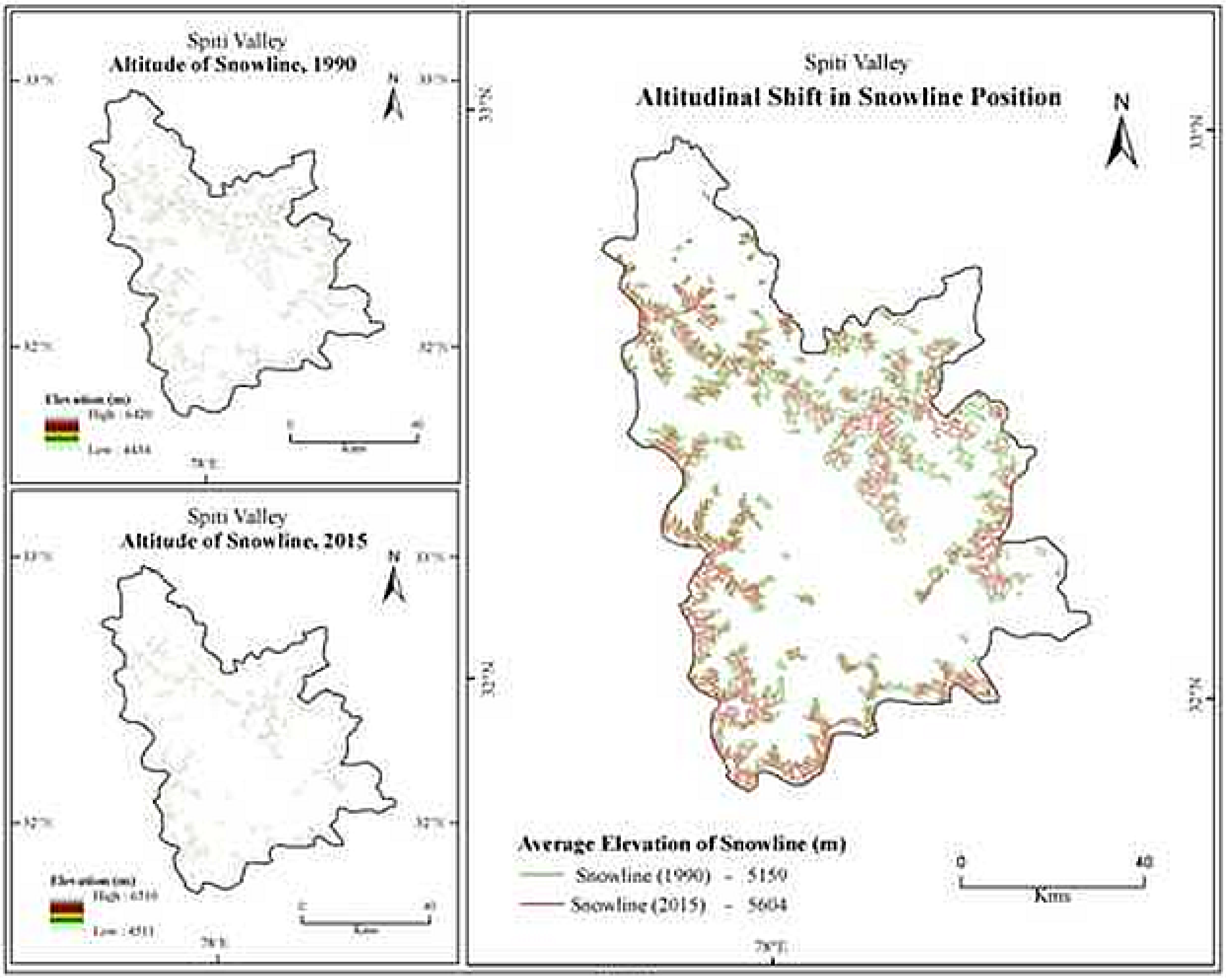

Figure 6. Altitudinal variation of snowline in Spiti valley

Table 5. Altitudinal shift in snow line position (1990 – 2015)

| Snow Line Altitude (in m) | | |
|---|---|---|
| 1990 | 2015 | 1990 – 2015 |
| 5159.37 | 5604.48 | -445.11 |

of temperature was analyzed by Singh and Pankaj, 2014 for Himachal Pradesh using band 6 of Thematic Mapper (TM) measured for four consecutive years from 1989, 1992, 2008 and 2011 for September and October. It indicates a temperature magnitude ranging from -1.5 to 3.5°C where the maximum part of Himachal Pradesh shows an increase in LST. An increase in LST was more pronounced in Kinnaur and north-east of Chamba and Spiti Valley (Singh and Kumar 2014). In the present study, Landsat TIRS band 10 and 11 and TM band 6 were used to prepare the thermal map of the Spiti Valley (Fig. 7). The maximum and minimum temperatures were recorded 44 and -13°C in 1990, whereas they were 46 and -12°C in 2015. An average LST was 11°C in 1990, but it has increased by 2°C and reached at 13°C in 2015 (Table 6). The changing pattern of snow's temperature was calculated for both reference years 1990 and 2015. The average temperature was calculated by averaging all the selected pixels as samples of the satellite images. The maximum and minimum LST of the snow cover were recorded 10 and -12°C in 1990, and 12 and -10°C in 2015; meanwhile, the average LST was recorded -03°C in 1990 and -02°C in 2015. It is evident that the mean temperature of 1°C has increased during the study period.

The previous study suggests that the snow-covered regions affect the heat, cold and moisture content of the earth surface, the ecosystem at several scales and the biological characteristics due to the

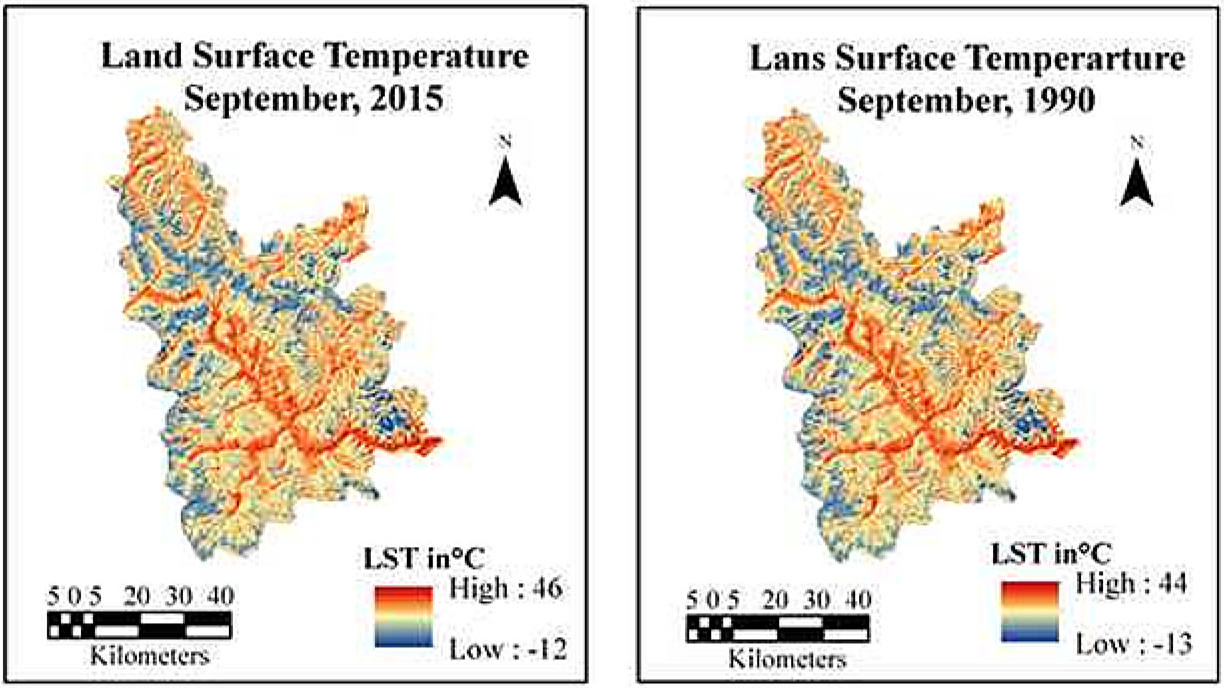

Figure 7. Spatial distribution of LST in Spiti Valley

Table 6. Variations in LST in relation to snow cover and snowline (1990 – 2015)

| | Temperature ($^{o}$C) | | | | | |
|---|---|---|---|---|---|---|
| | September, 1990 | | | September, 2015 | | |
| | **Minimum** | **Maximum** | **Mean** | **Minimum** | **Maximum** | **Mean** |
| Spiti Valley | -13 | 44 | 11 | -12 | 46 | 13 |
| Snow Cover | -12 | 10 | -03 | -10 | 12 | -02 |
| Snow Line | -11 | 10 | -04 | -09 | 13 | -03 |

radiation characteristics and thermodynamic properties of the snow (Brown 2000).

The maximum and minimum temperatures at the height of snowline position were - 10 and -11°C in 1990, and 13 and -09°C in 2015. While the average LST was -04°C in 1990 and -03°C in 2015, indicates that the temperature of 1°C increased at the height of the position of the snow line position. This may happen due to global warming/climate change or an overall increased in LST of Spiti Valley.

In addition, a relationship was established using the Karl Pearson correlation between Land Surface Temperature (LST) and Normalized Difference Snow Index (NDSI), which shows a negative relationship with high correlation coefficients of R2 0.9416 and 0.9684 in 1990 and 2015, respectively. According to our approach, LST is an independent variable and snow cover is a dependent variable. Snow cover and LST are negatively related to physical changes in the land surface, surface emissivity and albedo of the area. A stronger negative correlation indicates that increase in LST is not good for snow cover which may induce the rate of snowmelt in Spiti Valley.

## Implications of Changing Snow Cover, Snowline and LST

The implications of snow cover can be easily evaluated by a simple cause-and-effect relationship in Spiti Valley, where most people are engaged in primary sectors such as agriculture, livestock and orchard farming etc. The climatic constraints have made the people more dependent on agriculture and livestock's and as a result, they have diversified their resource use practices. It should also be mentioned that most of the farmers had no idea of the dynamics of snow cover, snowline, and LST.

The field survey was conducted in the villages of Kaza, Hikkim, Rangrik, Komic, Dhankar, Langza and Kibber in order to assess the perception of mountain dwellers on the effects of the declining snow cover, change in the altitude of snow line position and LST on the daily life of the inhabitants (Fig. 8). In total, 120 households were interviewed based on certain sets of questionnaires where several questions were asked about the past and present state of temperature, snow cover, an altitudinal shift in snowline position, snowmelt – and water supply for irrigation. Spiti's unique contribution to agriculture is an irrigation system that uses Kuhls (snow and glacier-fed streams) to bring water from the snow and glacier to villages.

As per respondents, most of the people felt that water supply for irrigation has been decreasing where the maximum effect of decreasing snow cover was observed on water availability in Kuhls. Nowadays, water does not remain available in Kuhls for long-duration, unlike earlier times. This view of respondents is in line with the results obtained from satellite images extracted for surface temperature, snow cover, and height of snowline position.

## CONCLUSION

Snow cover has an important role for mountain dwellers in the high altitudinal region of the Himalaya, where it provides fresh water for irrigation and household activities throughout the year. It becomes an important natural resource in itself because no other sources of freshwater are found in Spiti valley. The present study provides useful information on the extent and nature of changing snow cover area in relation to LST that occurred from 1990 to 2015, where approximately 98,422.08 ha. area was converted to the non-snow cover area over the last 25 years. Analysis of Landsat data obtained from the USGS revealed that snow cover decreased at an average rate of 3,937 ha/year. This can be attributed to environmental degradation, the concentration of greenhouse gases and global warming. Continued depletion of snow cover in the study area can lead to serious environmental degradation. The average LST of snow cover was -03°C in 1990 and -02°C in 2015, which indicates that the temperature has increased by 1°C during the study period. Analysis of the altitude of snowline position revealed that the snowline has moved upward by 445.11 m in Spiti Valley. In 1990, the snow line was visible at the height of 5,159.37 m at the end of the summer, but it has shifted at 5,604.48 m height in 2015, marking the loss of snow accumulation in the lower heights. So, periodic monitoring of snow cover by digital image processing at different times scale can play a vital role in water harvesting.

The relationship between LST and NDSI shows a strong negative correlation which indicates that rise in surface temperatures would become a major problem for mountain dwellers. Increase in LST may

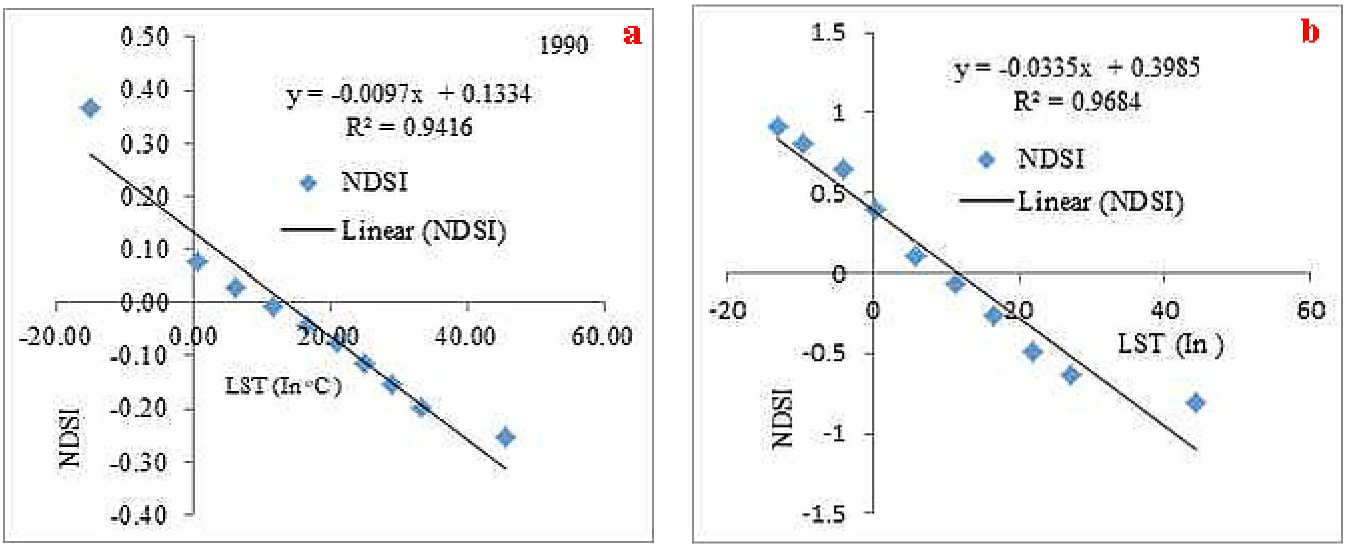

Figure 8. A correlation between NDSI and LST in 1990 (a) and 2015 (b).

induce the rate of snowmelt, where water will no longer be available for agricultural and domestic activities. The maximum effect of decreasing snow cover was observed on availability of water in Kuhls (streams which carry water from snow/glacier to villages) where water is not available for a long duration, unlike earlier times. The flow of Spiti River is primarily dependent on the accumulation of snow, ice and the energy input indirectly related to LST. This can influence the runoff pattern of many tributaries of the Spiti River.

A continued geospatial monitoring of spatial patterns of snow cover will help in identifying critical areas that are extremely sensitive to climate change and necessary for watershed management planning. This suggests that meteorological data collection methods should be improved at the higher Himalayan region by installing new monitoring stations in the basin area for more effective study of the snow cover and its determinants.

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