# Temporal Variations in Land Cover Area in High Altitude Glacierised Area in Central Himalaya during Last Three Decades

**Tamil Selvan, M.,[1] Ahmad, S.[2] and Rashid, S. M.[3]**
[1]Centre for the Study of Regional Development, Jawaharlal Nehru University, New Delhi – 110 067, India
E-mail: mtselvan@mail.jnu.ac.in
[2]Department of Geology, Aligarh Muslim University, Aligarh – 202 002, UP, India
[3]Department of Geography, Faculty of Natural Science, Jamia Millia Islamia, New Delhi – 110 025, India

**Abstract**
*Temporal variations in land cover area are studied in high altitude Bhagirathi valley in higher Himalaya. The various land cover area is classified using 1980, 1990, 2000 and 2006 LANDSAT and IRS series images by semi automated techniques. Change in various land cover area between 1980 -2006 suggests that open rock (thick debris cover over glaciers and open rocky surface) and vegetation area has increased, and snow/ice area has decreased during this period. The relationships were evaluated between climatological, physiographic and geomorphic characteristics and change in land cover areas since 1980 and 2006. Decrease in thin debris cover ice show direct relationship with percentage of glaciations in various sub-basins. However, decrease in snow covered area does not show relationship between percentages of glaciations, but showing good polynomial relationship between debris factor. Over the period, the vegetation cover has been increased due to amelioration of atmospheric temperature and change in vegetation show direct relationship with decrease in snow covered areas and increase in open rock area.*

## 1. Introduction

Land covers are sensitive to ongoing climate change in Higher Himalaya ecosystems as glacier and ice is major part of the ecosystem. Increase in air temperature in this region profound impact on melting of snow and ice area. The decrease in snow and glacier area further increases the air temperature due to more absorption of the sun radiation. Hence, the higher altitude snow cover area is more susceptible to more warming than the other low altitude area. Along with climate change the anthropogenic activity brought the environmental degradation and impact on health of forest, snow and glaciers. The change one type of land cover may impact on other adjoin land cover, which may alter the dynamics of ecosystems and impact on livelihoods on various populations in region and downstream. Therefore, it is important to study the temporal change in land cover area and its relationship among each other in substantial time frame. The analysis of the change in land cover area can be done using the inventories of these land cover in various time. The preparation of land cover area inventory need ariel or field survey data in the form of image for various time. The remote sensing images for different time and various techniques were used efficiently in such remote area by various researchers (Krishna, 1996, 1999, Roy et al., 1990 and Pant et al., 2000). Most of these studies were conducted on references to characterizing, classifying and land cover change in forest and crop land in lesser and middle Himalayas and Central Himalaya. The snow cover, glacier characterisation and glacier areal and thickness change has been studied in the remote area by Aniya et al., 1996, Arora and Mathur, 2001, Bishop et al., 2000, Ahmad et al., 2004, Kulkarni and Bahuguna, 2002, Bahuguna and Kulkarni, 2005, Berthier et al., 2007, Racoviteanu et al., 2008, Haritashya et al., 2009, Gardelle et al., 2010 and Bolch et al., 2008, in Himalayas. The higher Himalaya is dominated by snow and ice cover, lesser vegetation area and diversity discouraged to study the temporal change in land cover area in these regions. Moreover, the change in glacier, ice and snow area changes were studies in higher altitude in isolation. Therefore, there is need to study the inter-relationship among the variation of landover covers area change in substantial time frame. It will help in drawing the conclusive dynamics of various land cover relationship among them. Hence present study is conducted for analyzing temporal variation in land cover area and its relationship among vegetation cover change in snow and glacier area.

## 2. Study Area

The Bhagirathi basin is located in the Uttarkashi District of Uttaranchal State. The Bhagirathi basin is bounded by long. 78°15′00″ E and 79°20′00″ E, and lat 30°07′00″ N and 31°15′00″ N. The basin is defined in the north by the International boundary (China), and by the water divide between Satluj and Bhagirathi basins. In the south, Devprayag (the confluence of Alaknanda river and Bhagirathi river) marks the limit of the basin. The basin limits are marked by the water divide between Bhilangna ganga (a tributary of Bhagirathi river) and Mandakini river (tributary of Alaknanda river) on the east, and water divide with the Yamuna basin on the west (Figure 1). The river Bhagirathi originates at an elevation of 3,812 m from the Gangotri glacier at Gomukh on the western slope of Chaukhamba in Uttarkashi district. The basin is characterized by glacier- fluvial activity, but the upper portion of the basin is dominated by glacial processes. The Bhagirathi river valley is a broad U-shaped with high sidewalls, which is a characteristic of its glacial – fluvial origin. Morainic material present between Chirwasa and Gomukh in the form of tillite hillocks are considered as evidences of the extent of Gangotri Glacier.

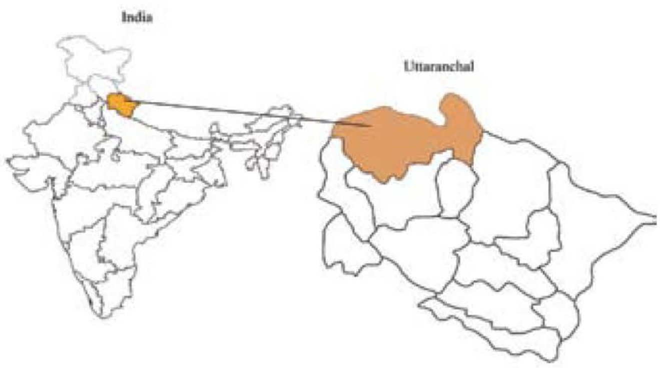


Figure 1: Location map of Uttaranchal State, India


Figure 2: Location map of Bhagirathi basin

It is NW-SE trending valley within the granitic terrain. The prominent geomorphic landforms formed by the glacial environment are different levels of lateral and recessional moraines, U-shaped glacial troughs, terraces and outwash plains. The location map of the study area with sub-basins watersheds are shown in Figures 1 and 2. Bhagirathi valley is subdivided into six sub–basin namely Bhagirathi, Bhilangna, Jahnvi, Jalandri, Kaldi, Pilang. The biggest sub-basin in the region is bhagirathi with 47% glaciation and contain 78 glaciers and smallest sub–basin in the area is Kaldi with minimum glaciations of 2% and contain 5 small glacier. Janvi and Jalandri are the medium size glaciated basin associated with 38 and 27 % glaciation along with 60 and 64 glaciers respectively. Bhilangna and Pilang are smaller size basins with 20 and 24% glaciations and contain 64 and 60 glaciers respectively.

### 3. Datasets and Methodology

Landsat (name indicating Land + Satellite) imagery is available since 1972 from six satellites in the Landsat series. These satellites have been a major component of NASA's Earth observation program, with three primary sensors evolving over thirty years: MSS (Multi-spectral Scanner), TM (Thematic Mapper), and ETM+ (Enhanced Thematic Mapper Plus). Landsat supplies high resolution visible and infrared imagery, with thermal imagery and a panchromatic imagery. For this study bands listed in table 1 were used to identify the glaciers and land surface area. The Landsat images of December 1980, October 1990, October 2000 and IRS-P6 LISS 3 image of October 2006 were used in the present study. Present study utilizes the multi-temporal and multi-wavelength remote sensing images. Therefore the same atmospheric correction technique is applied to the field spectra to removes certain external influences, such as atmospheric absorption, and provides a truer indication of the natural reflectances of the materials themselves through same dark object subtraction techniques. The suitability of a particular scene depends on the presence/absence of seasonal or temporary snow, the percentage of cloud cover and the date of acquisition. Glaciological investigation can be through remote sensing images and ideally the image should be acquired at the end of the ablation season for minimal seasonal snow cover and instrument gains high contrast over the various type of land cover in the region during this time. The vegetation is in full growth during the October because of preceding months of the monsoon season, which is ideal for vegetation growth. Because of the high temperature in summer and monsoon time all the seasonal snow cover is melted and only clean stable ice and snow is remains on glaciers also the shower of monsoon also clean the dust from the rocky material. Therefore, the images for this season provide a unique opportunity with maximum contrast and gain for remote sensing images Data used in present study belong to relatively same wavelength and observation season.

Table 1: List of satellite sensors and bands used in this study

| Satellite/ Sensors | Band #s | Spectral Range(μm) |
|---|---|---|
| **IRS P6** | 2 | 0.62 - 0.68 |
| **LISS III** | 3 | 0.77 - 0.86 |
| | 4 | 1.55 - 1.70 |
| **Landsat 7** | 3 | 0.63 - 0.69 |
| **ETM+** | 4 | 0.75 - 0.90 |
| | 5 | 1.55 - 1.75 |
| **Landsat 4-5** | 3 | 0.63 - 0.69 |
| **TM** | 4 | 0.76 - 0.90 |
| | 5 | 1.55 - 1.75 |
| **Landsat 1-4** | 2 | 0.6 - 0.7 |
| **MSS** | 3 | 0.7 - 0.8 |
| | 4 | 0.8 - 1.1 |

Table 2: Reflectance of the snow/vegetation and soil for various wave length bands

| Band used in unsupervised classification ( μm) | Clean Snow reflectance | Vegetation reflectance | Soil/Clay/Loam reflectance |
|---|---|---|---|
| 0.4 – 7. | *84* | 34 | 24 |
| 0.7 -0.8 | 34 | 11 | 41 |
| 0.8- 1.7 | 14 | 11 | 21 |

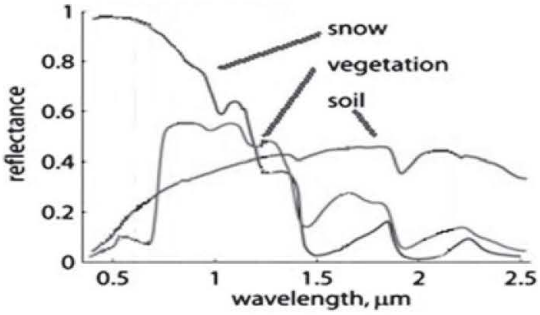


Figure 3: Relationships between wavelength of the EMR and corresponding Reflectance for the snow, vegetation and soil

Therefore different satellites normalization may not required specially if sufficient spectrum contrast exist among various land cover. The comparative spectrum of the Snow/ice, debris as soil and vegetation is shown in figure 3. It indicates a high contrast among vegetation, debris and snow for the bands and corresponding reflectance and therefore used for unsupervised classification for few category of land cover (Table 2). A mixed classification technique is followed in this study using ERDAS Imagine Tools. In the first step, Unsupervised Classification is performed and each image was classified into 50 sub-classes. The each class has been identified its category and grouped into its corresponding category. In the second step, the Supervised Classification is performed for the pixel classes which were indentified in Unsupervised classification and new signature files have been generated for each image. Using this signature files, supervised classification has been done. Finally all the images classified into four major classes as open rocks (open rock surface and debris cover over glaciers), vegetations, debris covered ice and snow cover. The entire Bhagirathi basin is divided into six sub-basins and the imagery analysis was carried out for all sub-basins. The imageries of 1980, 1990, 2000 and 2006 are analysed for the entire basin as well as for each sub-basin (Figure 4a-d). The result of an accuracy assessment typically provides us with an overall accuracy each class in the map. As a general rule, the level of accuracy obtainable in a remote sensing classification depends on diverse factors, such as the suitability of training sites, the size, shape, distribution, and frequency of occurrence of individual areas assigned to each class, the sensor performance and resolution, and the methods involved in classifying (visual photo interpreting versus computer-aided statistical classifying), and others. The random points were generated for different land use cover.

The accuracy assessment performed on the above classification using the Google Earth, most latest LISS III image (2006). It showed different accuracy level with respect to remote sensing satellite data MSS, Landsat TM, Landsat ETM+, IRS LISS III and Class. The MSS, Landsat TM, Landsat ETM+ and LISS III image shows the overall total accuracy of 75.3%, 80.7%, 85.6% and 86.8% and overall accuracy of 82.1%. The most inaccuracy is observed among the snow /ice and rock due to shadow effect of the mountain peaks on snow cover resulted in the over estimation of the rock areas. The misclassified pixels in each image were masked and replaced with their accurate classes by local editing of pixels and incorporated in final maps.

**4. Results and Discussion**

Imageries of the entire basin has been classified with latest available geo-techniques mentioned in the methodology to differentiate various land cover separately as Vegetation, Open Rocks, Thin Debris Covered Ice and Snow. The year wise and sub-basin wise detailed imagery data is shown in Table 3. It is shown in the table that vegetation and open rocks have been increased in all the basins, while debris covered ice and snow covered area decreased (Table 4). Lower portion of the glaciers surface is covered by rocks (boulder, cobbles and sediments) distributed on Himalayan glaciers. These debris covered areas over glaciers are included in open rock category, because of similar nature of spectral characteristics. Hence, open rock category represents the debris on glacier surface and other open areas without vegetation near the glaciated areas. The temporal variations in open rock in each glaciated sub-basin indicate a significant increase since 1980. Temporal change in ratio of open rock (total debris covered ice + total snow cover) also shows continuous significant increasing trend in all the basins in last twenty five years (1980 - 2006). It indicates that area is increased by the decreased in combination of snow and thin debris covered ice area and represent as increase in open rock area. Increase in open rock surface and debris factor (Ratio of thin debris cover ice/ snow covered ice) is investigated in each sub-basin. The result shows strong direct relationship; higher the debris factor higher the increase in open rock surface area in the basin (Figure 5). The studies conducted by Japanese glaciologists over Himalayan glaciers suggested that thick debris cover inhibit the glacier melting while thin debris cover increase snow melting (Nakawo, 1979, Nakawo et al., 1993, Nakawo and Rana,1999, Kayastha et al., 2000 and Takeuchi et al., 2000).

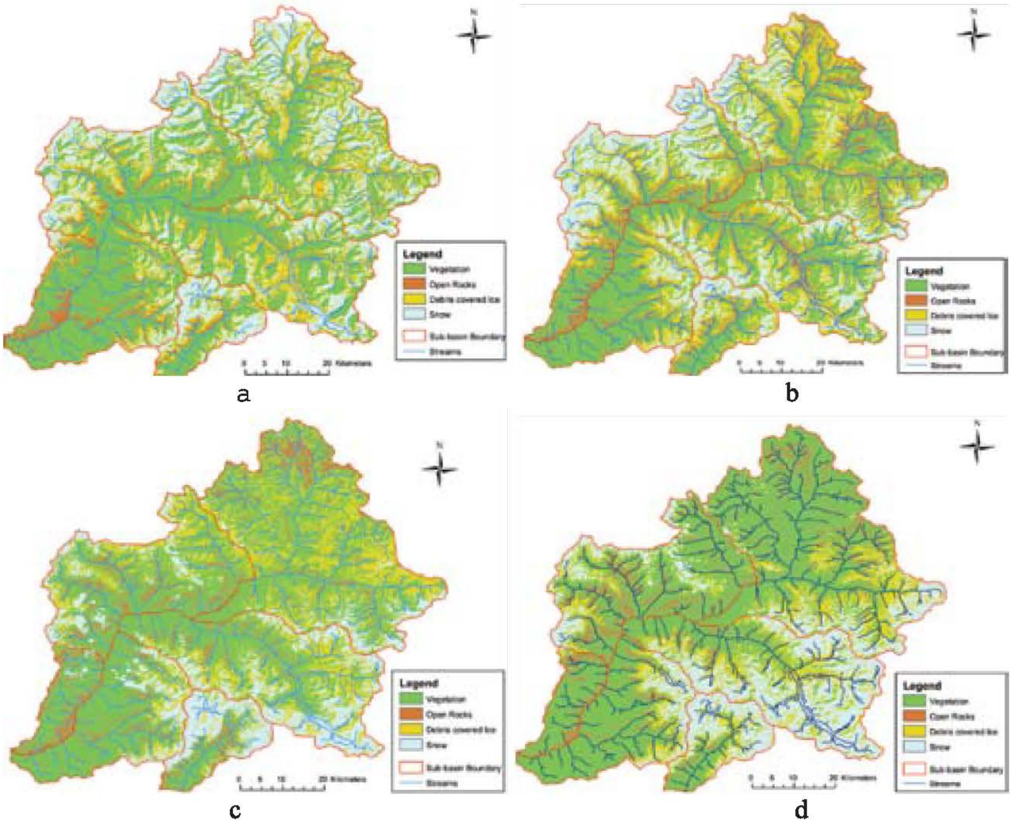


Figure 4(a-d): Classified Imagery of the Bhagirathi Basin for the year 1980, 1990, 2000 and 2006

Table 3: Temporal change in Land covers area in Bhagirathi valley (sq.km.)

| | Vegetation | Open Rocks | Debris Covered Ice | Snow covered area |
|---|---|---|---|---|
| | | **1980** | | |
| **Bhagirathi** | 321 | 96 | 328 | 260 |
| **Bhilang** | 103 | 26 | 95 | 98 |
| **Jahnvi** | 435 | 182 | 531 | 353 |
| **Jalandri** | 250 | 66 | 253 | 325 |
| **Kaldi** | 130 | 58 | 15 | 10 |
| **Pilang** | 364 | 63 | 132 | 91 |
| | | **1990** | | |
| **Bhagirathi** | 329 | 103 | 319 | 252 |
| **Bhilang** | 108 | 45 | 89 | 78 |
| **Jahnvi** | 540 | 209 | 521 | 229 |
| **Jalandri** | 276 | 118 | 240 | 256 |
| **Kaldi** | 102 | 73 | 23 | 14 |
| **Pilang** | 390 | 69 | 100 | 89 |
| | | **2000** | | |
| **Bhagirathi** | 369 | 124 | 273 | 237 |
| **Bhilang** | 127 | 54 | 68 | 72 |
| **Jahnvi** | 577 | 217 | 508 | 195 |
| **Jalandri** | 347 | 169 | 211 | 164 |
| **Kaldi** | 117 | 85 | 3 | 6 |
| **Pilang** | 399 | 88 | 76 | 85 |
| | | **2006** | | |
| **Bhagirathi** | 374 | 158 | 246 | 225 |
| **Bhilang** | 124 | 66 | 63 | 68 |
| **Jahnvi** | 627 | 297 | 400 | 173 |
| **Jalandri** | 408 | 239 | 117 | 126 |
| **Kaldi** | 140 | 66 | 3 | 2 |
| **Pilang** | 415 | 84 | 72 | 81 |
| **Total** | **2088** | **910** | **902** | **675** |

Table 4: Temporal change (1980 - 2006) in different land cover area in Bhagirathi valley

| Basins | Glaciations in % | Number of glacier | Area in sq.km. | Average glacier area size | % increase Vegetation area cover | % increase Open Rocks | % Decrease thin debris Covered Ice | % Decrease in Snow | Debris Factor (Thin debris cover/thin debris cover + total snow cover) |
|---|---|---|---|---|---|---|---|---|---|
| **Kaldi** | 2.0 | 1.0 | 5.0 | 5.0 | 7.7 | 13.8 | -80.0 | -80.0 | 0.2 |
| **Bhilangna** | 20.0 | 13.0 | 131.0 | 10.1 | 20.4 | 153.8 | -33.7 | -30.6 | 0.5 |
| **Pilang** | 24.0 | 23.0 | 153.0 | 6.7 | 14.0 | 33.3 | -45.5 | -11.0 | 0.6 |
| **Jlandhari** | 27.0 | 64.0 | 243.0 | 3.8 | 63.2 | 262.1 | -53.8 | -61.2 | 0.4 |
| **Jahnvi** | 38.0 | 60.0 | 273.0 | 4.6 | 44.1 | 63.2 | -24.7 | -51.0 | 0.6 |
| **Bhagirathi** | 47.0 | 78.0 | 471.0 | 6.0 | 16.5 | 64.6 | -25.0 | -13.5 | 0.6 |

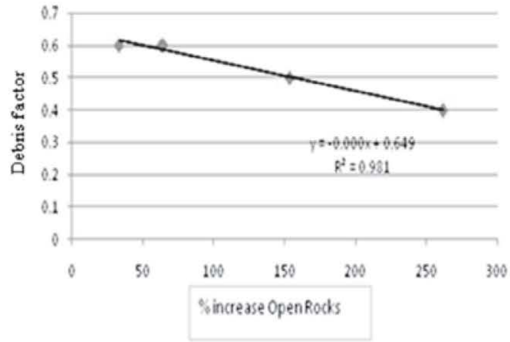


Figure 5: Scatter diagram between debris factor (thin debris cover/ thin debris cover + snow and ice cover) and increase in open rock surface

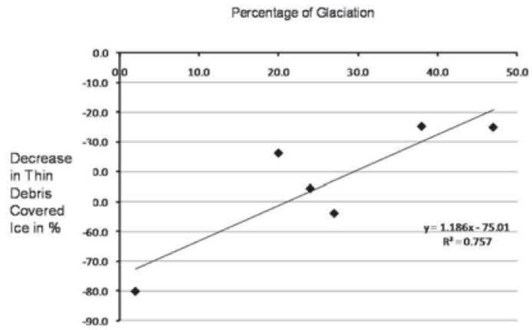


Figure 6: Scatter diagram between percentage of glaciations and decrease in thin debris covered ice area in percentage

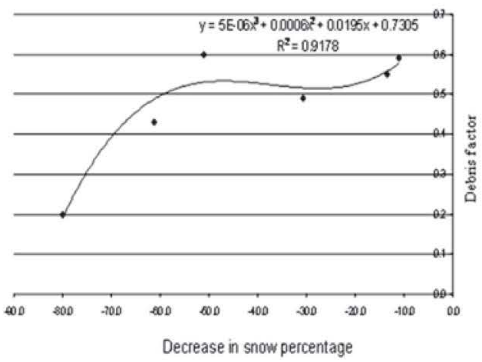


Figure 7: Scatter diagram between Debris factor and decrease in snow and ice area in percentage

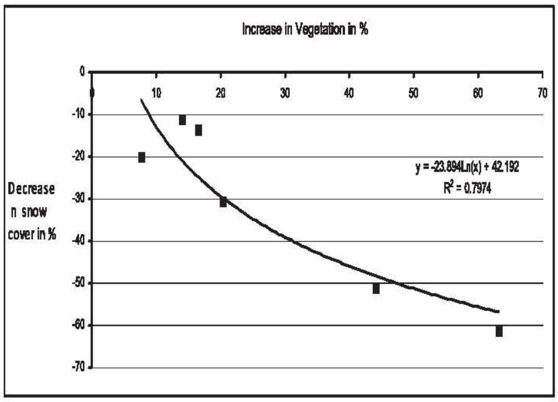


Figure 8: Scatter diagram between decrease in snow and ice area in % and increase in vegetation area in percentage

Increase in thin debris covered ice causes to fast melting which result in thinning of the glacier surface and therefore increased in relative height between glacier surface and lateral moraine. The small disturbance during monsoon and avalanches time brought the old lateral moraine on glacier surface and causes increase in thick debris cover over glacier and increases the open rock area through time during thinning processes of the glacier. Temporal variation in thin debris covered ice suggests decreasing trend in areas in each sub – basin in Bhagirathi valley. Decrease in thin debris covered ice through time is result of more burial of debris covered ice with debris transport from glacier lateral moraine. Hence, through time the thick debris glacier cover (mentioned under open rock) area has been increased and thin debris covered ice area has decreased through times. The relationship between decrease in thin debris covered ice and glaciations is shown in Figure 6. Decrease in thin debris covered ice and glaciations show logarithm relationship. It indicates that the basins covered by higher percentage of glacier show less degree of shrinkage on thin debris covered ice area and vise verse. It also suggested that the higher degree of glaciations inhibit the thickness loss and keep the environment at low temperature for longer time and therefore the impact is less than the basins holding less percentage of glaciations (Rathore et al., 2009, Negi et al., 2009, Rakesh et al., 2009 and Ahmad and Islam, 2011. Temporal variation in snow covered area suggests that it is continuously decreasing since 1980s. The maximum decrease is observed in Kaldi basin and minimum decrease in observed in interior of Bhagirathi valley. The least rate of snow shrinkage is associated heavily glaciated area and high shrinkage is associated with low glacier cover and just frontal portion of the basin. Decrease in snow cover area and its relationship initial debris factor does not fallow linear relationship but polynomial of second order relation shows a significant relationship as shown in Figure 7. It shows that decrease in snow cover increases with lower debris factor, however higher debris factor show a negative relationship. This can be clearly seen, as a large difference in deglaciation was observed between large and small glaciers. Loss in glaciated area for large glaciers was 12% compared to 38% for small glaciated basins in Bhagirathi valley. This can be explained by considering three fundamental glacial parameters, namely depth, mass balance and rate of melting at the terminus. Glacial depth is normally related to its areal extent and small glaciers have relatively lesser depth. Since glacier response time is directly proportional to its depth, it could vary between 4 and 60 years, depending upon glacial size. This could be the fundamental reason for large retreat of small glaciers. Therefore, small glaciers are considered as more sensitive to global warming. This process could have been further accelerated as small glaciers and ice fields are situated on small mountain plateaus or on gentle mountain slopes. On the other hand valley glaciers are usually located in mountain valleys, surrounded by steep mountain cliffs. This can cause further accumulation of debris and less solar radiation will be received on the glacial surface, affecting glacial retreat. The observations made in this investigation suggest that small glaciers and ice fields are significantly affected due to global warming from the middle of the last century. The increase in air temperature at higher altitude resulted in decrease in snow and debris covered ice. Increase in air temperature has influenced on vegetation growth in these areas. A rate of increase in vegetation area in various basins suggests that maximum increase is observed in Jalandhari basin, while least increase is observed in Kaldi basin. The rate of significant increase in vegetation area cover and its relationship with decrease in snow covered area is shown in Figure 8. It suggests that more decrease in snow cover related with more increase in vegetation cover. Higher decrease in snow cover resulted due to high temperature in basin, which causes to absorption of radiation by the ice free debris and brings about the moderate atmospheric temperatures and supports to the vegetation growth. The studies conducted by the Grabherr et al., 1994, Nemani et al., 2003, Körner, 1999 and Nautiyal et al., 2005 also indicate the general rise in tree line in these areas as a result of the general increase in atmospheric temperature. The limiting factor for the plant growth in this area is mainly temperature, because the monsoon brought sufficient water in the area. Hence, just improving in temperature caused to proliferation of vegetation in the higher altitude. A scatter diagram between increase in vegetation and open rock area show direct relationship. It indicates that these open rocks are now showing good vegetation coverage in previous inhabitant area. The increase in vegetation areas may probably result due anthropogenic disturbances or natural. But, this area is far away from human activity and hence change in vegetation cover is related to natural processes. The increase in vegetation cover in these areas is due to moderation of the limiting factor of the atmospheric temperature.

### *4.1 Impact on Society*

The studies conducted by People foundation Dehradun (2010) and Oxfom, 2009 in the region indicating that these areas are experiencing the effects climate change on traditional crops and fruit production, which were supporting the life of the inhabitant since long time. The series of extreme events supports the farmers' claims that unpredictable weather and extreme events are on the rise. The survey indicated that villagers have recognized the inevitability of climate change and the increasing unsuitability of the area to traditional crops. The cultivation of tomatoes and other vegetables indicates that this aspect is recognized by village communities. Nearly all the villages visited show increasing adoption of plains crops such as wheat and vegetables and a lack of interest in traditional hill crops such as millets, buckwheat, and barley. However, with winter aridity, the wheat yields have been decreasing. Potato yield has also decreased, and in addition it is beset by pests. Interviews with the villagers failed to reveal any efforts being made to improve agricultural yield. A oft-repeated complaint was the lack of winter rainfall, which led to a decrease in yield. However, alternative sources of water were not accessed instead. However, shifts in flowering times are directly influenced by the changing climate. The early flowering of rhododendron in the Pindar valley is directly linked to rising temperatures. Similarly, the observed lack of regeneration in oak, and deodar can be indicators of a lack of the freezing temperatures required by the seeds in addition to over-grazing (Rana and Sharma, 2009). The pollution of the atmosphere has led to climate change or more accurately climate instability and climate chaos. This has impact on agriculture, on water systems, on forest and biodiversity, on people's livelihoods. In Bhagirathi and other adjoining valley, the participatory research reveals that over the past decade, 34% of perennial streams have become seasonal, or have completely dried up. Water discharge has reduced by an average of 67%.In 2007-2008, 50% - 60% of the crop failed due to drought. The 2009 drought has led to crop failure of 90%. 95% of the Chir Pine forests have had forest fires in 2009. The drought has led to fodder scarcity which has led to a rapid decline in livestock. Livestock population has declined by 74% in Bhagirathi Valley, 72% in Mandakini Valley, 64% in Yamuna Valley and 57% in Alaknanda Valley. In Ladakh, a high altitude desert, unprecedented rainfall has led to flash floods and washing away of villages. Communities in the Himalaya face a threat of survival due to climate instability and climate chaos (http://peoplesscienceinstitute.org/activities/rcg/cc%20final%20may2010-2.pdf).

## 5. Conclusions

Temporal variation in land cover area derived from LANDSAT and IRS series of imageries using latest techniques suggest that vegetation and open rocks area have been increased and debris covered ice and snow covered area decreased in last twenty five years. The previous thin debris covered areas has thinned and resulted in debris mobilization from the lateral moraine and shows the increase in open rock category in the glaciated basin. The glaciers covered by relatively more thin debris covered ice show more increase in open rock cover area. Temporal variation in area of the thin debris covered ice suggests decreasing trend. Decrease in thin debris covered ice and glaciations show logarithm relationship, it indicates that the basins covered by higher percentage of glacier show less degree of shrinkage for thin debris covered ice area and vise verse. Climate change is an ongoing process and its impacts are yet evolving. However, studies indicate that increasing warmth could also result in increasing snowmelt, which will increase the availability of moisture. It can be speculated that this increase in warm and humid conditions will further result in modification of local environment. It is therefore recommended to adopt the agriculture and other suitable system to maintain the livelihood of the community living in these areas immediate to glaciated valley.

**Acknowledgments**

The authors would like to express their thanks to Chairman, Department of Geology, Aligarh Muslim University; Chairman, Department of Geography, Jamia Millia Islamia, New Delhi for providing the laboratory and library facilities. Dr. S. Ahmad the co-author in this publication would like to appreciate the financial assistance provided by Department of Science and Technology, New Delhi, India and UGC, Ministry of Human Resources and Development, Government of India for the financial support to conduct the present research work.

## References

Ahmad, S. and Islam, Z., 2011, Control of Terrain Parameters on Glacier Shrinkage Pattern in Pin Parbati Valley, Himachal Himalaya, India. *Asian Journal of Water, Environment and Pollution*, 8(1), 81-85.

Ahmad, S., Hasnain, S. I., Arha, C. D., Ramamurthy, V. S., Mathur, K. N. and Bassi, U. K., 2004, Analysis of Satellite Imageries for Characterization of Glacio-Morphological Features of the Gangotri Glacier, Ganga Headwater, Garhwal Himalaya. *In: Proceedings of Workshop on Gangotri Glacier Special Publication Series - Geological Survey of India*, 80, 61 - 67.

Aniya, M., Sato, H., Naruse, R., Skvarca, P. and Casassa, G., 1996, The use of Satellite and Airborne Imagery to Inventory Outlet Glaciers of the Southern Patagonia Icefield, South America. Photogramm. *Eng. Remote Sens.*, 62(12), 1361–1369.

Arora, M. K. and Mathur, S., 2001, Multi-Source Classification using Artificial Neural Networks in a Rugged Terrain. *Geocarto Int.*, 16(3), 37–4.

Bahuguna, I. M. and Kulkarni, A. V., 2005, Application of Digital Elevation Model and Ortho Images Derived from IRS-1C Stereo Data in Monitoring Variations in Glacial Dimensions. *Journal of Indian Society of Remote Sensing*, 33(1), 107-112.

Berthier, E., Arnaud, Y., Rajesh, K., Sarfaraz, A., Wagnon, P. and Chevallier, P., 2007, Remote Sensing Estimates of Glacier Mass Balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing of Environ*. 108(3), 327-338.

Bishop, M. P., Kargel, J. S., Kieffer, H. H., MacKinnon, D. J., Raup, B. H. and Shroder, Jr, J. F., 2000, Remote Sensing Science and Technology for Studying Glacier Processes in HIGH ASIA. *Ann. Glaciol.*, 31, 164–170.

Bolch, T., Buchroithner, M. F., Pieczonka, T. and Kunert, A., 2008, Planimetric and Volumetric Glacier Changes in the Khumbu Himalaya since 1962 using Corona, Landsat TM and ASTER Data. *Journal of Glaciology*, 54(187), 592-600.

Gardelle, J., Arnaud, Y. and Berthier, E., 2010, Evolution of Glacial Lakes along the Hindu Kush Hiamlaya Mountain Range between 1990 and 2009. *International Symposium on Benefiting from Earth Observation: Bridging the Data Gap for Adaptation to Climate change in the Hindu-Kush Himalayan Region*, Kathmandu, Nepal, October 2010.

Grabherr, G., Gottfried, M. and Pauli, H., 1994, Climate Effects on Mountain Plants, *Nature*, 369 (6480), 448.

Haritashya, U. K., Bishop, M. P., Shroder, J. F., Andrew, B. G., Bush, Henry, N. and Bulley, N., 2009, Space-Based Assessment of Glacier Fluctuations in the Wakhan Pamir, Afghanistan. *Climatic Change*, 94, 5-18.

Kayastha, R. B., Takeuchi, Y., Nakawo, M. and Ageta, Y., 2000, Practical Prediction of Ice Melting Beneath Various Thickness of Debris Cover on Khumbu Glacier, Nepal, using a Positive Degreeday Factor, in: Debris-Covered Glaciers, C.F. Raymond, Nakawo, M., Fountain, A., Eds; IAHS: Wallingford, UK, 264, 71-81.

Körner, C., 1999, Global Change at High Elevation, In Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystem, *Springer-Verlag*, Berlin, 298.

Krishna, A. P., 1996, Satellite Remote Sensing Applications for Snow Cover Characterization in the Morphogenetic Regions of Upper Tista River Basin, Sikkim Himalaya. *Int J. Rem. Sens*. 1996, 17(4), 651-656.

Krishna, A. P., 1999, Snow Cover and Glacier Assessments in parts of the Sikkim Himalaya by Remote Sensing and GIS. *In: Proceedings of NSSW'99 National Snow Science Workshop, Snow and Avalanche Study Establishment (SASE)*, Manali, India, DRDO, Govt. of India, 33-40.

Kulkarni A.V., and Bahuguna, I. M., 2002, Glacial Retreat in the Baspa Basin, Himalayas, Monitored with Satellite Stereo Data. *Journal of Glaciology*, 48 (160), 171-172.

Nakawo, M., 1979, Supraglacial Debris of G2 Glacier in Hidden Valley, Mukut Himal, Nepal. *J. Glaciol.*, 22(87), 273–283.

Nakawo, M., Morohoshi, T. and Uehara, S., 1993, Satellite Data Utilization for Estimating Ablation of Debris Covered Glaciers, in: Snow and Glacier Hydrology. *Proceedings of the International Symposium,* Kathmandu, Nepal, 16-21 November 1992, G.J. Young, Eds; IAHS/AISH Publication, 218, 75-83.

Nakawo, M. and Rana, B. 1999, Estimate of Ablation Rate of Glacier Ice under a Supraglacial Debris Layer. *Geogr Ann Phys Geogr*, 81A (4), 695-701.

Nautiyal, M. C., Nautiyal, B. P. and Vinay, P., 2005, Effect of Grazing and Climatic Changes on Alpine Vegetation of Tungnath, Garhwal Himalaya, India. *The Environmentalist*, 24, 125–134.

Negi, H. S., Kulkarni A. V. and Semwal, B. S., 2009, Estimation of Snow Cover Distribution in Beas Basin, Indian Himalaya using Satellite Data and Ground Measurements, *J. Earth Syst. Sci.,* 118 (5), 525-538.

Nemani, C. D., Keeling, H. H., William, M. J., Stephen, C. P., Compton, J. T., Ranga, B. M. and Steven, W. R. R., 2003, Running Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. *Science*, 1560- 1563.

Pant, D. N., Susane Groten, M. E. and Roy, P. S., 2000, Forest Vegetation/Landuse Change Detection and Impact Assessment in Part of Western Himalaya. *International Achieves of Photogrammetry and Remote Sensing*, 33 Part B7: 1111-1118.

Racoviteanu, A., Mark, W. and Roger, G. B., 2008, Optical Remote Sensing of Glacier Characteristics: A Review with Focus on the Himalaya. *Sensors*, 8, 3355-3383.

Rakesh, K., Sasikumar, D. A., Kulkarni, V. and Chaudhary, B. S., 2009, Variation in Snow Cover and Snow Line Altitude in Baspa Basin, *Current Science*, 96(9), 1255-1258.

Rathore, B. P., Kulkarni, A. V., and Sherasia, N. K., 2009, Understanding Future changes in Snow and Glacier Melt Runoff due to Global Warming in Wangar Gad Basin, India, *Current Science*, 97(7), 1077-1081.

Roy, P. S., Diwakar, P. G., Vohra, T. P. S. and Bhan, S. K., 1990, Forest Resources Management in Himalaya on Watershed Basis - An Approach using Indian Remote Sensing Satellite. *Asian Pacific Remote Sensing Journal*, 3(1), 11-22.