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Monitoring of Temporal Variation of Snow Depth Using Remote Sensing in Western Himalaya

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Abstract: **Snow cover monitoring is an important parameter for various hydrological, climatological and snow hazard applications. Snow Depth is a vital parameter in assessment of snow melt run-off, snow avalanche forecasting, estimation of water equivalent and many other hydrological applications. In this paper snow depth has been estimated at spatial level using the model developed by Snow and Avalanche Study Establishment and temporal variation has been presented for the winter season 2013-14. The snow depth model has been applied for the Western Himalayan region of Jammu and Kashmir. The mean spatial snow depth increases from November onwards and maximum snow depth appears in the month of March and thereafter, snow depth decreases and observed lowest during the month of June. Spatial snow depth maps have been validated for the winter season and error of 10-30% with recorded data has been observed. These spatial snow depth maps have many applications in hydrology and avalanche forecasting in Western Himalaya.**

Keywords: Digital Elevation Model, Advanced Wide Field Sensor-II (AWiFS-II), Normalised Difference Snow Index (NDSI), Moderate Imaging Spectroradiometer (MODIS).

I INTRODUCTION

Large part of Western Himalaya is seasonally covered with snow. The study of various snow properties at remote areas is an important parameter for the forecasting of avalanches, for hydrological projects and climatological studies. So the monitoring and analysis of snow cover is a crucial factor in cryospheric regions. Snow depth is required for the assessment of snow melt run off, avalanche forecasting and snow water equivalent. In Western Himalaya this parameter is recorded at very sparse point and Snow and Avalanche Study Establishment (SASE) has some manual as well as automatic observation locations where snow depth has been recorded. In this paper we have generated spatial maps of snow depth using the model developed by SASE [1]. These maps have been analysed for the study of temporal variation of snow depth during the season 2013-14 and results have been presented in this paper.

II STUDY AREA AND DATA

Indian Himalaya stretches about 2500 km from east to west [2] and passes through the border of the nations Pakistan, Afghanistan, China, Bhutan and Nepal. The Himalayan ranges are many parallel ranges often referred to as the Pir Panjal, Greater Himalayas, Zanskar, Ladhakh and Karakoram [3, 4]. Study area of the present study comprises of Pir Panjal and Great Himalayan ranges of Jammu and Kashmir state of India. These ranges are vulnerable for snow avalanches and many human fatalities have been reported in past in these ranges.

Snow and Avalanche Study Establishment (SASE) have its own snow-meteorological observatories in Western Himalaya and network of observation locations are shown in Figure 1. Snow meteorological data at these observatories have been collected at 0830 hours morning and 0530 hours evening of Indian Standard Time. Snow depth data from these observatories has been used to generate spatial snow depth maps with the help of remote sensing data and digital elevation model. Remote sensing images of the Advanced Wide Field Sensor-II (AWiFS-II), Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) have been used to generate snow cover images of the study area. Almost cloud free multi-temporal satellite images of AWiFS-II, MODIS and AVHRR have been used for the winter season of 2013-2014.

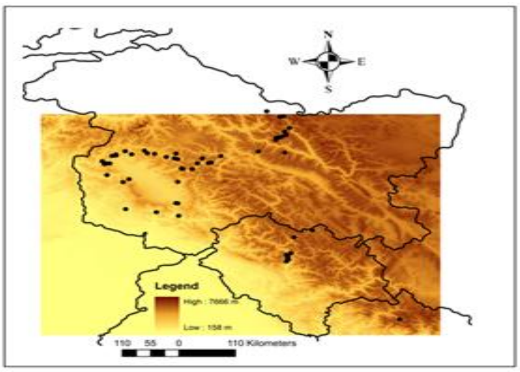

Figure 1: Data observation locations in Western Himalaya

The salient characteristics of AWiFS-II [5],

MODIS [6, 7] and AVHRR [8, 9] sensors are shown in Table1, Table2 and Table3 respectively.

Table 1: Specification of AWiFS-II sensor

Spectral bands	Spectral wavelength (nm)	Spatial Resolution (m)	Quantization (bit)
B2	520-590	56	12
B3	620-680	56	12
B4	770-860	56	12
B5	1550-1700	56	12

Table 2: Specification of MODIS sensor

Spectral bands	Electromagnetic Region	Spatial Resolution (m)	Quantization (bit)
1-2	NIR, VIS	250	12
3-7	VIS, SWIR	500	12
8-36	VIS, NIR, SWIR,TIR	1000	12

Table 3: Specification of AVHRR sensor

Spectral bands	Spectral wavelength (nm)	Spatial Resolution (m)	Quantization (bit)
1	0.58-0.68	1090	10
2	0.725-1.00	1090	10
3A	1.58-1.64	1090	10
3B	3.55-3.93	1090	10
4	10.30-11.30	1090	10
5	11.50-12.50	1090	10

Shuttle Radar Topographic Mission (SRTM) DEM [10] of spatial resolution 90 m has been used in the study. This DEM has been downloaded from internet (http://srtm.usgs.gov). Snow depth data has also been recorded in Western Himalaya using automatic weather station network of SASE and has been used for validation of spatial snow depth maps during the season.

III METHODOLOGY

In-situ recorded snow depth data at few locations have been used to generate the spatial maps of snow depth in the study area. The model developed by SASE has been used to generate the snow depth maps. Input data sheet for the model has been prepared in excel sheet in .xls format and the input parameters are snow depth at observation locations and elevation values of the observation locations. Model first generates a base snow equation based on elevation and snow depth values. This base snow equation is applied on each pixel of the digital elevation model to get the initial snow depth values. Then compensation factor is applied at each pixel for the adjustment of snow depth according to variation in local region of the study area [1]. Satellite images mentioned in the section 'study area and data' have been used to generate snow cover area in the study area. Using these snow cover maps the snow area in the study region has been masked and snow depth maps has been generated.

A. Generation of Snow Cover Area Using Remote Sensing Images

Remote sensing data cannot be used directly because of the presence of distortions in the raw image. So it becomes necessary to correct the raw images received from the sensors for atmospheric and geometric corrections. The process of assigning map coordinates to image data is known as geometric-corrections. The geometric corrections have been done using master image of AWiFS in ERDAS IMAGINE 9.3.

Radiometric corrections have been done for the path radiance using dark object subtraction (DOS) method. Each image received from the sensor is in the form of pixels, which are described by a meaningful digital number (DN). DN reflects the amount of radiations reflected by the earth's surface that are measured by the sensor. These DN values have been converted to radiance values. Spectral Radiance in $mW/cm^2/sr/\mu m$ is estimated using the following equation

$$L_\lambda = (DN)\,(L_{max} - L_{min}) / DN_{max} + L_{min} \quad \text{--(1)}$$

Where L_λ= spectral radiance at the sensor's aperture, DN= input digital number image,
DN_{max} = maximum digital number, L_{max} = maximum radiance value, L_{min}= minimum radiance value.

For MODIS image spectral radiance has been estimated using radiance scale and offset values.

The estimated values of spectral radiance at each pixel were corrected using combination of dark object subtraction (DOS1 and DOS3) model for atmospheric correction and given in detail in [11]. After estimating radiance, reflectance has been estimated by the equation given as following [12],

$$R_\lambda = \pi\,(L_\lambda - L_p).d^2 / (t_v t_z E_0 \cos\theta_z) \quad \text{-------- (2)}$$

Where, t_v and tz are the transmittances of the atmosphere in the viewing and illumination directions respectively, R_λ is the reflectance of a pixel in a particular band, ($L_\lambda - L_p$) is the corrected spectral radiances, Lp is the path radiance, d is the Earth–Sun distance in astronomical units (AUs), E_0 is the mean solar exo-atmospheric spectral irradiance and z is the solar zenith angle calculated for each pixel of the study area [13].

Estimated reflectance values in different bands of the image have been used in estimation of NDSI (Normalized Difference Snow Index). NDSI is an important parameter for the monitoring of snow covered area. NDSI is defined as the ratio of difference of two bands, one in visible and one in the short wave infrared parts of the spectrum and useful to map snow [14, 15]. NDSI is estimated for each image as following,

$$NDSI = (R_{GREEN} - R_{SWIR}) / (R_{GREEN} + R_{SWIR}) \quad \text{-------------------------------------} (3)$$

Where, R_{Green} is the reflectance of Green Band and R_{SWIR} is the reflectance of Short Wave Infra-Red Band.

The snow cover area in the image has been selected and no-snow covered area has been masked using the criteria of NDSI >= 0.4 and reflectance in NIR >11 [16, 15]. This criteria has been applied in the ERDAS Imagine modeler to generate images of snow cover only. For generated snow cover area the snow depth maps has been developed using SASE model [1]. Snow depth maps have been generated for more than 10 days of the season 2013-14 and temporal variation in snow depth has been monitored and analysed in the study area.

IV RESULTS AND DISCUSSION

Figure 2 shows the spatial snow depth map in the Pir Panjal and Great Himalaya ranges of Jammu and Kashmir for 27-January-2014. Area with gray colour shows the no-snow region in the study area and regions with altitude below 1800 m are generally free from snow on 27-January-2014. Red colour shows snow depth up to 50 cm, Green colour shows snow depth from 50 to 75 cm, Blue colour shows snow depth from 75 to 100 cm and yellow colour shows snow depth above 100 cm in the study area. Similar snow depth maps have been generated for other days of the season 2013-14 and given in Table 4. Average snow depth values of the spatial snow depth maps for different days are also given in the Table 4. It has been observed that snow depth builds up from average snow depth of 3 cm on 18-November-2013 to maximum of 196 cm on

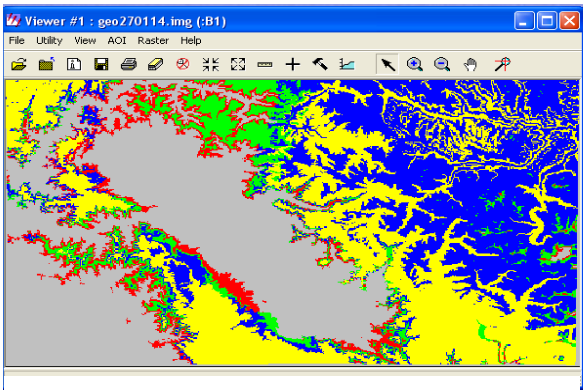

Figure 2: Spatial snow depth map for 27-January-2014 in the study area

Table 4: Temporal variation of average snow depth in the study area

DATE	Average Snow Depth (cm)
18-11-2013	3
12-12-2013	2.9
19-01-2014	48
21-01-2014	42
26-01-2014	73
27-01-2014	67
28-01-2014	65
31-01-2014	55
12-02-2014	120
13-02-2014	119.6
20-02-2014	106
24-02-2014	120
26-02-2014	114
06-03-2014	124
17-03-2014	196
31-03-2014	189
01-04-2014	188
09-04-2014	185
20-04-2014	134
24-04-2014	124
29-04-2014	104
02-05-2014	76
09-05-2014	46
16-05-2014	38

17-March-2014. After that snow depth start depleting in the region and on 16-May-2014 the mean snow depth has been observed 38cm. Snow depth increases from November onwards in the Western Himalayan region due to wide spread snowfall from western disturbances. The frequency of western disturbances increased from November to March and so snow depth also increases in the region. March onwards due to rise in temperature, snow depth start melting and so snow depth depleted. Figure 3 shows the temporal variation in average snow depth during days of the winter season 2013-14.

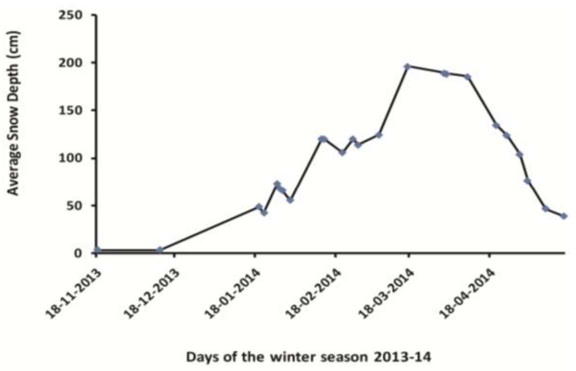

Figure 3: Temporal variation of average snow depth in the study area during winter season 2013-14

The spatial snow depth maps thus produced have also been validated at few locations in the study region and error of the order of 10-30% has been observed during different days.

V CONCLUSION

In this paper temporal variation in spatial snow depth maps have been observed in the Western Himalayan region. The spatial snow depth maps have been generated from point snow depth data of few locations using remote sensing images. For the winter season 2013-14 maximum snow depth has been observed for the month of March. Snow depth starts building up from November onwards due to snow fall from western disturbances and snow depth increases in subsequent months as frequency of snowfall increases. March onwards snow cover starts depleting due to rise in temperature and snow depth decreases in the region. These spatial snow depth maps may be of immense importance in the applications of hydrology and glaciology in the Western Himalaya.

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