GIS based Estimation of snow depth in mountainous Himalayan region: A case study

Chander Shekhar*1, S K Dewali*, Snehmani*

*Snow and Avalanche Study Establishment, Chandigarh, India – 160036, India

1 Corresponding Author: cskanda@gmail.com

Abstract:

High reflectance in visible region and large spatial extents of seasonal snow in Indian Himalayas allow it to play important role in deciding the climatology and hydrology of Indian sub-continent. There is high spatial variability in seasonal snow cover in Himalayan in terms of the areal extents and various snow characteristics. Morphological evolution of snow cover takes place as a result of the snow deposition during various snow storms and thermo dynamical processes within snow pack. Stability of snow over a mountain slope is of importance for various recreational, developmental and transportation activities. Large mass of snow moving downhill (i.e. Snow Avalanche) can affect adversely all these activities and thus affect economy of nation. Stability of snowpack over a mountainous slope is governed by various snow, meteorological and terrain parameters. Snow depth is one of the important variable that contribute significantly in the avalanching of snow loaded slope, given favorable terrain parameters. To assess the avalanche hazard potential, accurate modeling of snow depth is necessary. In the present study, a GIS based method for estimation of the snow depth in a part of North-West Himalaya has been attempted. A hybrid method was adopted for the estimation of the snow depth to cover the limitation of limited observatory network in Himalaya. Firstly, a model factor (λ) is calculated to establish the relation between snow depth at observation points and their elevations in the study area. Snow depth is calculated at each pixel of study area using snow depth of known observation points, model factor(λ), weight factors and DEM. MODIS satellite data is used to restrict the snow depth maps to snow covered areas only. Snow depth maps for one winter period 2007 to 2008 were generated and analyzed. Snow depth data of Automatic weather stations (AWS) installed in study area were used for validation. Correlation values of around ~ 0.9 have been found between modeled and measured data. Limits and limitation of the method have been discussed. The study reveals that regular monitoring of snow depth near avalanche prone areas along with other terrain and meteorological information can provide valuable inputs for snow pack stability assessment that serves as an important input to avalanche forecasters.

About the Author:

Mr. Chander Shekhar received his M.Sc. (Physics) degree from Panjab University, Chandigarh in 2005 and pursuing PhD (Physics) from Panjab University, Chandigarh, India. Presently, he is working as a researcher in Snow and Avalanche Study Establishment (SASE), Defence Research and Development Organization (DRDO). His research interest includes study of radio-metric properties of snow, glaciers in optical region of EM Spectrum; Hyper-spectral remote sensing for snow parameters retrieval; Geo-spatial modeling of snow physical properties.

E mail ID: cskanda@gmail.com

Contact No: +91 – 0172 2699804 (391)

Introduction

A large part of the Himalayan Mountain regions get covered with seasonal snow during winter season (that remains mainly from November to April). April onwards the seasonal snow starts melting and permanent snow bodies remains depending on altitude and temperature regimes. During successive snow-storms in winters, snow pack formation over the earth takes place as a group of different snow layers with different physical properties. Seasonal snowpack evolves over time due to change in microclimatic variables as the winter advances. The morphological changes in snow pack are continuously occurring as a result of which the strength and stability parameters of snow pack over a particular region are changing. Over a mountain slope, with the increase in the amount of snow during successive snow spells, the chances for downhill movements of large chunks of snow (called snow avalanche) increase given favorable terrain and weather parameters. Snow avalanches affects economy of nation in indirect manner. So, the stability of snow pack over a slope is a parameter of interest for avalanche forecaster that is further linked to number of developmental, tourism, transportation and mountain sports related activities during the winter season [1]. So accurate modeling of snow depth is important for assessing the avalanche hazard potential on a snow covered mountain.

Generally, the data on snow amount deposition is collected from a distributed networks of ground observatories using snow depth measuring rod (manual method) and Automatic Weather Stations i.e. AWS that uses radiation sensors. There is observed a large spatial variability in the snow amount at relatively short distances and that too dependent on a number of factors interacting with each other in a complex fashion. Some of the factors having an influence on snow depth amount are exposure to the sun, the physical properties of the effective surface, air moisture content, the water supply of vegetation and the actual surface-atmosphere exchange characteristics [2]. Also the temporal information is not adequate which further restricts the possibilities for accurately interpolating the spatial and temporal information at regional scale. The remote sensing and GIS tool is very helpful to obtain the continuous information about the snow cover over the spatial and temporal domains. A number of attempts have been made by various researchers to interpolate the snow depth, but their usefulness is restricted as many variables causing the spatial variability (i.e. topographic variations) are not included in these models. In addition, a number of researchers have used the remote sensing based techniques for snow-cover parameters extraction in optical and microwave domains. It is observed that snow depth cannot be determined directly using VIR (Visible and Infra Red) imagery. Polari-metric SAR (Synthetic Aperture Radar) has also the potential to be used to measure snow depth. Over the local scale, snow depth amount can be determined from airborne digital stereo-photogrammetric and airborne laser profiling schemes. Over the global scale, snow depth patterns on the earth's surface are determined by the use of space borne passive microwave remote sensing techniques.

Indirect approaches are utilized to extract the required information about snow depth [3]. Spatial interpolation of snow depth had been another indirect method in many research projects for snow depth estimation. As per these, the interpolation procedures must incorporate the effects of physical processes which determine the climate spatial distribution [4-6]. Various authors have used simple procedures, which include the latitude and longitude of weather stations. Liston *et al*, 2006 [7] showed that the inclusion of elevation was critical to account for strong influence of topography on snow depth amount variations. In the present study, we have integrated the topographic variable i.e. altitude (by using Digital Elevation Model) and the snow depth observations from the point network in a GIS frame work to model mean snow depth.

Study area and Data used

The study area covers the snow covered mountains those falls in districts of Tithwal and Kupwara in Jammu & Kashmir (India). The area negotiates and crosses the Pir Panjal ranges of Indian North West Himalayans. The geomorphology of area is typical of Pir Panjal ranges with no vegetation beyond 3300m above m.s.l. (mean sea level). This area receives heavy snowfall during winter due to western disturbances [8]. There are a number of major avalanche sites affecting the road along this axis. These avalanche sites trigger during winter due to failure of weak snow layers and causes hazard along the highway by affecting vehicular traffic and unavoidable pedestrian movements. A snap view using Landsat imagery of the study area along with reference observatory stations is shown in Figure 1 for an easy outlook.

Snow meteorological data (SMD) that includes temperature, standing snow amount, fresh snow amount, wind speed and relative humidity etc. collected from four observatory locations of winter season 2007-08 has been used for the present study. To include the effect of terrain variables i.e. topographic variations, the high resolution (40m) Digital Elevation Model (DEM) generated from survey of India topo-sheets was employed. The data of MODIS (Moderate Resolution Imaging Spectral-radiometer) sensor onboard terra and aqua satellites was processed to obtain the snow and non-snow areas information for the study duration on days having minimum cloud free conditions [9]. Snow depth data from two AWS (Automatic Weather Station) locations have been used for validation purpose.

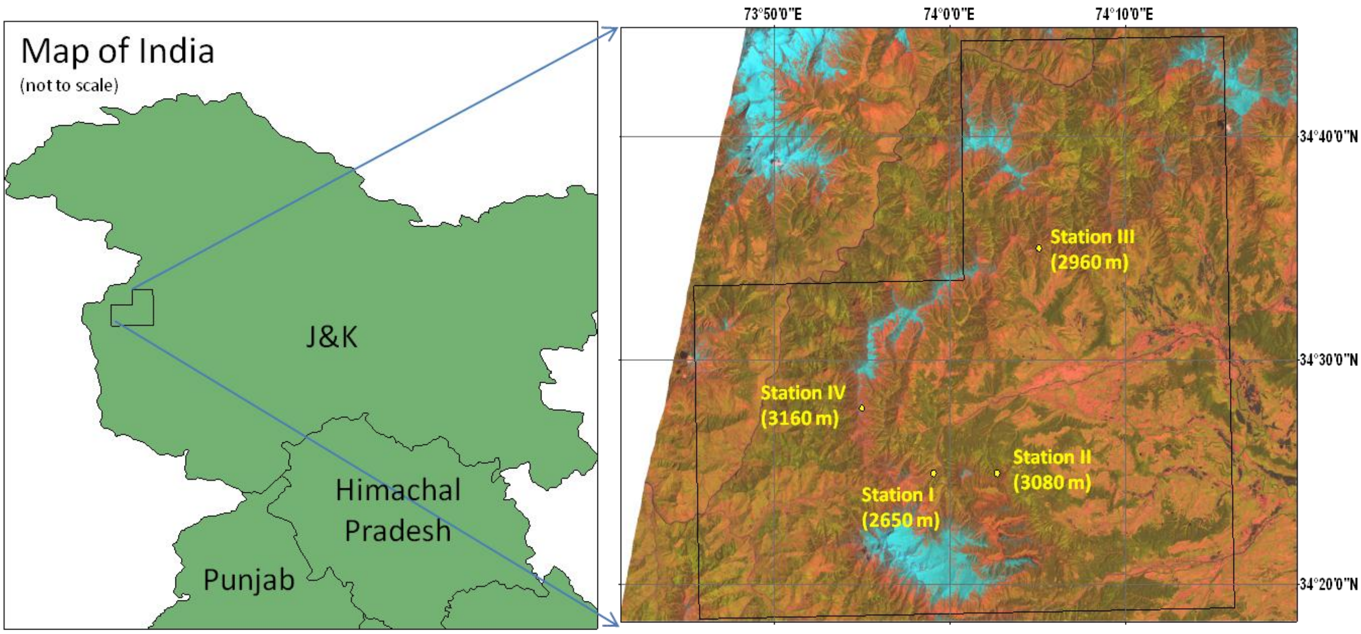

Figure 1: The study area shown using Landsat imagery in false color composite

Methodology

The approach used for snow depth modeling is a hybrid approach that utilizes the physical relationship between snow depth at a particular point and the topography. GIS (Geographic Information System) software ArcGIS had been used for this analysis. To generate the snow depth map from point observation, snow depth is calculated at each pixel of the study area with respect to observation point using the elevation variation from DEM. A weighted inverse distance has also been calculated for each pixel from the four observational reference point observatories. Final snow depth map was generated by taking weighted sum of the snow depth maps of all observation points. To restrict the study to the snow cover region of the study area, MODIS images of the study period were processed. The reflectance maps were obtained and then NDSI index calculations were done to obtain the snow and non-snow areas. The snow depth maps were generated for the period Nov 2007 to April 2008. The calculated snow depth maps have been validated using data from AWS (Automatic weather station) situated in the study area.

Model parameters calculation

In present study, the variation of snow depth with altitude above m.s.l. had been the main focus. This is observed that variation of snow depth with altitude is non linear in Himalaya. The modeling has been done based on the model equation obtained using variation of snow depth with altitude (Point basis) as proposed by Liston et al, 2006. i.e.

$$S_p = S_o \left[\frac{(1+\lambda\,(E_p - E_o))}{(1-\lambda\,(E_p - E_o))} \right] \qquad (1)$$

Where Eo and Ep are the altitudes of the known base station and station whose snow depth has to be determined respectively. S_o is the snow depth of known base station. S_p is derived snow depth amount of a station located at an altitude of E_p. 'λ' is called the model factor (or λ value). Snow depth data of four observatory locations (situated within altitude range of 2650 - 3160 m above m.s.l.) of winter season 2007-08 along with equation (1) had been used to calculate the model parameter (λ) for the study area. The λ values have been calculated for all the dates of each month of study duration and then an average value of model factor is calculated for the respective month for further use in snow depth estimation at other locations.

Snow depth estimation and Validation

To incorporate the elevation variation, high resolution digital elevation model generated using SoI topo-sheets had been used. To calculate the Euclidean distances, the observatory location had been brought in GIS environment. Based on above equation the distance maps for each station had been generated. These distances had been normalized in the range 0 to 1 in such a way that the sum of all four distances (distance of any pixel or point from all four field stations) is one. These normalized distance maps were finally converted into the inverse distance weights ranging from 1.0 to 0.0. To generate the snow cover area information, the data from Moderate resolution Imaging Spectro-radiometer (MODIS) sensor onboard terra and aqua satellites had been utilized. The snow cover area information was used to restrict the snow depth estimation to snow covered areas only. The modeled snow depth maps of four different dates have been shown in figure 2. For validation, the snow depth amount data of two AWS locations had been utilized. Calculated values of the snow depth (from modeled maps) had been compared with measured snow depth data of AWS.

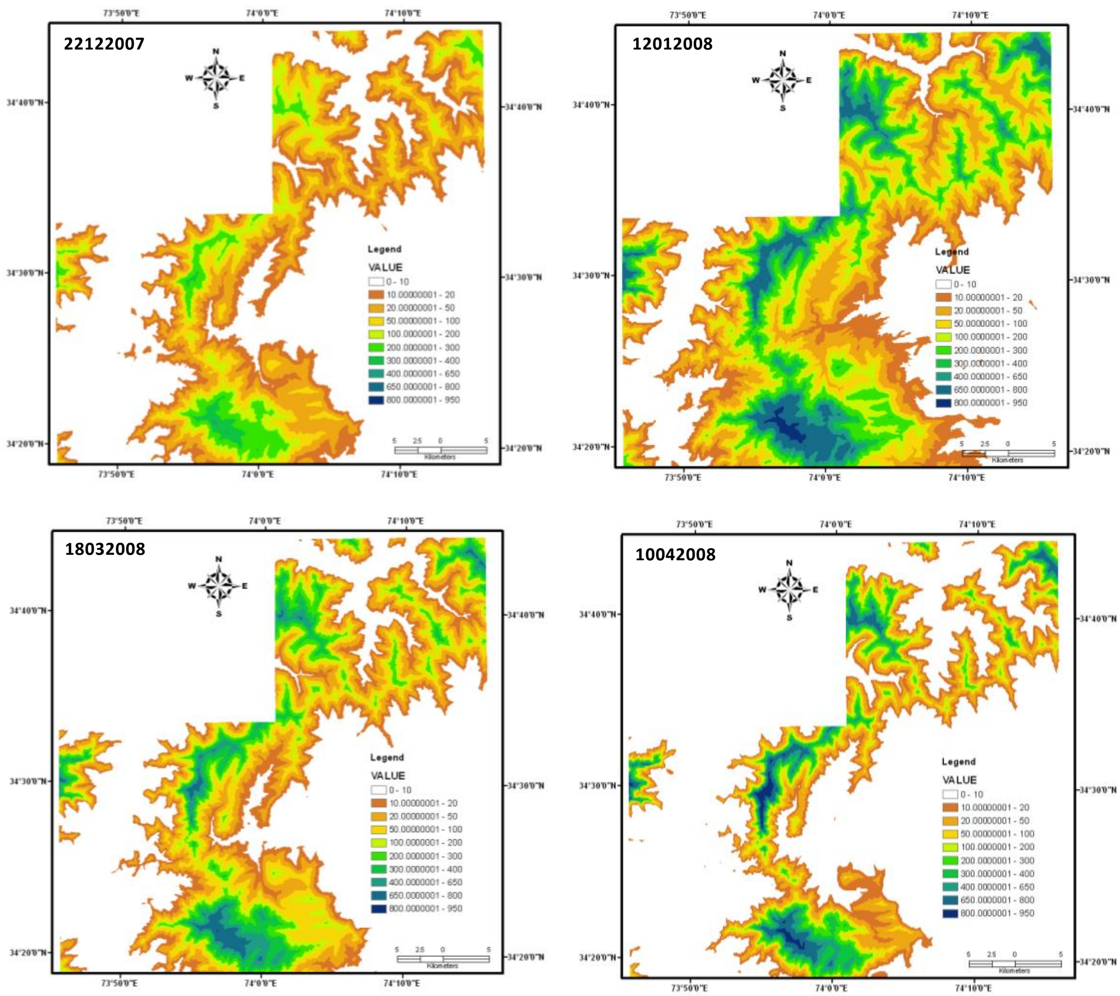

Figure 2: Modeled Snow Depth maps for different months (a) 22 Dec, 2007 (b) 12 Jan, 2008 (c) 18 Mar, 2008 (d) 10 April, 2008.

Results and Discussion

Analysis of data shows that variations in the snow cover buildup among different stations are not same for all the winter months, but varying on the monthly basis. So the model factor (λ) has been calculated month wise to capture the variation of the snow depth with elevation more accurately during a particular period. This model parameter is found based on various combinations of different stations located at different altitudes and then average values have been taken for each month. Average λ values for months December, January, Feb, Mar, April have been 0.00150, 0.001, 0.00112, 0.00144 and 0.00254 respectively. The λ factor value is found to be decreasing for the duration December to January and then increasing from January to April. The variation in model parameter helps to decide the boundaries with in which the GIS based model for snow depth will provide good results. The higher altitude difference between the two reference observatories locations will lead to higher coverage range of prediction for the snow depth hybrid model. For validation of snow depth maps, snow depth amount values from the pixels where automatic weather station (AWS) installed were taken. These values were compared with the measured snow depth values. Figures 3 shows comparison for two different stations. A very good correlation of the predicted snow depth amount was found with the AWS site data. One probable reason the slight difference between the measured and ground AWS values may be due to the local terrain effects. The coefficients of correlation for AWS I and AWS-II have been found to be 0.98 and 0.9 respectively.

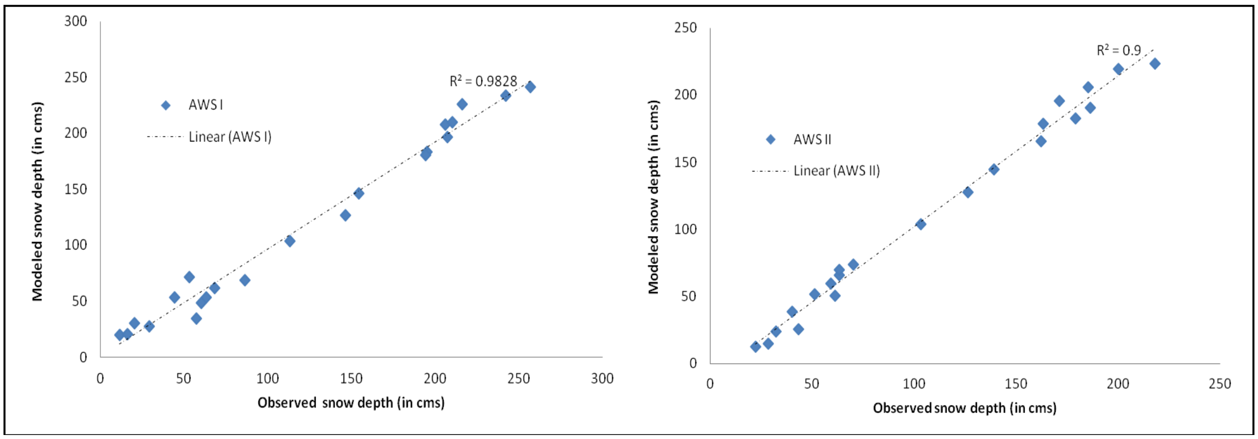

Figure 3: Comparison of modeled and observed snow depth using AWS data

The limiting values of elevation (minimum and maximum) for calculation of λ will be decided by the elevations of the observation station in the study area. In case λ is negative, snow depth will decrease with increase in altitude. Snow depth will become negative when product i.e. λ (Ep- Eo) < -1, which has no physical significance (no snow above this elevation). So λ (Ep- Eo) < -1 is the limit below which model cannot calculate significant snow depth values. From calculation point of view, negative snow depth values can be assigned zero values. To increase the altitude range for which model calculate snow depth, more observation points with wider altitude variations need to be included. This would be worth to mention that very limited stations data is available for the study in the used study area. This is practical problem. So Eq.(1) and interpolation methods have been used collectively to address the limitation of limited data availability. Observation data of more point locations (presently not available for this area) need to be included in the future. Also more manual observations and snow depth calculated from microwave SAR data will be used for more realistic validation. The inclusion of more parameters like slope, aspect and solar illumination corrections will further help to achieve more accurate results. This type of information can prove to be very helpful for avalanche forecasters and other snow depth based applications.

Conclusions

The results found based on GIS based modeling of snow depth (with-in certain limits as discussed in section 4) are found to be encouraging. The inclusion of data of more number of years and more number of stations will further help to get improved results. The integration of multispectral information for snow covered area help in improving the accuracy of results obtained by removal of the non snow area. Also this approach can be integrated with other methods of retrieving snow depth information. For example in passive microwave domain, the AMSR-E sensor gives average value of snow depth over a larger area [10]. GIS model outputs snow depth maps at better resolution than passive microwave method, meaning thereby that the model could be used to focus on small topographical variations which could help deriving better outputs. Decreasing snow depth patterns in the late winter are also required to be analyzed and correlated with the ablation of snow cover. During the late winter months melting starts and the inclusion of melt factor based on slope, aspect and solar illumination conditions can provide better results. A regular monitoring of snow depth amount near avalanche prone areas along with other meteorological information can provide a valuable input for stability assessment to avalanche forecasters.

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