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Climate Change Impact on Snowmelt Runoff Modelling for Alaknanda River Basin

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Abstract
Variable Infiltration Capacity hydrology model is a physically based, Semi-distributed macroscale hydrological model that represents surface and subsurface hydrologic processes on spatially distributed grid cell. In mountainous watersheds Snow melt can have a significant impact on the water balance and at certain times of the year it could be the most important contribution to runoff.In this study the Variable Infiltration Capacity Hydrology model has been successfully applied for Alaknanda River Basin. As input to the model long-term(1999-2008) daily meteorological dataset such as temperature, precipitation, wind speed and geospatial dataset such as land cover data, Elevation data , soil data were provided from multiple sources (NRSC,NBSS&LUP,NOAA and IMD). In addition, the spatial distribution of runoff, snow cover and snow depth were analyzed and compared with the monthly stream flow data obtained from rudraprayag (lat-30.285, lon-78.98), MODIS 8 day snow cover product (MOD10A2) and AMSRE snow depth product. The model runs resulted in an increase in Snowmelt Runoff for the period of record (2001–2006), as a result of decrease in Snow Cover and Snow Depth for the monsoon period. In this study Nash–Sutcliffe efficiency is 0.92 which indicate a good fit between observed and simulated runoff.
Keywords: VIC, Snow, Snow depth, Snow cover, GEFS, IMD, AMSRE, MOD10A2, Discharge

1. Introduction

In snow covered area, snow melt runoff is predominant during summer, which when failed to be managed properly leads to inadequate fresh water supply in mountainous region, downstream flooding and consequent rise in the sea level. Uttarkhand state receives considerable amount of rainfall & snowfall. It also serves as origin for major rivers like Yamuna, Alaknanda & Bhagirathi. Still the state is facing severe water scarcity due to improper management of water. It also faces disastrous events owing to its topography. In order to overcome these problems, proper management practices have to be implemented, for which an accurate estimate of total runoff from the basin is to be estimated, which can be achieved through hydrological modeling. In India, the perennial Himalayan rivers are fed by snowmelt and glacier melt run-off. The regular mapping and monitoring of snow cover and glaciers remain a challenge in these hilly areas due to inaccessibility and few ground observation sites. Therefore the importance of seasonal snow cover, glaciers and their associated melt run-off of this region is to be considered. The objective of this study is to carry out macro scale hydrological modeling for snow clad basin to estimate the runoff generated from the snow covered area using VIC model. Hydrological modeling is one efficient way for consistent long term behavioural studies. Hydrological modeling is a mathematical representation of natural processes that influence primarily the energy and water balances of a watershed. The fundamental objective of hydrological modeling is to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner. Powerful spatially-distributed models are based on physical principles governing the movement of water within a catchment area, but they need detailed high-quality data to be used effectively. Some of the basic data requirements of hydrological modeling are:

i) Meteorological data (precipitation, temperature, wind speed, relative humidity, atmospheric pressure, albedo, longwave radiation, shortwave radiation, atmospheric density, cloud cover)
ii) Terrain data (elevation, slope, flow direction, flow accumulation)
iii) Land use / land cover data (land use classes & their area, vegetation classes & its properties like root depth, root distribution, height, leaf area index, roughness, displacement, canopy resistance)
iv) Soil data (layer-wise physical, hydraulic & textural properties like soil size, thickness of each layer, soil temperature, particle density, bulk density, bubbling pressure, texture)

The conversion of snow and ice into water is called snowmelt, which needs input of energy (heat). The physics of melting snow and transformation of melt water into runoff are very important aspect of snow hydrology. Snowmelt is the overall result of different heat transfer processes to the snow pack. The sun is the ultimate source of energy responsible for the melting of snow pack. There is a complex interaction between the incoming solar radiation, earth’s atmosphere and terrain surface. Hence a number of intermediate steps in the process of energy transfer to the snow surface have to be considered to understand the process of snowmelt and also to make quantitative estimations of the melt.

2. Methodology

Variable Infiltration Capacity (VIC) model, which is a physically based land-surface model, is capable of simulating energy and water balance. The model simulated a number of hydrologic and climatic variables, such as frozen soil, snow depth, snowmelt, soil temperature, and river discharge. The late winter flood events are typically driven by snowmelt, or a combination of snowmelt and rainfall, due to seasonal increases in temperature to above freezing. Snowmelt simulation using the VIC model has been analyzed by Sinha and Cherkauer (2010), Sinha et al. (2010), Tan et al. (2011), Andreadis et al. (2009), and others. Particularly, Feng et al. (2008) compared the VIC and the Snow Thermal Model (SNTHERM) by Jordan (1991) and showed a good agreement between the two models in snow simulation. The snow processes model has been incorporated into the macro scale Variable Infiltration Capacity (VIC) hydrologic model, which essentially solves an energy and mass balance over a gridded domain [Liang et al., 1994]. Aggarwal et al found snowmelt runoff in Himalayan Basins depending on the sophistication of representation of snowmelt (Temperature index vis a vis energy balance model) and integrating remote sensing-based SCA, DEM data and traditional hydrometeorological data. Haddeland et al. (2011) investigated snow accumulation and melt in Himalayan basins using land surface characteristics such as number of snow layers, snow albedo, and routing of melt water though the snowpack and snowmelt approach (Siderious et al.,2013). In this study VIC large scale hydrology model was chosen in order to estimate snowmelt runoff based on different climate dataset and 25 elevation band. Overall snowmelt runoff per grid cell (0.5 degree resolution) in the Alaknanda basin was averaged over the period 2001 to 2006.GEFS Reforecast ensemble data for maximum temperature, minimum temperature, rainfall (0.5 degree) (Hamill et al., 2013) and IMD 0.5 degree daily gridded rainfall data (Kumar et al., 2013 and Srivastava et al., 2009) for the period 1999 to 2008 were used to derive the VIC hydrology model.). A 3min ×3min grid level modeling framework had been set up for the entire country using the geospatial and meteorological dataset (Fig. 1). During the rainy season (Jun-Sep) IMD rainfall and for other season (Oct-May) GEFS rainfall data was used as input for this model. Daily Discharge data from Rudraprayag (lat-30.285, lon-78.98) was acquired for the validation of the large scale catchment model. In the models, runoff is generated from water that has percolated through the soil column. Such water arises from both rainfall and snowmelt. In this study we compared observed snow cover and snow depth data with the output of the VIC model for 2001-2006 and showed that the model was able to predict snow depth and snow cover reasonably well (Cherkauer and Lettenmaier, 1999; Cherkauer et al., 2003).Table1. gives a description of general characteristics and snow module characteristics of VIC.

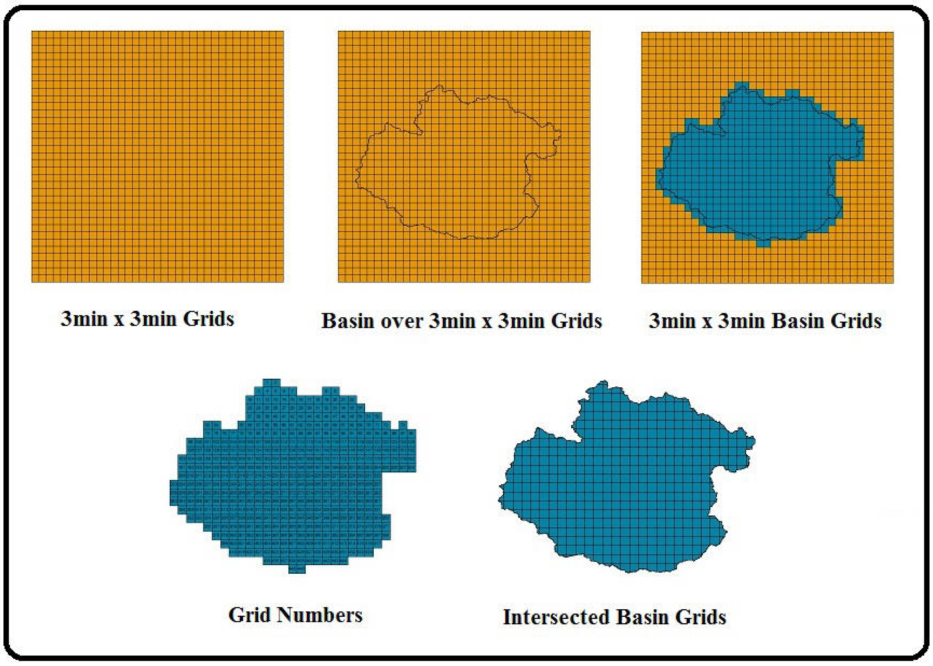

Fig. 1 3min×3min Grid for Alaknanda River Basin

Table 1. General characteristics and snow module characteristics of the VIC model used:

Snowmelt generation	Internal energy balance
Elevation bands	20
Structure	Grid (0.05 degrees) sub daily timestep
Forcing variables for snow module	Minimum and maximum temperature, precipitation and wind speed
Snow–rainfall split	Internal, based on temperature threshold (0.5 °C)
Period of calculations	Spin up period from 1999 to 2008
Data sources Land use	Bhuvan
Soil	NBSS & LUP

3. Results

3.1 Discharge Validation

The vegetation, soil, and forcing (meteorological) data as described were applied to the VIC-2L model to simulate evapotranspiration, runoff, and soil moisture at each grid over the Alaknanda River basin (Fig 2.) for year 1999 to 2008. To compare the VIC-2L model simulated runoff with the observed stream flow, the simulated runoff is routed through the river network using a simple routing model as suggested by Lohmann et al, (1998) (Fig 5.). The routed monthly runoff at these stations was compared with the monthly observed stream flows, respectively as shown in Fig. 4. The R^2 showing agreement between the trends of simulated and observed stream flow records were found to be as 0.85, after calibration. The models show flow regime patterns with discharge peaking in July to August. There is good correspondence between the observed runoff in terms of rise, maximum and decline of the discharge peak patterns. Observed daily stream flow data from 1999 to 2008 were obtained from rudraprayag (lat-30.285, lon-78.98). Figure 3. Shows the base map of Alaknanda Basin up to Rudraprayag.

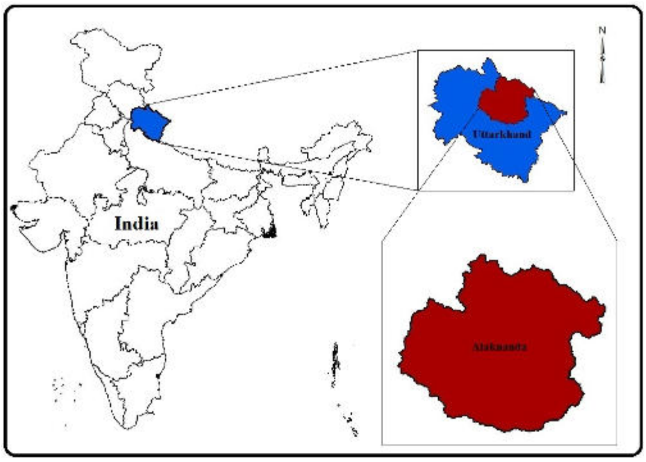

Fig. 2 Location of the Study area

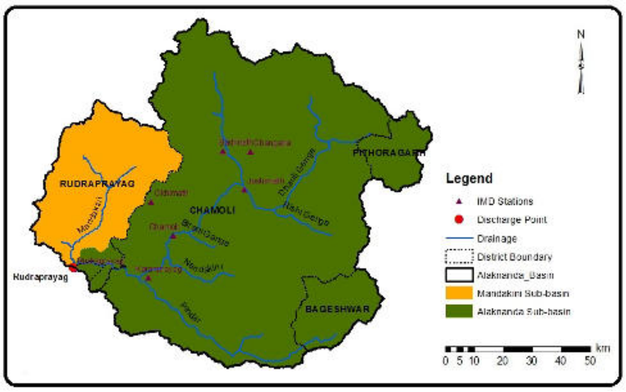

Fig. 3 Base map for Alaknanda Basin upto Rudraprayag

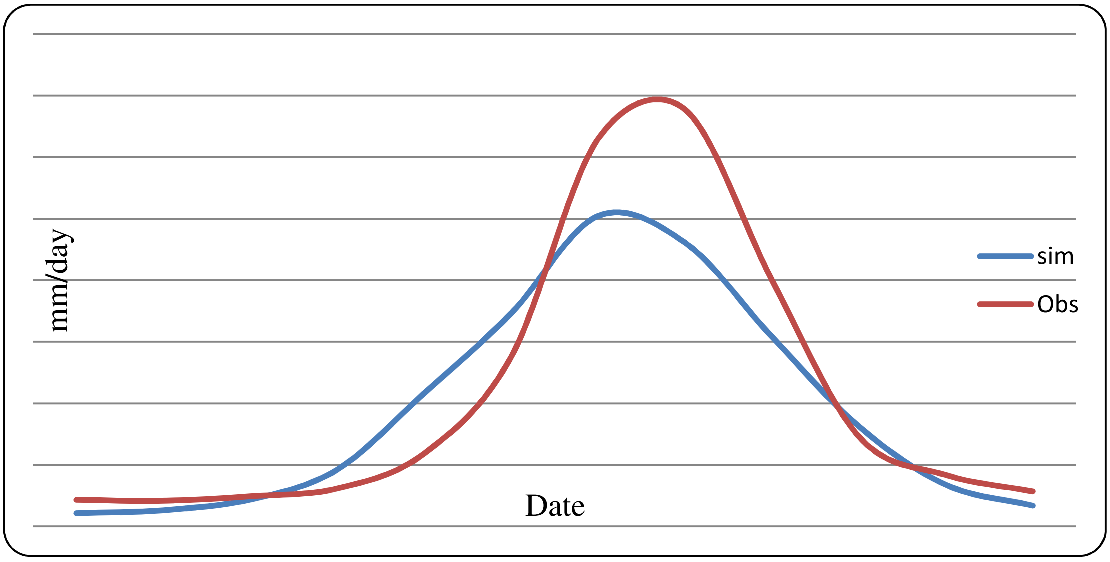

Fig. 4 Modeled and measured monthly average Discharge for Alaknanda River Basin

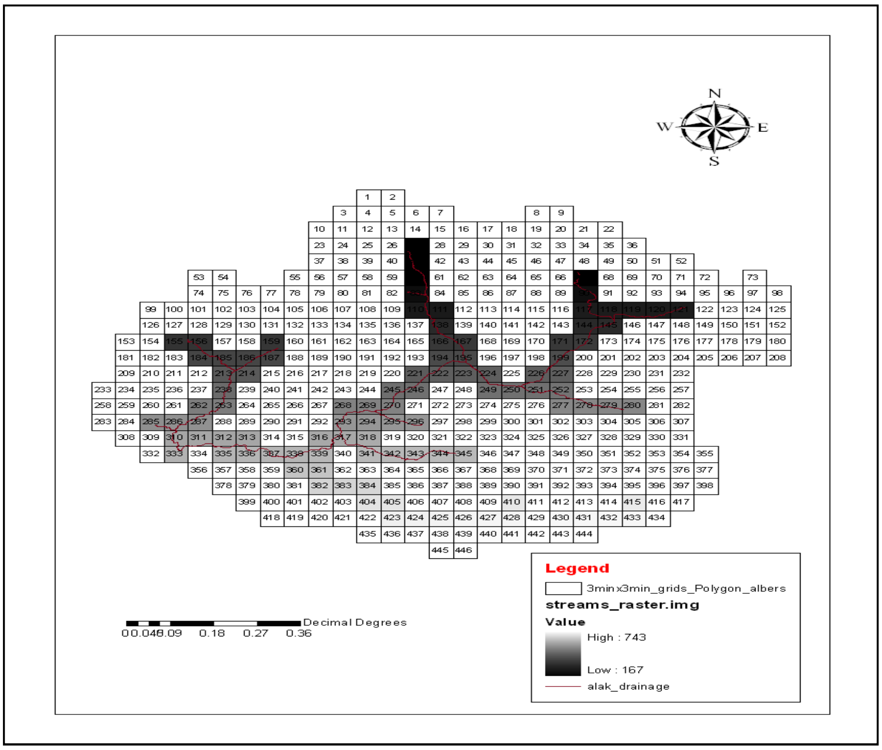

Fig. 5 Alaknanda delineation and river routing network with grid cell numbering

The performance of the VIC model simulations was evaluated using the Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) index (Eq. (1)).NSE can vary minus infinity to one. In this study NSE is 0.92 which indicate a good fit between observed and simulated runoff.

$$\mathrm{NSE} = 1.0 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \longrightarrow \qquad 1$$

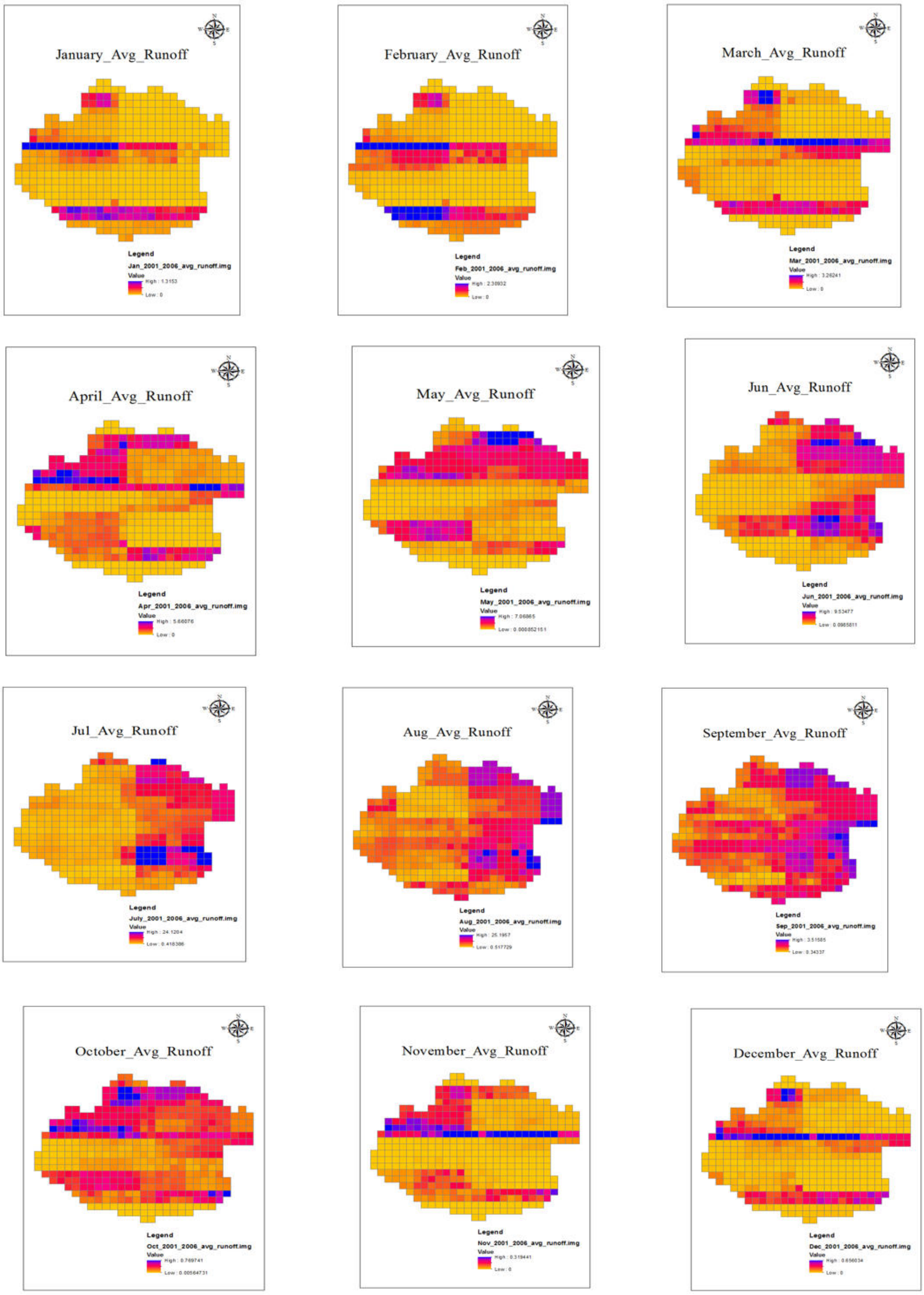

Fig. 6 Gridded Image of Runoff for Alaknanda River Basin

Figure 6 indicates the runoff in the gridded image format generated by a Java programme from the VIC hydrology model output fluxes. It is clear from the picture that the runoff is more for rainy season (July-September).

3.2 Snow Depth Validation

The global data providing the snow depth available from AMSR-E is shown in the Fig 8.The snow depth data is equirectangular (lat. 90°S and long. 0°E). The passive microwave data is acquired from Advanced Microwave Scanning Radiometer - Earth Observing System Sensor on the NASA's Aqua Satellite for the year of 2002. The Level- 3 land surface product of AMSR-E includes Brightness temperature, Snow Depth, Soil Moisture, Sea Surface Temperature, SeaIce Concentration. Ancillary data includes time, geolocation, and quality assessment. The data was acquired from JAXA (Japan Aerospace Exploration Agency). The data is in the units of mm and the type is signed int. The dataset acquired from passive microwave remote sensor that is AMSR-E was first extracted for the study area and then multiplied with the scale factor 1.0.The minimum and maximum values are 0 and 10000. The available AMSRE images were processed and projected with the WGS 1984 UTM ZONE 43N projection system. The Alaknanda River basin area was then extracted from this mosaicked scene to assess the snow depth in the study area. Observed snow depth data with the output of the VIC model for the years 2001 to 2006 showed the model was able to predict snow depth reasonably well for both sites (Figure 7). The maximum snow depth was from April to June. Correlation coefficient between the observed and simulated snow depth was 0.7.The Nash-Sutcliffe-Efficiency is 0.95 which indicates a best fit between observed and simulated snow depth.

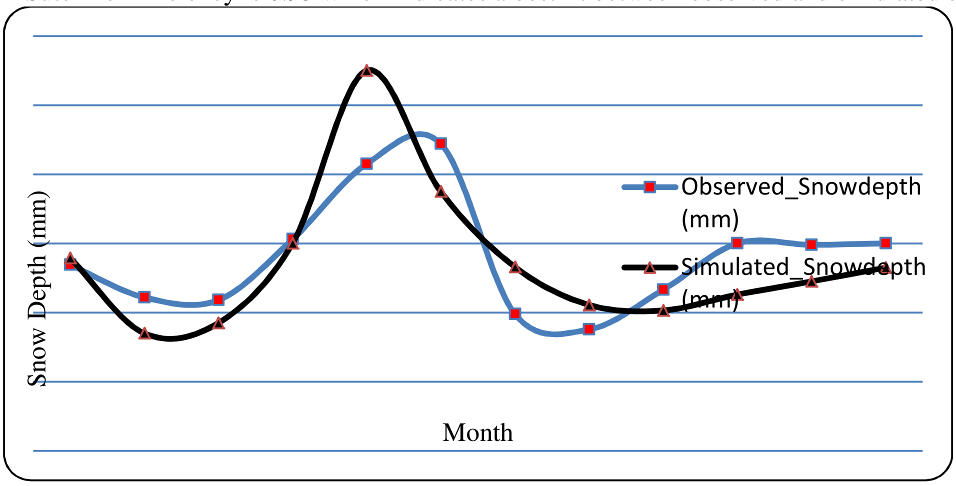

Fig. 7 Modeled and measured monthly average Snow Depth for Alaknanda River Basin

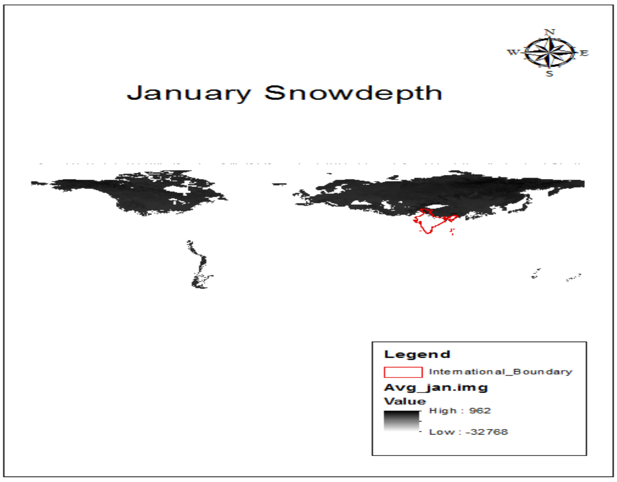

Fig. 8 AMSRE Global 0.25 degree Snow depth product

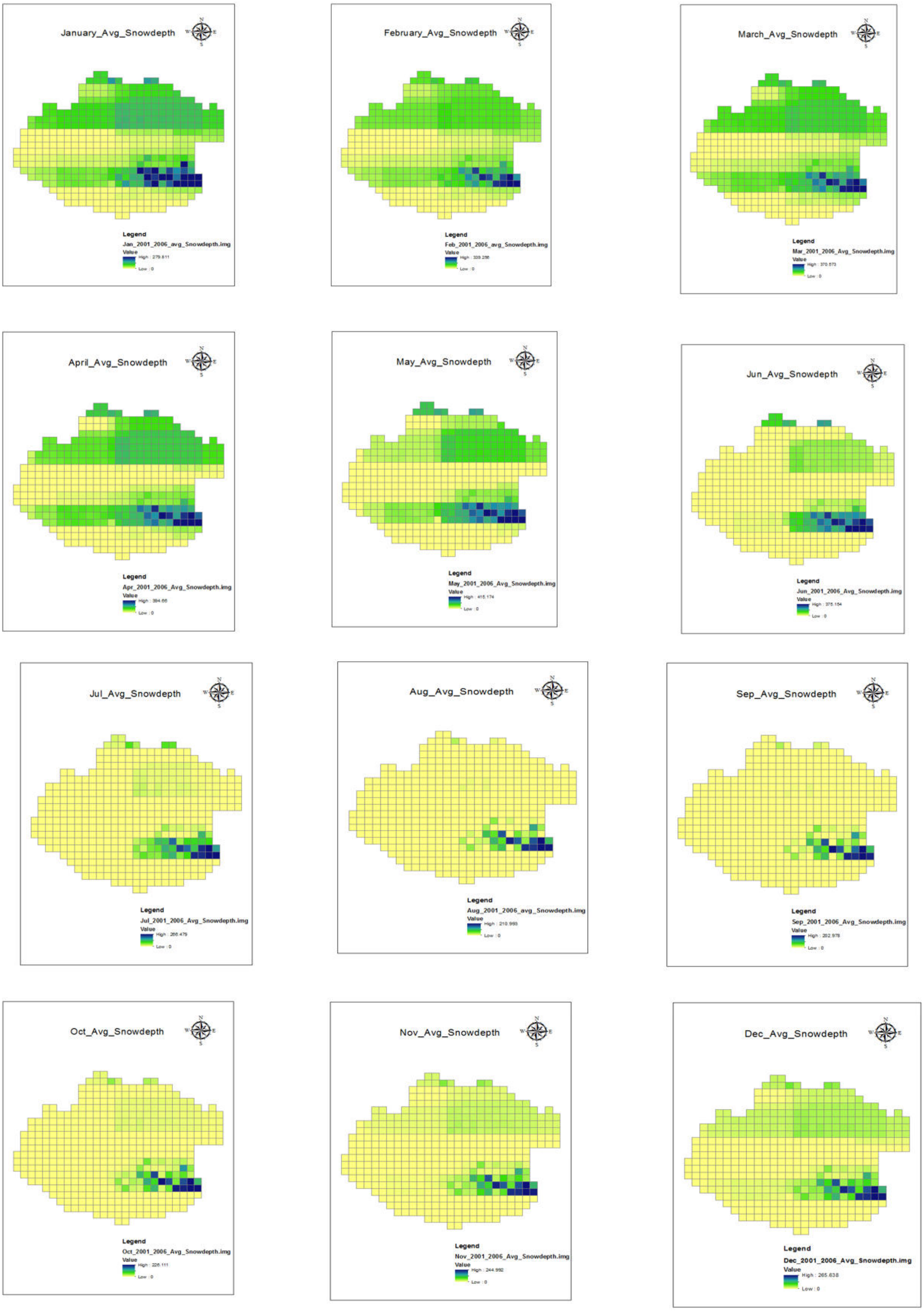

Fig. 9 Gridded Image of Snow Depth for Alaknanda River Basin

Image generated for Snow depth (Fig 9) from VIC hydrology model shows that the snow depth is more for the months January to May and after that season it Depletes.

3.3 Snow Cover Validation

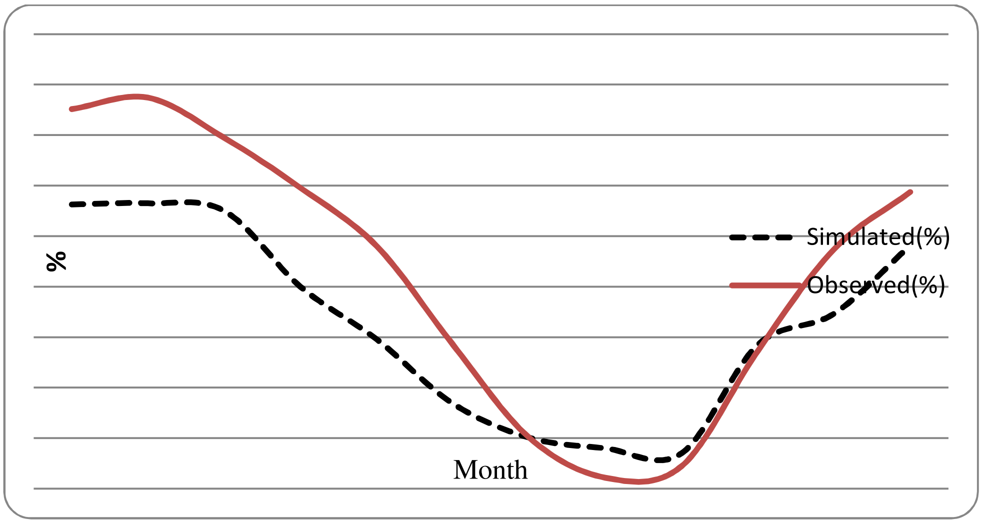

Fig. 10 Modeled and measured monthly average snow cover fraction

The Moderate Resolution Imaging Spectroradiometer (MODIS) snow products were selected to calculate the percentage of snow cover area in the study area. MODIS snow cover products were used by several researchers to use as input for the snowmelt runoff model (e.g., Bookhagen and Burbank, 2010; Immerzeel et al., 2009; Prasad and Roy, 2005).MODIS 8-Day composite, 500 m resolution MOD10A2 (Hall et al., 2006) snow cover product, proven in estimating snow cover under cloud-free conditions (Parajka and Blöschl, 2006), was available for the period 2000 to 2010 at Reverb website.(Siderius et al.2013). The MODIS/Terra Snow Cover 8-Day L3 Global 500 m Grid (MOD10A2), used for this study, contains data fields for maximum snow cover extent over an 8-day repeated period (Hall et al., 2006, updated weekly.) and has a resolution of approximately 500 m completely covering the Alaknanda River basin. The available MODIS images were mosaicked and projected with the WGS 1984 UTM ZONE 43N projection system. The Alaknanda River basin area was then extracted from this mosaicked scene to assess the percentage of snow and ice cover (cryosphere) in the study area. Monthly average snow cover generated by the model was validated against MOD10A2. The MODIS/Terra Snow Cover 8-Day L3 Global 500 m Grid (MOD10A2), used for this study, contains data fields for maximum snow cover extent over an 8-day repeated period (Hall et al., 2006, updated weekly.) and has a resolution of approximately 500 m completely covering the Alaknanda River basin. Fig. 10 shows a validation against MODIS snow cover dynamics over a whole year with the modeled snow cover. In MODIS, for the entire basin, snow cover starts to build up from an average minimum cover of 2.17% during August and September as a result of the monsoon, and then continues to build up during the winter to reach a peak average areal coverage of 77% in February before declining again. The average of yearly Snow cover simulated by VIC, with its 20 elevation bands, slightly delayed but parallels MODIS both in magnitude and seasonal pattern. Fig. 12 shows the distribution and occurrence of snow cover over the Himalaya within the Alaknanda River Basin.

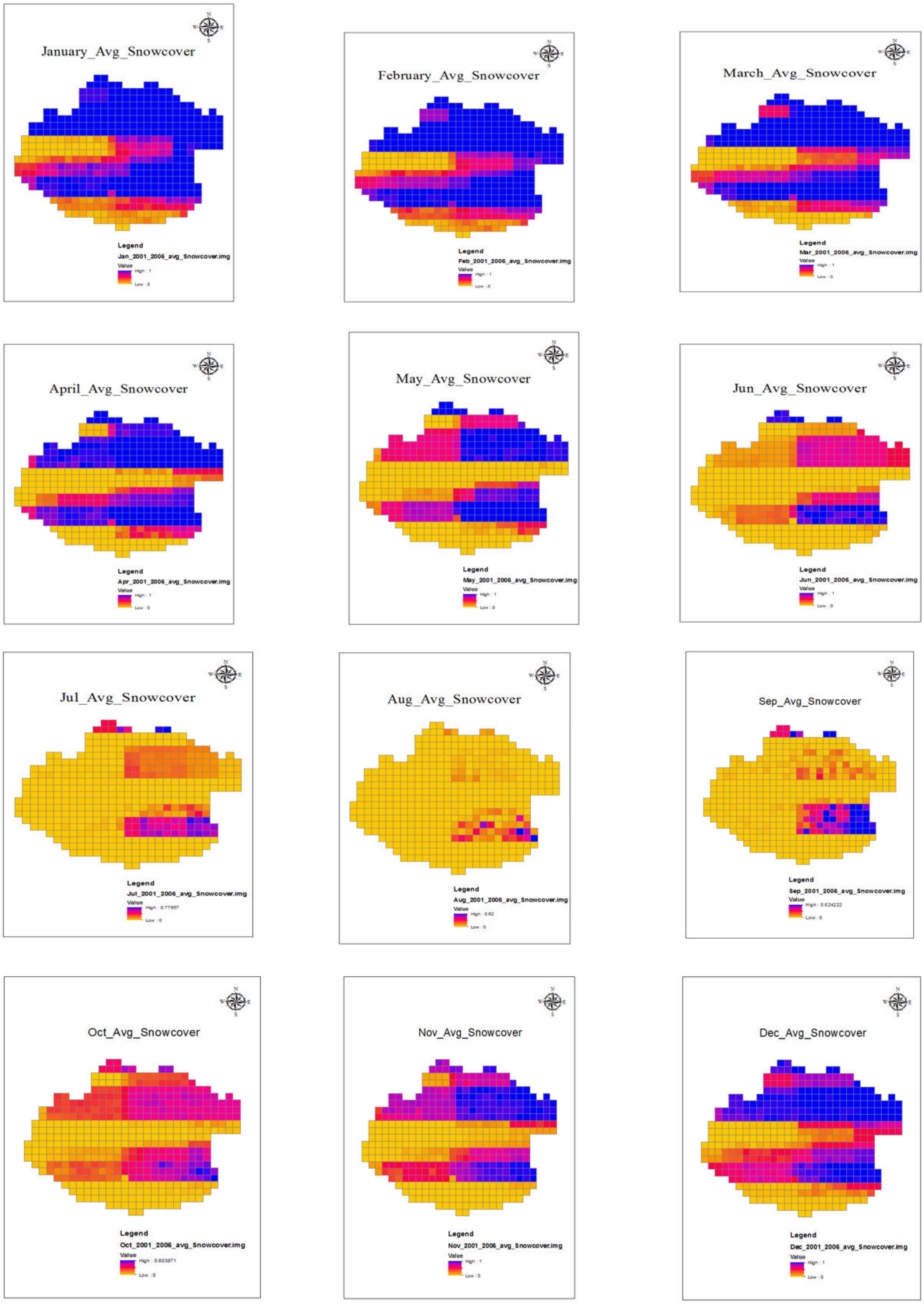

Fig. 11 Gridded Image of Snow Cover for Alaknanda River Basin

Fig 11 shows Gridded snow cover image generated from VIC hydrology model output fluxes indicates an increase of snow cover during winter season (November to February) and after that it depletes.

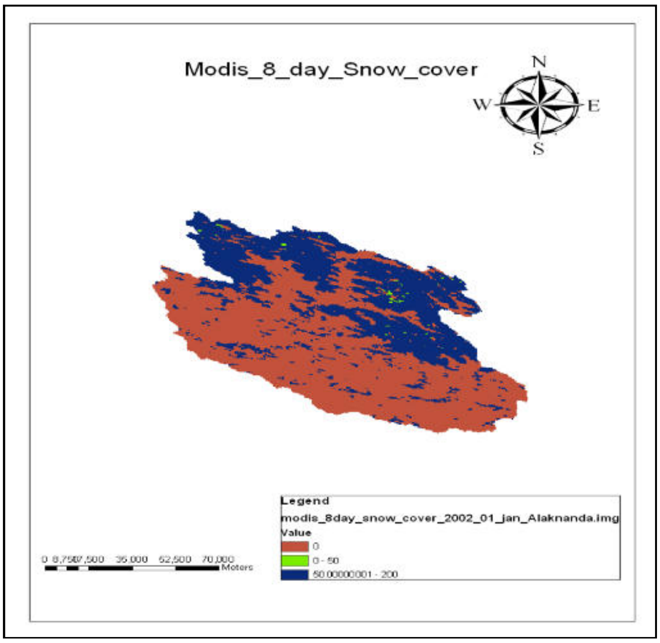

Fig. 12 Occurrence of snow (in % of 8-day periods in a year) in the Alaknanda part of the Himalayas derived from MODIS (MOD10A2) 8-day aggregated snow cover product

4. Discussion and conclusion

Macroscale hydrological models useful for estimating the impacts of climate change on large river basins with low data requirements and little calibration effort are inevitably challenged by the heterogeneity of mountainous areas. The model however, use different routines to represent snow accumulation and snowmelt processes, and use temperature index as well as full energy balance for computation of melt. Use of elevation bands captures the heterogeneity of mountains and by allowing temperature and precipitation to vary with elevation in models tends to compensate for grid cell schematization. Depth and area of snow cover are key variables in snow melt runoff generation. In inter-annual monitoring, the trend of snow cover fluctuates with season in response to seasonal fluctuations in temperature. While in between-annual snow cover monitoring, the trend of annual snow cover is mainly dominated by local climate and environment conditions. The trend knowledge of snow cover is important for snow cover pattern understanding, snow cover forecasting and policy making. In summer time, the snow cover percentage in the Alaknanda region is in its minimum while the snow cover area percentage in February is the maximum in whole year with almost 77%. However, at the end of February, the snow starts melting resulting in a gradual decrease in snow cover percentage. The snow percentage decrease continues until the end of July, arriving at the bottom for the whole year with the percentage of 2%. From August onwards, the snow freezing rate is higher than melting rate so the snow covers begins to increase. The snow cover percentage increase extends to winter time. The response of snow cover change with time is obviously related to local temperature and precipitation because precipitation directly determines the snow water accumulation and temperature directly determines in what forms (snow or rainfall) the precipitation is. Each year, a short period with no precipitation is in end of autumn and winter. When the air temperature is lower than the critical temperature of snow melting, precipitation begins influencing snow accumulation. Therefore, seasonal snow cover change is dominated by local temperature and precipitation together. The analysis was based on the total amount of precipitation and mean air temperature for the period with a durable snow cover (Nov-Mar), as well as on the mean snow depth in March taken as the maximum value of the cold season snow accumulation. The snowmelt process is defined as the phase transition of solid snow ingredients parts (ice crystals, Ice grains) into liquid water, for which about 340 joules per gram (j/g) of energy are needed. Snowmelt processes is determined by the energy balance of the snowpack. During the ablation, the runoff is characterized as a function of the radiation due to more or less pronounced diurnal variations. With reduced snow depth and snow cover at the end of ablation, the regular runoff development is modified increasingly. At any time during winter or spring, there may be sporadic snow cover up and depletion that controls the runoff. Characteristic of the lower regions are also secondary rain induced melting peak runoff, prevent the development of regular outflow. Generally temperature in months between end of December to middle March fall to below 0°C and this time all the rainfalls fall as snow. Again after March temperature increase to above 0°C and snowmelt start in this time and increasing of temperature will continue and in end of July and August reach to above 30°C. It falls at low elevations as rain (winter discharge) and at high elevations as snow, which produces spring discharge as it melts. In general, snow accumulation and snowmelt processes represent low and relatively constant discharges in winter and high variable discharges in spring when the highest flows of the year tend to occur. The decrease in winter precipitation is responsible for lower discharges in winter, lower discharges in spring due to a lower snow accumulation in winter. The actual snow ablation begins when the snow cover curve starts to diminish and from this time, melt water runoff prevails and the refreezing processes can be considered negligible. The Snow depth percent increase in winter season starts from January and start depleting after June.The maximum snow depth in the whole year 55 cm at the month of May. The Snowmelt runoff is strongly affected by the phenomenon of changes of snow cover and snow depth. As the Snow cover start to deplete the snow depth also begin to reduce and the snowmelt amount start to increase and an increment observed in case of Snow melt Runoff. The Snowmelt runoff start to increase from June peaking at July to August and decrease continues until the end of December while the snow cover start to deplete after February and it continues up to end of November which can be a main reason for increased Snow melt Runoff at this time period. The Snow depth up and depletion also affects the Snow melt Runoff process. During the month of January to May there is a significant snow depth at Alaknanda region and start to deplete at the start of Jun which can be a major factor of increased Snowmelt Runoff. As climate warms, inter annual changes and trends in snowmelt contributions to flow in spring will be of considerable importance for sustaining agriculture. The VIC model should provide a robust framework for modeling future snowmelt in the context of changing availability of, increasing demand for, and possible vulnerability of water resources in the Alaknanda basin.

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