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Estimating Daily Stream Flow in the Glacierized Mountainous Kashmir Himalayan Basin

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ABSTRACT

The paper describes the integration of remote sensing, and the degree day based SRM (Snow melt Runoff Model) for estimation of snow melt runoff from the glacierized Lidder basin spread over an area of 1263 Km2. The study involved the use of various data types including Digital Elevation Model (DEM), MODIS satellite images, historical hydro-meteorological data and the field observations. The SRM model simulates daily stream flow in mountainous basins where snowmelt is a major runoff factor. The model was initiated with observed discharge data and run for the hydrological year 2002-2003 using temperature, precipitation and snow covered area. The requisite input model parameters like runoff coefficient, degree-day factor, temperature lapse rate, critical temperature, rainfall contribution area, recession coefficient, lag time were estimated using standard methods. Multi-temporal satellite images from MODIS for the year were used for extraction of snow cover and snow depletion curves for different elevation zones. Stream discharge data was used for calibration and validation of the SRM. The model was run for the entire watershed and the average computed runoff is 9.587(m3/s) compared to the average measured runoff 9.782 (m3/s). The simulations showed good agreement with the observations with the coefficient of determination (R2) of 0.8676.

Key words: Snowmelt runoff, glacierized basin, remote sensing, digital elevation model.

INTRODUCTION

Snow and glacier resources are vital components of the hydrological systems and can be considered reservoirs of water that have ability to mediate yearly fluctuations in runoff by providing water in warm and dry years and storing water in wet and cool years (Fountain and Tangborn, 1985). Snow represents about 5 % of all precipitation reaching the earth's surface (Hoinkes, 1967). The volume of fresh water stored in snow and ice is estimated at about 75 % of the total earth's fresh water volume (Shiklomanov, 1990). Information on spatial and temporal variation of snowmelt runoff is of basic interest for hydrology, water management and climate change research (Koike *et al.*, 1994; Nagler and Rott, 2000; Saraf *et al.*, 1999). Prediction of snow- and glacier-melt runoff requires an understanding of melt water production processes in snow-covered and glacierized areas (Conway and Banedict, 1994). The knowledge of the spatial and temporal distribution of snow cover and hydrometeorological conditions at watershed scale is also essential for the accurate predictability of snowmelt and glacier-melt runoff (Kulkarni *et al.*, 2002; Rango and Martinec 1995; Rango 1996). Different models have been developed in various parts of the world to estimate snow- and glacier-melt discharge (Anderson, 1976; Hock, 2003; Marshall, 2006, Martinec and Rango, 1979). Earth observation from space is the optimum tool for monitoring snow cover dynamics from the catchment scale to the global scale. Combining the remote sensing derived snow and ice cover maps with a hydrologic runoff model, the daily runoff can be predicted using various methods and procedures (Kulkarni *et al.,* 2002; Martinec and Rango, 1979).

Snow- and glacier-melt are important contributors to the total yearly runoff volume in Kashmir Himalayan basinsand is a major source of water for irrigation, drinking water supplies, hydropower and other water related services, that contribute predominantly to the GDP in the state of Jammu and Kashmir. Melting from seasonal snow cover during summer forms is important to maintain the flow regimes ofmany rivers originating in the Higher Himalayas. Therefore, prediction of runoff from the glacierized basins is important for optimal utilization of the Himalayan water resources (Maurer, 2002). Because of the tremendous economic importance of the snow and glacier resources in the region andin light of the fact that the glaciers in the Kashmir Himalayas have been reported to be receding rapidly due to climate change, it is important to develop a strategy for operational predication of the snow- and glacier-melt runoff from the glacierized basins of the Himalayas for optimal utilization of the water resources for various sectors. This paper describes the integration of remote sensing, hydro-meteorological observations, field data and the degree day based SRM (Snow melt Runoff Model) for estimation of snow melt runoff from the glacierized Lidder basin.

STUDY AREA

Lidder valley, a famous pilgrimage destination, located in the southeastern part of the state of Jammu and Kashmir, is spread over an area of 1263 Km^2 and falls approximately between 75° 30' to 75° 45' longitude and 34° 15' to 34° 30' latitude. A considerable area of the catchment is covered by the glaciers and the largest glacier in the basin, Kolhai glacier is located in the basin.Lidder River emanating from the Kolhoi glacier is one of the main tributaries of the Jhelum basin. Fig. 1 shows the location of the study area. A vast amount of snow is deposited on the mountain slopes of the study area during winter months, which melts continuously and feeds the river throughout the year and forms one of the biggest sources of water supply in Kashmir Valley being used for irrigation, recreation, hydropower generation and domestic purposes. The study area exhibits typical temperate climate with four seasons.The area receives precipitation both in the form of rain and snow. The mean annual precipitation from 1979 to 2007 was 1242.6 mm (Fig. 2). The season from April to October is pleasant while in the rest of the year, the study area experiences extreme cold and continuous snowfall. In the study area, the temperature varies between a monthly mean maximum of 19°C in July and a minimum of 1.7 °C in January with an average of 9.5 °C (Fig. 3).

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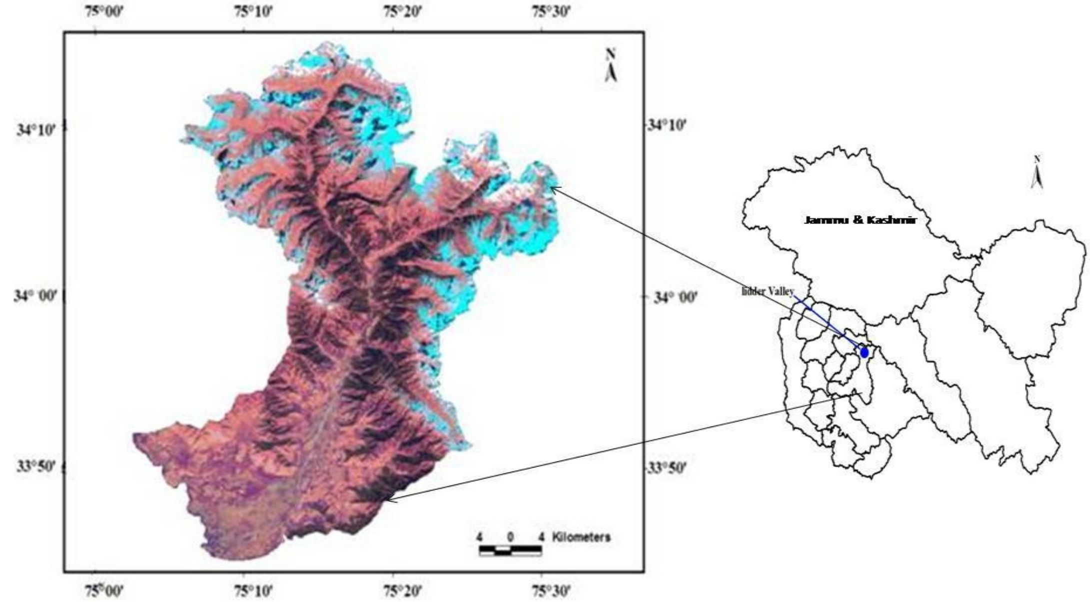

Fig. 1. Location of the study area

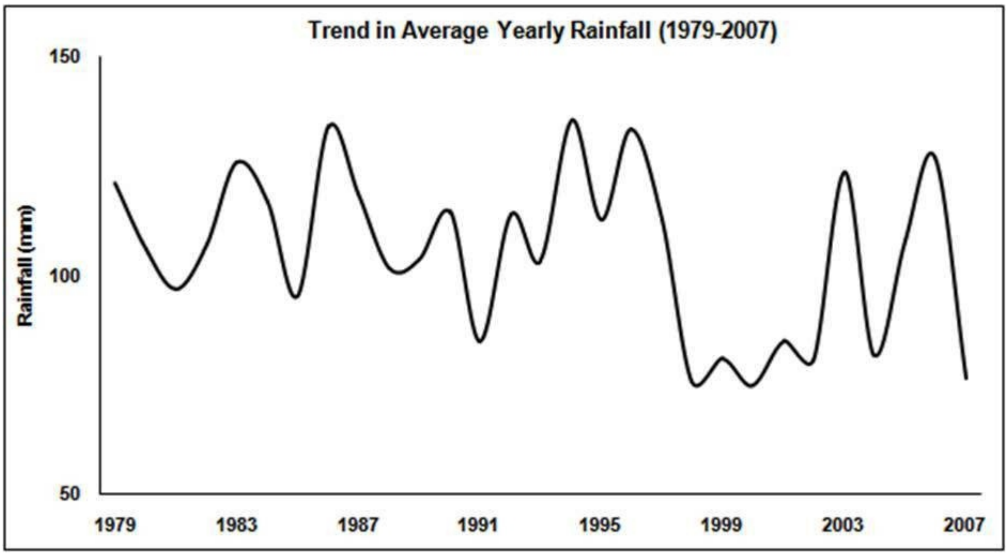

Fig. 2. Average yearly rainfall showing slight decrease in trend from 1979-2007.

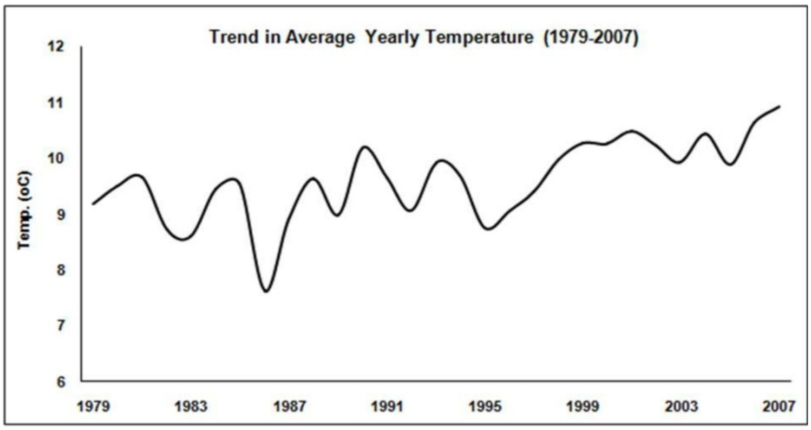

Fig. 3. Average yearly temperature shows almost increase of 1o C from 1979-2007.

Snowmelt Runoff Prediction Methodology

The overall methodology adopted for predicting the snow-melt runoff from the basin is shown in the Figure 4. The study is based on the integrated use of the data from remote sensing, digital elevation model, hydrometeorology and field observations in a degree day based SRM (Snow melt Runoff Model) for estimation of snow melt runoff from the glacierizedLidder basin. The detailed description of the SRM is given hereunder:

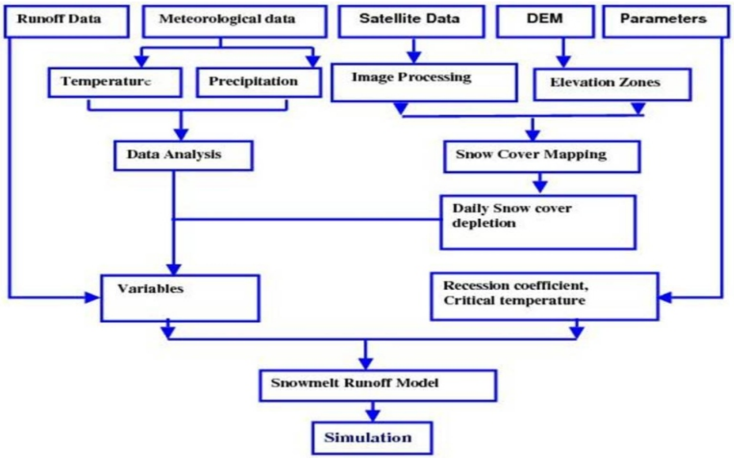

Fig. 4. Methodology adopted for predicting snow-melt runoff from the Basin

The Snowmelt Runoff Model (SRM)

Snowmelt Runoff Model (SRM) is designed to simulate and forecast daily stream flow in mountain basins where snowmelt is a major runoff factor (Martinec, 1975). SRM can be applied in mountain basins of almost any size ranging from 0.76 to 120,000 km2 and any elevation range from 305-7690 m a.m.s.l. to estimate and forecast snowmelt runoff. A model run starts with a known or estimated discharge value and can proceed for an unlimited number of days as long as the input variables - temperature, precipitation and snow covered area are provided (Martinec and Rango, 1986).The snowmelt process is influenced by a number of factors and taking all the factors into consideration is practically impossible. In temperature index degree-day approach adopted in SRM, maximum atmospheric temperature is taken as an index, which is the representative of all the melting factors. Precipitation and temperature are generally observed in the lower altitudes of the Himalayan basins and more often are not representing the meteorological conditions in the higher altitudes. Therefore, it is important that while extrapolating these parameters to higher altitudes, appropriate lapse rates are used to compute the accurate degree day factor. The overall structure of the model is described by the following equation:

$$Q_{n+1} = [C_{5n} . a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] \frac{4.10000}{86400} (1 - k_{n+1}) + Q_n k_{n+1}$$

Where,

Q = average daily discharge (m^3/s)
$C_{s:}$ = runoff coefficientfor snow (index s) and rain (index r)
a = degree-day factor (cm. $C^{-1}.d^{-1}$)
T = number of degree-days (C.d)
ΔT =temperature lapse rate adjustment
S = ratio of the snow covered area to the total area
P = precipitation contributing to runoff (cm)
A = area of the basin or zone (km^2)
k = recession coefficient indicating the decline of discharge in a period without

snowmelt or rainfall:

$k = \frac{Qm+1}{Qm}$ (m, m+1 are the sequence of days during a true recession flow period)

n = sequence of days during the discharge computation period

10000/86400= Conversion from cm.km^2 to m^3 s^{-1}

The above equation is written for a time lag between daily temperature cycle and the resulting discharge cycle of 18 hours (Martinec and Rango, 1998). T, S, and P are variable to be measured or determined each day C_R, C_S Lapse rate to determine ΔT, T_{CRIT},k and the lag time are parameters which are characteristics for a given basin or more generally, for a given climate (Martinece and Rango, 1998; Eigdir, 2003). Since the basin elevation ranges from 1500 to 5500m, the basin was subdivided into four elevation zones. The average daily runoff Q was calculated by linear combination from the runoff contributionsfrom each elevation zonewhich were calculated separately as shown below:

$$
\begin{aligned}
Q_{n+1} = \{ & [C_{SAn} \cdot a_{An} (T_n + \Delta T_{An}) S_{An} + c_{RAn} P_{An}] \frac{A_A \cdot 10000}{86400} + \\
& [C_{SBn} \cdot a_{Bn} (T_n + \Delta T_{Bn}) S_n + c_{RBn} P_{Bn}] \frac{A_B \cdot 10000}{86400} + \\
& [C_{SCn} \cdot a_{Cn} (T_n + \Delta T_{Cn}) S_n + c_{RCn} P_{Cn}] \frac{A_C \cdot 10000}{86400} + \\
& [C_{SDn} \cdot a_{Dn} (T_n + \Delta T_{Dn}) S_n + c_{RDn} P_{Dn}] \frac{A_D \cdot 10000}{86400} \} (1 - k_{n+1}) + Q_n \cdot k_{n+1}
\end{aligned}
$$

The indices A, B, C and D, in the above equation refer to the respective elevation zones in the study area. Runoff from all elevation zones is added together before routing. Therefore, location is not taken into account in the model. SRM input Data Parameters

For predicting the snow-melt runoff at the basin scale, the SRM required input parameters that are discussed under the following sub-sections.

Basin Characteristics

The basin boundary was delineated from the Survey of India (SOI) topographic maps at 1:50,000 scale. Using 40 m resolution DEM, the basin with the altitude ranging from 1500-5500m a.m.s.l was subdivided into 4 elevation zones (Fig. 5). The area elevation curve (hypsometric) was also generated from DEM as shown in the Figure 6. The zonal mean hypsometric elevation was determined for each of the elevation zone using hypsometric curve. The temperatures from the base station are extrapolated to each of the zones using the zonal mean hypsometric elevation for calculation of the degree days.

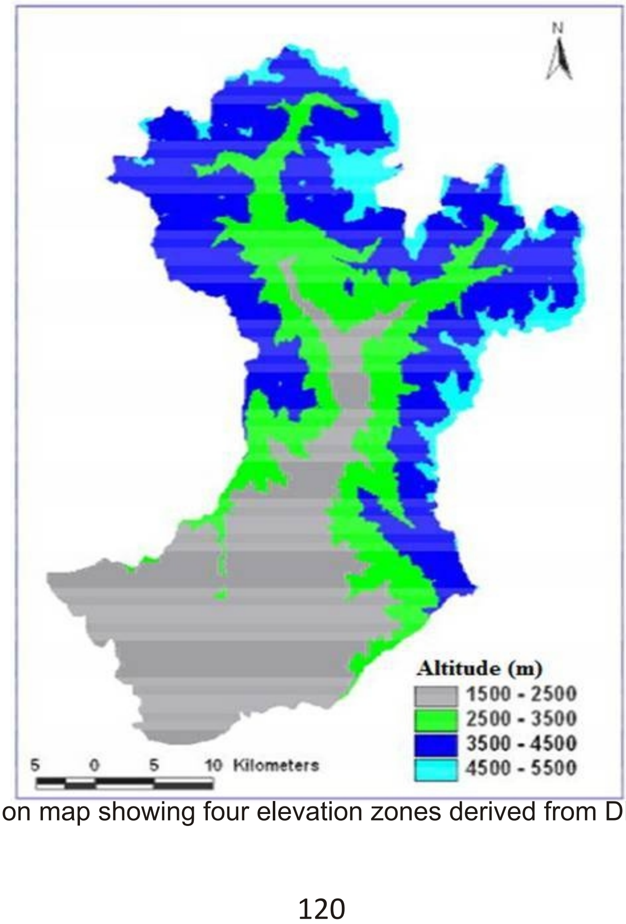

Fig. 5. Elevation map showing four elevation zones derived from DEM of the Area

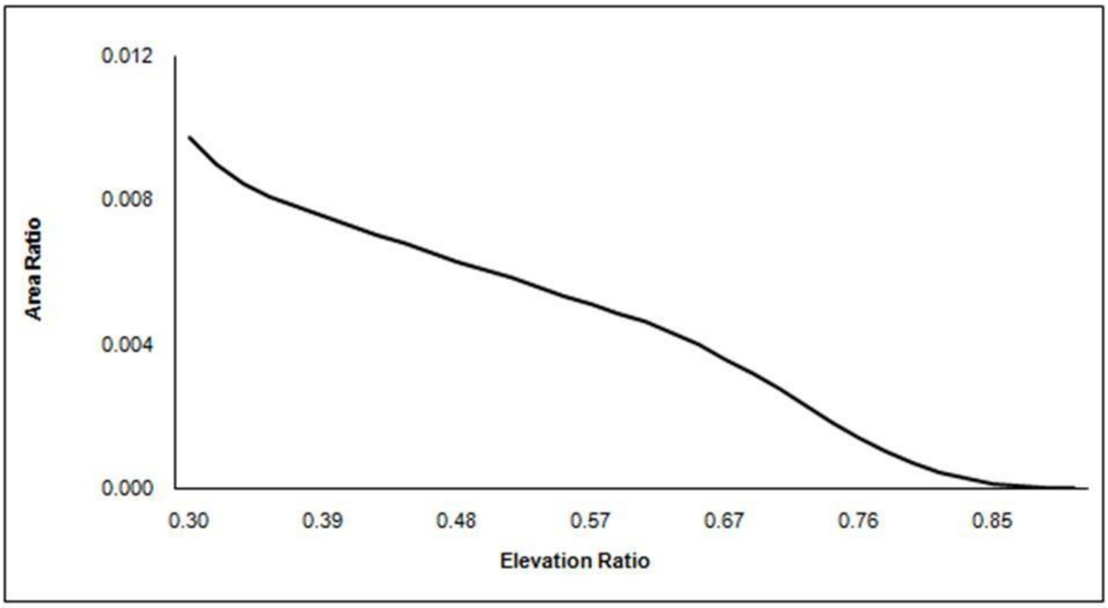

Fig. 6. Hypsometric curve of the study area.

Hydro-meteorological Variables

Analysis of the hydrological, meteorological and remote sensing data was carried out to calculate model input variables for SRM like temperature, precipitation and snow covered area. For hydrometeorological data, we used the observed variables like temperature and precipitation from the Indian Meteorological Department (IMD) station located at the Pahalgam town. The detailed methods for generating input variables for the SRM model run are briefly discussed in the following paragraphs:

Temperature (T): The daily mean temperature data was extrapolated to the hypsometric mean elevation of the different zones using the lapse rate of 0.65°C per 100 m. In each zone, snowmelt depth and rate was predicted from the temperature measurements, determining the number of degree days, with the criteria that there will be no snowmelt, if, the temperature was < 0°C and one degree is computed when the average temperature is one degree above 32°F. The temperature lapse rate was also used to determine whether precipitation falls as rain or snow, but in this case the critical temperature need not be 0°C. If snowfall occurs in a zone with SCA >0 the part falling outside the SCA is supposed to create a temporary snowpack, which generates extra melt once sufficient degree-days occur. Rainfall outside the SCA generates runoff, as do the rainfall onto the SCA if the snowpack is assumed to have ripened, but rainfall onto a still cold snowpack is neglected .

Precipitation (P): The SRM model accepts either a single, basin-wide, precipitation input from one station or from a “synthetic station” combined from several stations or different precipitation inputs zone by zone (Martinec and Rango, 1998). For the study area, precipitation data was extrapolated to different zones. For extrapolating the precipitation to the higher altitude zone, the rainfall-altitude relationship curve developed for the Hindu Kush Himalayas was used (Eigdir, 2003). As discussed above, a critical temperature is used to decide, if, a particular precipitation event will be treated as rain or snow. Also, if the precipitation event is decided to be snow, its effect on runoff is treated differently depending upon whether it falls on the snow-covered area (becomes a part of the existing snowpack) or snow-free area (treated as precipitation to be added to the snowmelt) of the basin. The SRM model uses a daily rainfall threshold of 6 cm to better simulate the rainfall peaks.

Discharge Data: A study of the decennial averages (1979 to 2003) of the monthly discharge of Lidder as shown in the Figure 7, reveals that 74.9 % of the total annual runoff flows during the months of March to August and only 8.6 % of the total runoff flows during the winter months (Dec-Feb) and 16.8 % flows in September and November. The SRM run was initiated with the known discharge values from the observation station.

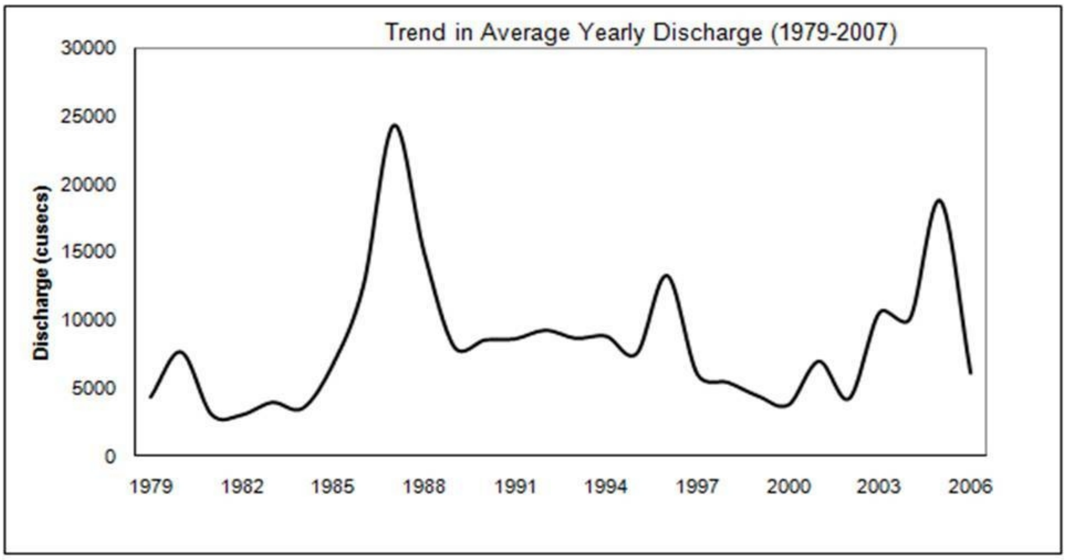

Fig.7. Average yearly Discharge showing slight increase in trend from 1979-2003.

Snow Covered Area (S):Snow extent, snow depth and snow water equivalent (SWE) are important snow parameters required for assessing snowmelt runoff from snow covered basin for optimal water management and flood control (Koning *et al*., 2001). Therefore, daily snow cover depletion information is the most important input variable to the Snowmelt Runoff Model (Martinec and Rango, 1998). A time series of Multi-temporal satellite images from MODIS were used for snow cover area extraction.Satellite data was used to define the snow line and snow depletion curves for the four elevation zones. The six satellite images available for the simulation period (2003) were pre-processed using standard image processing techniques (Lillesand and Kiefer, 1987).The snow covered areas were extracted from the image using Normalized Difference Snow Index (NDSI) (Klein and Barnett, 2003). On the NDSI images, the snow is characterized by higher NDSI values than other surface types. Pixels with a NDSI value greater than or equal to 0.40 are considered as snow (Hall *et al*., 2002). Figure 8 shows the spatial and temporal distribution of the snow cover extent and the snow depletion curve is shown in Fig. 9.

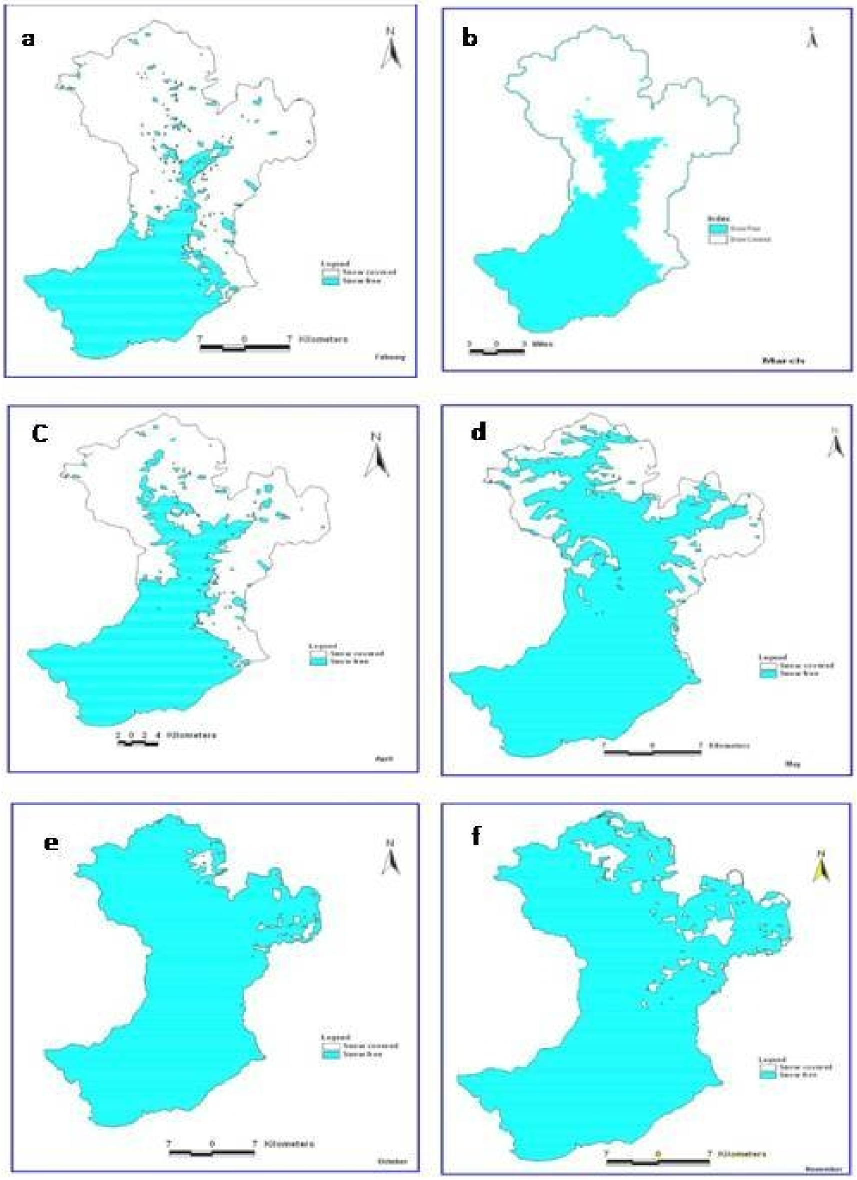

Fig. 8. Spatial and temporal variation of snow cover distribution in the study area during the simulation year.

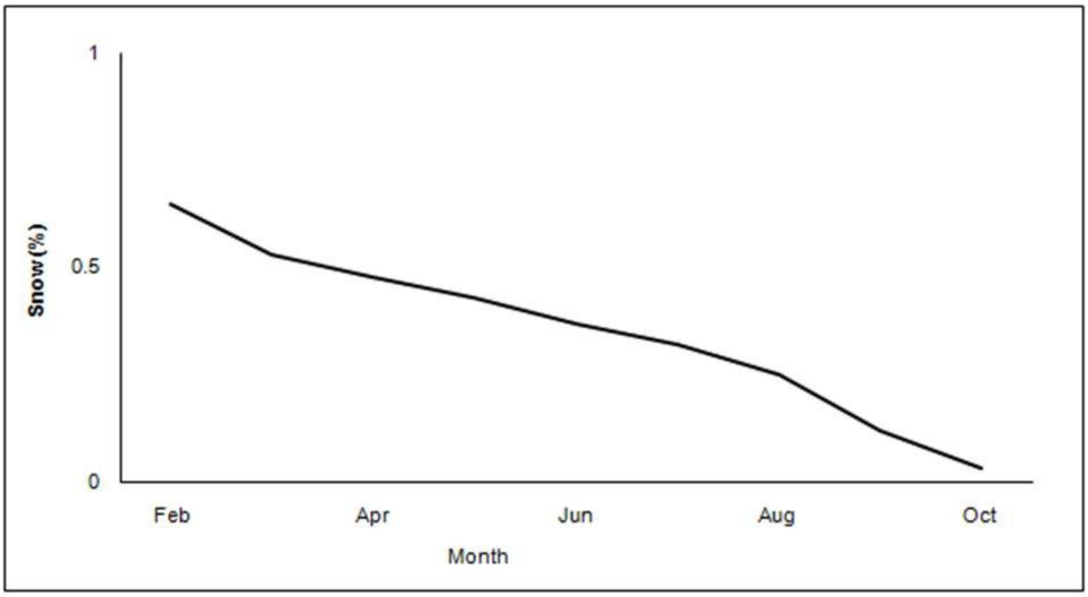

Fig. 9. Periodic snow cover depletion in the study area during the simulation year.

Other model parameters

The other SRM parameters required for predicting the snowmelt runoff are either determined from measurement or estimated based upon basin characteristics, theoretical and empirical relations. These parameters need to be calibrated or optimized using historical data and should never exceed the range of physically acceptable values (Martinec and Rango, 1998).These parameters include Degree day factor (a) Rainfall contributing area (RCA) the recession coefficient (k) the time lag, (t lag) Lapse rate (γ) Runoff coefficient (C)critical temperature (T CRIT).

Simulation Results

Runoff simulation has been carried out for the Lidder catchment as shown in Figure 10. The simulation was done using snowmelt runoff modeling (SRM) for the period of (2003-03). The average computed runoff is 9.102 (m^3/s) compared to the average measured runoff of 9.222 (m3/s). Graphical display of the computed runoff and the measured shows that the simulation is successful because the coefficient of determination (R^2) is 0.8676.and the volume difference (Dv) is 1.2283 %. Results obtained so for, have revealed that SRM is a suitable tool to calculate runoff using hydro-meteorological data and remote sensing-derived snow cover maps. The study shows a method to calculate runoff from snow- and ice melt using meteorological data and remote sensing derived snow and ice cover maps.

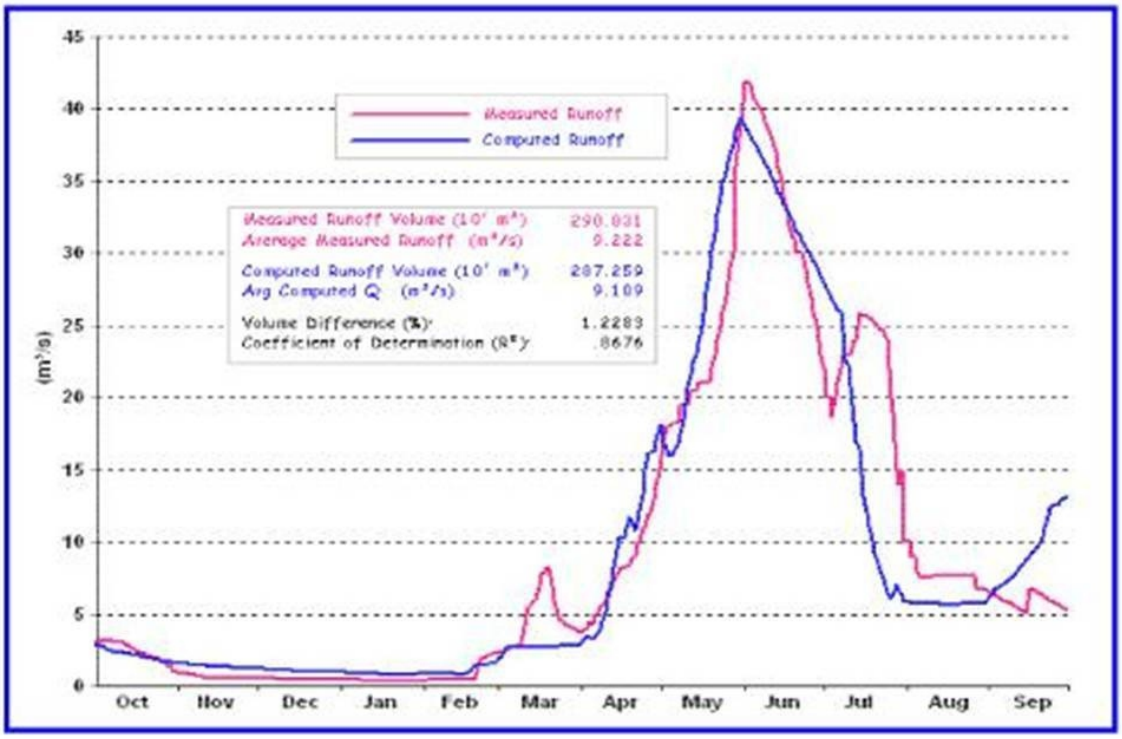

Fig. 10. The estimated snowmelt runoff along with the observed runoff from the catchment

DISCUSSION

Lidder Valley one of the important Himalayan watersheds is located in the southeastern part of the state of Jammu and Kashmir. The main part of the precipitation appears as snow in winter and feeds the famous river, Lidder. Determination of snow cover based on field observation is difficult in mountainous areas, but the use of satellite images overcomes this difficulty. Using the MODIS satellite images in Lidder catchment helped snow-covered area estimation. A time series of images were used for the snow cover mapping. The Normalzed Difference Snow Index (NDSI) was used for the identification of snow and ice and for separating snow/ ice and most clouds. In view of the cloud cover, DEM was used to extrapolate the snow line visible on the cloud free parts of the image. Overall snow cover is very high during winter months. However, from March snow cover started to reduce and the trend continues up to the end of August. Hydrological analyses were carried out to highlight the relation between snow, rain and the discharge. Snowmelt runoff hydrographs have a typical pattern reflecting the daily cycle of temperature and solar radiation. The effect of seasonal snow cover on the daily distribution of runoff in the basins is illustrated in Fig. 10. Since snow cover is considerably less in summer and it has caused the computed runoff to settle lower than measured runoff in this period, also in period of winter especially in February and March there isn't any snowmelt that is because of low temperature and degree-days. Since the melt water volume is a product of the melt depth and snow covered area, the daily snow melt depth as an average over the basin area starts decreasing in the second half of the June although temperature is still rising.

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