International Conference on Hydroinformatics

2014

# Snowmelt Modelling Of Dhauliganga River Using Snowmelt Runoff Model

Dhyan Singh Arya

Amar Kant Gautam

Asmita Ramkrishna Murumkar

# SNOWMELT MODELLING OF DHAULIGANGA RIVER USING SNOWMELT RUNOFF MODEL

D.S. ARYA (1), AMAR KANT GAUTAM (1), A. R. MURUMKAR (1)
*(1): Department of Hydrology, IIT Roorkee, Roorkee 247 667, Uttarakhand, India*

Snowmelt modeling was attempted in this study using Snowmelt Runoff Model (SRM) to simulate streamflow in Tamak Lata catchment located in the Indian Himalayas. The daily snow cover data was generated using the depletion curves prepared using snow cover information obtained from MODIS remote sensing images during May 2009 to August 2012. Discharge, temperature and rainfall data observed at Tamak Lata during May 2009 to August 2012 were used for calibration and validation of the model. The characteristics of snow cover in the basin shows that the accumulation of snow at higher altitude starts from the second week of October and the snowline comes down to lower elevation up to lower zone. By the end of March, the snowmelt begins and the snowline recedes up to elevation of 5200 m by the end of the melt season. Till the start of the melt season, more than 75% of the basin area is covered with snow and it reduces to approximately 25% at the end of the melt season. The calibration of the model in terms of stream flow has indicated that the low flows and the peaks in the stream flow are well produced. Statistical evaluation of the model performance during calibration period, in the form of efficiency varied from 0.74 to 0.90 with an average value of 0.812 indicating a good model fit. The model performance during validation period was also found to be very good with efficiency with 0.8. The modeling of the snowmelt shows that snow and glacier runoff contribution in Tamak Lata catchment were 63.81% on annual basis and 65.34%, 52.64%, 73.4% for monsoon, post monsoon and, winter and pre-monsoon seasons.

## INTRODUCTION

The Himalayas are the highest mountain ranges in the world. The Himalayas range encompasses about 15,000 glaciers, which store about 12,000 $km^3$ of freshwater. India has about 9575 glaciers which almost cover 23000 $km^2$ of area [1]. That is why the Himalayas are generally referred as the ‘third pole’ or ‘Water tower of Asia’. The major rivers of Asia: the Indus, Ganges, Brahmaputra, Yangtze, Salween and Irrawaddy received seasonal flows of fresh water from snow and ice stored within glaciers present at high elevation. Till now there is huge uncertainty about snow and glacial melting in the Himalayan region. There is lack of available observational data for making quantitative assessments about the significance and extent of the issue.

In Himalayan region snowmelt is a major contributor to stream flow. Prediction of the melted water from snowpack is important to predict the discharge during the snowmelt period. The objective of the present study was the computation of snowmelt contribution to streamflows for Tamak Lata catchment which is the part of the Dhauliganga River basin by using a hydrological model, snowmelt runoff model (SRM) in conjunction with remote sensing data and geographic information systems (GIS).

**MODEL DESCIPTION**

This study uses a temperature index based model SRM developed for calculating the snowmelt and rainfall induced runoff [2].

The schematic diagram of SRM is shown in Figure 1.

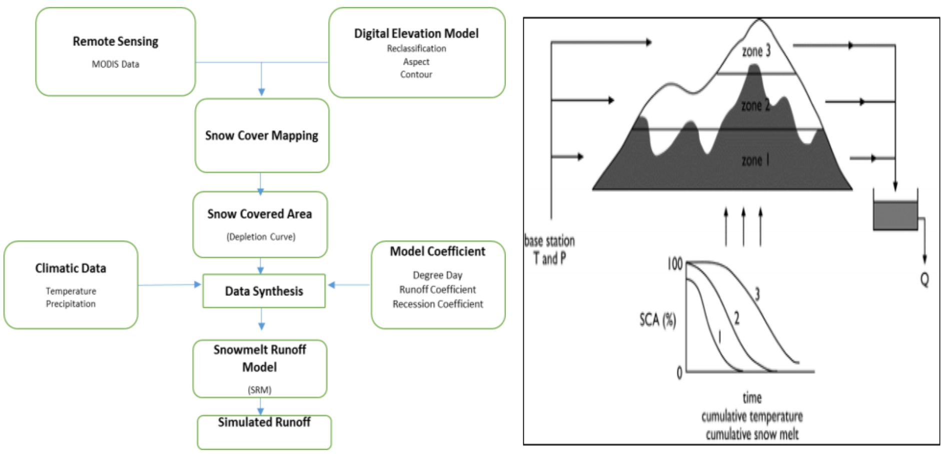


Figure 1. Schematic diagram of SRM and Components of SRM (source: HydAlp, 2000)

**Model Structure**

Daily discharge generated from snowmelt and from rainfall runoff is calculated, superimposed on the computed recession flow and changed into daily discharge from the basin as per the given equation.

$$Q_{n+1} = [C_{Sn}.\ a_n (T_n + \Delta T_n)\ S_n + C_{Rn}.\ P_n]\ (A.10000/86400)\ (1-k_{n+1}) + Q_n\ k_{n+1}\ ] \quad (1)$$

Where,

$Q$ = calculated daily avg. discharge [$m^3s^{-1}$]

$C_{Sn}$. = runoff coefficient devoting the losses to snowmelt

$C_{Rn}$ = runoff coefficient devoting the losses to rainfall

$T$ = total number of degree-days [$^oC$ .d]

$A$ = basin or zone area [$km^2$]

$\Delta T$ = adjusted by lapse rate of temperature when extrapolating the temperature data to different zones from the base station [$^oC$ .d]

$S$ = ratio between snow covered area to the total area of basin.

$a$ = degree-day factor [$cm^oC^{-1}d^{-1}$] representing the snowmelt depth due to one degree-day

$P$ = precipitation contributing to runoff [cm]

$k$ = recession coefficient showing the decreasing of discharge in a time period without snowmelt or rainfall

Where $k = (Q_{m+1}/Q_m)$ (m, m+ 1 are the order of days through a true recession time period).

T, S and P are variables to be measured or interpolated for each day. If the range of elevation of the basin is greater than 500 m, it is preferred that the basin be divided into sub-basin according to change in elevation range. Runoff from all elevation zones is collected together before routing. A daily time step is used. Snowmelt for each zone is computed from air temperature and rainfall if any is added on, and the total stream flow routed through a single store.

**Model Input and Accuracy**

Input data required are precipitation, temperature and discharge data at basin outlet. The parameters required for the model are degree day, critical temperature, lapse rate, lag time, recession coefficient, and rainfall contributing area, snowmelt runoff coefficient and rainfall runoff coefficient.

The SRM model has a graphical representation of the simulated runoff and measured runoff which results at first glance whether the simulation is successful or not. SRM uses two widely used accuracy criteria i.e. the coefficient of determination, $R^2$, and the volume difference, $D_{v.}$

Difference in the runoff volumes, $D_v$, is calculated from the following equation

$$D_v\,[\%] = \frac{V_R - V_R'}{V_R} \cdot 100 \qquad (2)$$

Where, $V_R$ = measured runoff volume, $V_R'$ = computed runoff volume

## STUDY AREA AND DATA

Dhauliganga River is a major tributary of Alaknanda River, located in Garhwal and Kumaon Himalayas rises from a glacier Kamet which is lying above 6060 m. Total area of the study basin is 1950.6 $km^2$ and elevation varies from 2494 m at the catchment outlet to 7696 m msl. Stream network and location of gauging station is shown in Figure 2.

In Dhauliganga river basin there is presence of 104 glaciers covering an area of 362 $km^2$. Most of the total glaciers are located range between 1 and 5 $km^2$. The Dhauliganga catchment receives the moisture bearing winds mainly from Arabian Sea. The monsoon season is usually considered as high river flow.nDhauliganga catchment derives runoff from both rainfall and snowmelt. The amount of streamflow received from the snowmelt makes the river perennial. The discharge varies from year to year due to change in extent of snowfall and variation in temperature in the catchment. The discharge data was obtained from the gauge and discharge station by Tamak village. Temperature varies from 34°C to -4°C. January and February are the coldest months after which the temperature begins to increase till June to July. Temperature greatly varies with altitude.

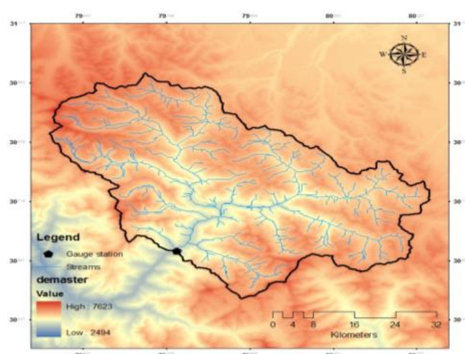


Figure 2. Stream network and gauging station map of watershed location

**Data Used**

**MYD10A2 - Eight day snow cover product**

In this study, MYD10A2 snow covered area products were used. MYD10A2 MODIS snow cover products are based on Normalized Difference Snow Index (NDSI) and other criteria tests. MODIS Band 4 (0.545~0.561µm) and Band 6 (1.628~1.652 µm) are used for estimation of NDSI.

NDSI = (Band 4-Band 6)/ (Band 4 + Band 6) (3)

Snow shows high reflectance in the visible compared to mid infrared portion of the spectrum yields.

## METHODOLOGY

### MODIS Data Processing Scheme for Snowmelt Runoff Model

The process of extracting snow cover information from the MODIS imagery is described in the Figure 3.

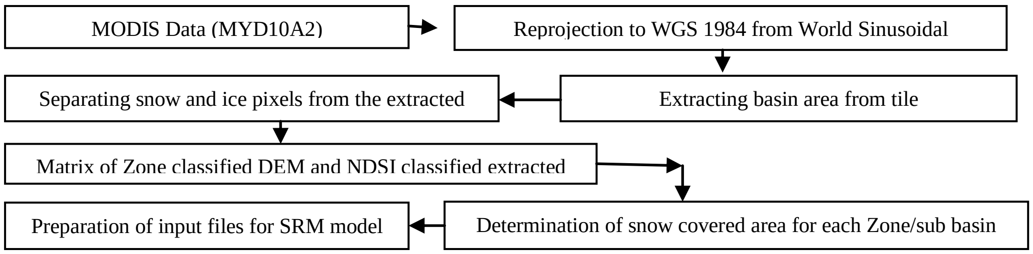


Figure 3. Preparation of snow cover input for SRM

MODIS image of the catchment area are shown in the Figure 4a. Pixel values for the Maximum Snow Extent data field are described in the Table 1 and shown in Figure 4b.

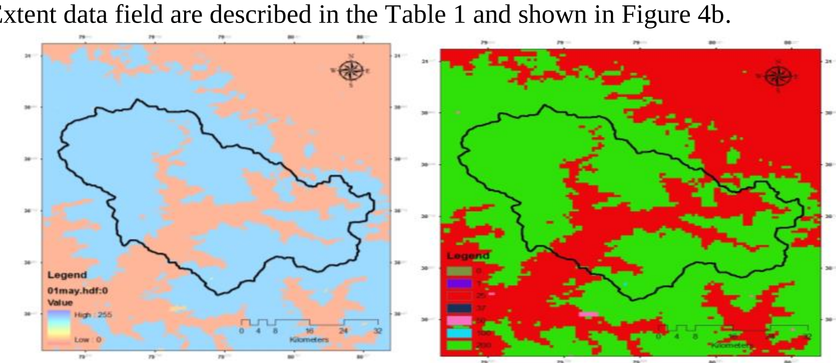


Figure 4. (a) MODIS image of the study area (01 may 2011) (b) Format converted image (.hdf to .img) of study area (01 may 2011)

Table 1. Legend for Land Classifications and their Pixel Identification Numbers (Riggs et al. 2006)

| 0 | 1 | 3 | 4 | 11 | 25 | 37 | 39 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|
| Missing | No decision | Scan angle limit exceeded | Erroneous data | Night | Snow-free land | Lake or inland water | Open water (ocean) | Cloud obscured | Snow-covered lake ice | Snow |

Version 5 data is used wherever possible because of better cloud screening from previous versions and comparatively better snow determination in forest area. Snow and ice pixel was separated by using ERDAS. Classified image of the catchment are shown in Figure 5.

The image is classified into snow and non-snow area by using Model Maker in ERDAS Imagine. The classified MODIS image is then matrix with Digital Elevation Model (DEM) which is sub-classified into different zone by using Knowledge Engineer in ERDAS Imagine to determine snow cover area of each zone. Change in snow cover for the period May

2009 to November 2009 and 2010 from May 2010 to November 2010 are shown in Figures 6 and 7 respectively.

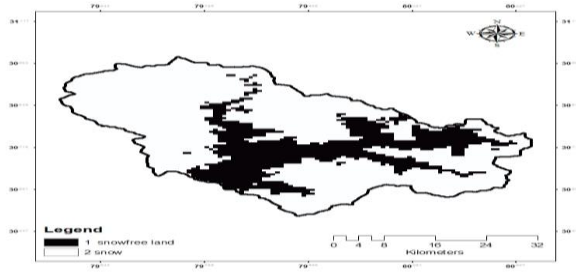


Figure 5. Classified image of study area (01 May 2011)

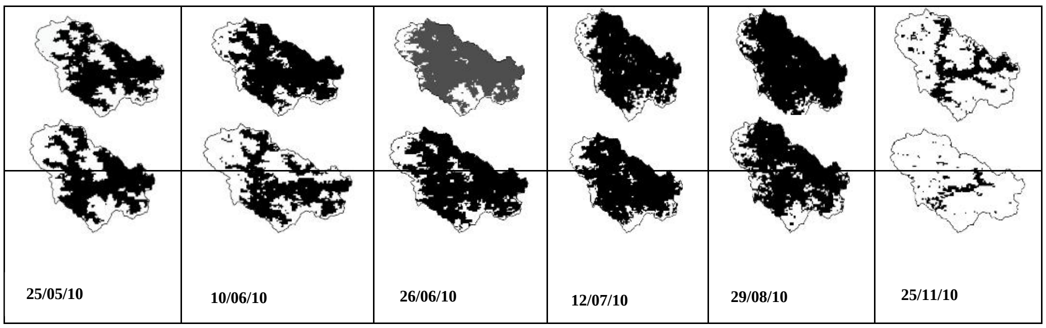


Figure 6. Change in snow cover extent in the Tamak Lata basin for 2009 and 2010 from MODIS data

## RESULTS AND DISCUSSION

### Basin Characteristics

#### *Preparation of digital elevation model (DEM)*

Using ASTER DEM the catchment area has been divided in 9 elevation zones starting from 2494m and ending at 7623m. The elevation zone map of the catchment area is shown in Figure 7. Zone wise area and percentage of catchment area is given in Table 2.

Table 2. Zone wise area of Tamak Lata catchment

| Elevation zone | Zones | zone area (sq km) | Percentage zone area |
|---|---|---|---|
| 2494 - 3000 | 1 | 16.107 | 0.82 |
| 3001 - 3500 | 2 | 69.530 | 3.56 |
| 3501 - 4000 | 3 | 147.089 | 7.54 |
| 4001 - 4500 | 4 | 295.744 | 15.16 |
| 4501 - 5000 | 5 | 556.324 | 28.52 |
| 5001 - 5500 | 6 | 550.237 | 28.21 |
| 5501 - 6000 | 7 | 239.393 | 12.27 |
| 6001 - 6500 | 8 | 59.506 | 3.05 |
| 6501 - 7623 | 9 | 16.361 | 0.83 |
| **Total** | | 1950.296 | **100** |

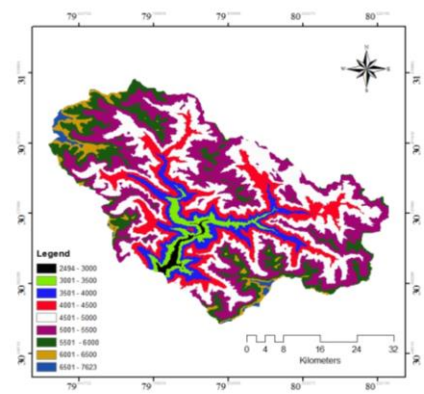


Figure 7. Elevation Zones of the Tamak Lata catchment

***Area elevation curve***

The area elevation curve prepared using the elevation statistics of 9 elevation bands is shown in Figure 8a. The curve was used to determine zonal mean hypsometric elevation for each elevation band.

***Physiographical and hydro-meteorological data used in the model***

Physiographical and hydro-meteorological data viz., daily precipitation, maximum and minimum air temperature, snow covered area, stream flow data of the basin are needed at the beginning of the simulation.

In this study, the daily rainfall and temperature of the dam site were used. This station belongs to zone 1. Remote sensing data were used to obtain snow-covered area for the study period for preparation of snow cover depletion curves.

***Snow – covered area***

**NDSI** based snow pixel classified images were used for calculating the snow covered area in the basin.

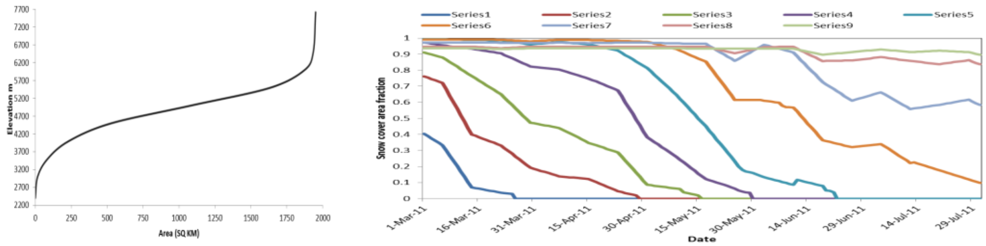


Figure 8. (a) Area-elevation curve of the Tamak Lata basin (b) Fractional snow-covered area of catchment during March 2011 to July 2011

***Preparations of Snow cover depletion curves***

45 L3 MODIS images at 8-days interval were downloaded and processed computation of % snow depletion/curve for different zones for the year 2010. Daily snow cover was computed through linear interpolation between 8-days interval. Fractional snow-covered area of Tamak Lata catchment during March 2011 to July 2011 is shown in Figure 8b.

**Degree day factor**

The value of degree-day factor used is between 0.45 to 0.75 cm$^{o}$C$^{-1}$day$^{-1}$. These values chosen for degree- day factor are in agreement with the values taken for Himalayan regions [3]. At the start of the melt season when glacier is covered with seasonal snow cover, low value of degree-day factor is used. Once the seasonal snow cover is depleted the glacier's main body is exposed, the higher values of degree- day factor is used.

**Runoff Coefficient from snow free area**

Runoff coefficient for different month was estimated from the available data of daily rainfall and runoff. The values of rainfall – runoff coefficient for this study varied between 0.55 to 0.9.

**Runoff Coefficient from snow covered area**

The standard values of runoff coefficient from snow-covered area have been taken from available literature for Himalayan region, which is varied in between 0.7 to 0.90.

**Temperature lapse rate**

Temperature lapse rate in the basin varied from season to season and zone to zone. The values have been varied from 0.45 to 0.70 $^{o}$C per 100m.

**Critical temperature**

The critical temperature determines whether the measured precipitation is rain or snow. To simulate the runoff, model depends heavily on this parameter not only in the ablation period but particularly in the accumulation period. The value of critical temperature has been taken as 0 °C to 3 °C for this simulation.

**Recession Coefficient**

Since (1-k) defines the portion of the daily melt water production (Equation 4.1), which immediately appears in the runoff, accurate determination of recession coefficient is a necessity for SRM. For the determination of the value of this parameter, analysis of historic discharge data was used.

## CALIBRATION OF MODEL

In the present study SRM model was calibrated using daily data of two hydrologic years i.e. from May 2009 to May 2011. The data sets of two years were arranged according to different seasons i.e. monsoon season (JJAS), post monsoon season (OND), and winter & pre-monsoon seasons (JFMAM). Winter and pre - monsoon are taken together because the flow during this period is low and considered as base flow only. The model parameters were calibrated considering the overall performance of the model and reproduction of the flow hydrograph for entire duration of two years. Two examples of observed and computed stream flow hydrographs for the calibration period are presented in Figure 9. As seen from Table 3 based on comparison of daily results, the efficiency varies from 0.74 to 0.82 and difference in volume of observed and computed stream flow varying from -0.011% to 9.288% during calibration indicating good model fit.

Table 3. model efficiency and volume difference for calibration period

| **Period** | 01/06/2009 to 30/09/2009 | 01/06/2010 to 30/09/2010 | 01/01/ 2010 to 31/05/2010 | 01/01/ 2011 to 15/05/2011 | 01/10/2009 to 31/12/2009 | 01/10/2010 to 31/12/2010 |
|---|---|---|---|---|---|---|
| Efficiency ($R^2$) | 0.7451 | 0.7805 | 0.7711 | 0.8587 | 0.8158 | 0.9046 |
| Dv, % | 0.0901 | - 0.0117 | 9.288 | 7.9159 | 7.539 | 6.1299 |

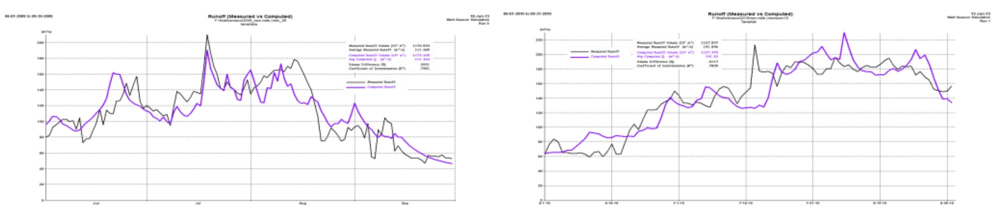

Figure 9. Observed and computed stream flow hydrographs for calibration period (a) 01Jun 2009 to 30 Sep 2009 (b) 01Jun 2010 to 31 Aug 2010

## VALIDATION OF THE FLOWS

After successful calibration of the model for a period of six different seasons during May 2009 to May 2011, the model was run to validate daily stream flow using the data of October 2011 and August 2012. Two examples of validation based on daily observed and simulated stream flow are shown in Figure 10. During the simulation period, efficiency varied from 0.68 to 0.90 and the difference in the computed and observed volume of stream flow varied from -.092% to 4.83%.

The seasonal contribution of snowmelt, rainfall for calibration and validation period at Tamak Lata shown in Table 4. The snowmelt and rainfall contributions to the stream flow vary significantly from season to season. For winter and autumn, the rainfall contribution exceeds the snowmelt contribution, while for summer and spring, the snowmelt contribution is higher. The majority of rainfall and snowfall contribution i.e., approximately 75% of annual flow, are generated during the summer and autumn season. The average contributions from snowmelt to the annual runoff are estimated to be 63.81%.

Table 4. Contribution of snowmelt and rainfall in stream flow

| Runoff/Seasons | Monsoon | Post-Monsoon | Winter and Pre-monsoon | Total |
|---|---|---|---|---|
| Snowmelt (%) | 65.34 | 52.64 | 73.45 | 63.81 |
| Rainfall (%) | 34.66 | 47.36 | 26.55 | 36.19 |

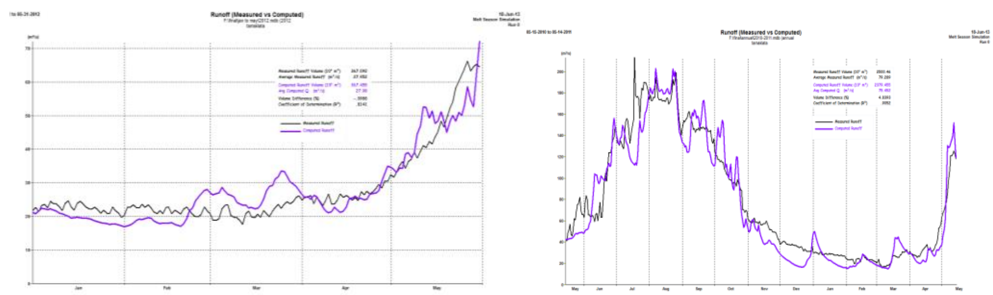

Figure 10. Observed and computed stream flow hydrographs for validation period (a) 01 Jan 2012 to 31 May 2012 (b) 15 may 2010 to 14 may 2011

## CONCLUSIONS

Model SRM performs well in the Tamak Lata catchment. Nash-Sutcliffe coefficients of were found to be 0.75 during calibration stage and 0.73 for the validation stage. Contribution of snowmelt in stream flow at Tamak Lata during calibration and validation period was 63.80% of total annual discharge observed at the catchment outlet. From the study snow and glacier runoff contributions in Tamak Lata catchment were found to be 63.81% on annual basis, 65.34%, 52.64% for monsoon and post monsoon seasons, and 73.4% winter & pre-monsoon seasons. The case study demonstrates that the application of SRM model that performs well in the Tamak Lata catchment. The results show that the model is capable of simulating the stream flow well in the Himalayan Rivers.

## REFERENCES


[1] Anand, A. Experts question theory on global warming. INSAM – International Society for Agricultural Meteorology. Agro Meteorology. (2007).

[2] Martinec. J. Snowmelt-Runoff Model for stream flow forecasts, Nordic Hydrol. 6(3), (1975), pp 145-154.

[3] Arora, M., Rathore, D.S., Singh, R.D. and Kumar, A. Estimation of Melt Contribution to Total Streamflow in River Bhagirathi and River DhauliGanga at Loharinag Pala and Tapovan Vishnugad Project Sites, J. Water Resource and Protection, 22, (2010), pp 636-643.