SNOWMELT RUNOFF MODELING IN A BASIN LOCATED IN BHUTAN HIMALAYA

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A major source of runoff and groundwater recharge in middle and higher latitudes are contributed through snowmelt from seasonal snow covered areas of the Earth's mountain region. All the major south Asian rivers originate in the Himalayas and their upper catchments are covered with snow and glaciers. The present study deals with the estimation of snow cover area and estimation of snowmelt runoff in Chamkharchu basin, Bhutan. In the present study, ERDAS imagine 9.3 and Arc GIS 9.3 have been used for creation of data base required for simulation of stream flow.

The study area i.e. Chamkharchu basin up to Kurjey is 1361.68 sq. km. and it has been divided into 9 elevation zones. The information on snow cover area is determined from the satellite data. After successful calibration of the model for a period of two years (2004-2005 and 2005-2006), the model was run to simulate daily streamflow up to Kurjey site using independent data for two years (2006-2007 and 2007-2008). The overall efficiency of the model over the study period of two years was 0.91 and 0.90 for 2006-07 and 2007-08 respectively and the difference in volume of computed and observed streamflow was 9.17% and 1.62%. The results indicate that the model performed equally well for the simulation years as for the calibration years. From this simulation rainfall runoff, snowmelt runoff and base flow have been computed separately. The model performed well for both calibration and simulation periods. The model was also used to estimate the contribution from the snowmelt and rainfall to the annual flows.

INTRODUCTION

Modeling of stream flow from a basin is based on transformation of incoming precipitation to outgoing stream flow by considering losses to the atmosphere, temporary storage, lag and attenuation. In most part of the world, the seasonal short-term variation in stream flow reflects the variation in rainfall. But in higher latitude and altitudes where snowfall is predominant, runoff depends on heat supplied for snowmelt also rather than just the timing of precipitation. Hence, to understand the hydrological behavior and simulate the stream flow in such area, it is very important to model the snowmelt runoff.

Satellite images were extensively used for snow study in Himalayan condition by several researchers. Dey and Goswami (1983) used NOAA-VHRR data to predict seasonal snowmelt runoff in Indus basin. Saraf et al., (1999) has used passive microwave (SMMR) data for snow-depth and snow-extent estimation in a part of Satluj basin in the Himalayan Mountains. Rango, (1996) has analyzed and reported that NOAA-AVHRR and Aqua/Terra-MODIS data are useful for snow study with basin area above 200 km^2. Gupta et al., (2005) have used Indian Remote Sensing satellite (IRS) LISS-III multispectral data to map dry/wet snowcover in Himalaya. Besides, many researches were conducted on snowcover study in Himalaya using satellite data The revolutionary role of remote sensing in snow study is discussed elaborately by Rango (1996), Hall et al, (1995), Jain (2001), Singh and Jain (2003) and Jain et al. (2008).

Many of the satellite data are made freely available to user community through World Wide Web, and few more can be procured through other agencies against a nominal charge. The NASA's Earth Observing System (EOS) Data and Information System (EOSDIS) and Satellite Active Archive site (NESDIS, 2006) are among the few of the communities which are involved in processing, archiving, and distributing different satellite data, thereby promoting the inter-disciplinary study and understanding of the integrated Earth system (Jain et al. 2008). In the study carried out by Jain et al.2008, the aim was to analyze the snowcover mapping potential of the three data sets (IRS-WiFS, NOAA AVHRR and MODIS) under different topographic and climatic conditions. The SCA was estimated from these three datasets for selected cloud-free dates for the year 2000 to 2004. The accuracy achieved in snowcover mapping and selection of the most suitable datasets for SCA estimation was discussed. They concluded that MODIS data can be used for larger Himalayan basin.

The conversion of snow and ice into water is called snowmelt, which needs input of energy (heat). Hence the process of snowmelt is linked to the flow and storage of energy into and through the snow pack (USACE, 1998). Snowmelt models have two basic approaches towards calculating the amount of snowmelt occurring from a snowpack: energy budget method and temperature index method. The energy budget approach attempts to make the process as physically based as possible. The goal is to simulate all energy fluxes occurring within the snowpack to give an accurate account of total snowmelt in response to each of these energy fluxes over time and space. This approach is extremely data intensive, requiring vast amounts of input data either to force an initial run of a model, or to calibrate it based on historical data before running a forecast. Too often, this approach suffers from inadequate data supply or simply that the level of data is unwarranted for the purpose at hand. In light of the intensive data requirements necessary for the energy budget approach, an alternative method known as the temperature index or degree day approach allows for snowmelt calculation with much less data input. The basis of the temperature index approach is that there is a high correlation between snowmelt and air temperature due to the high correlation of air temperature with the energy balance components which make up the energy budget equation.

There are several temperature index based snowmelt models like the SSARR Model, the HEC-1 and HEC-1F Models, the NWSRFS Model, the PRMS Model, the SRM, the GAWSER Model. The Snow Melt Runoff (SRM) model is widely used for snowmelt modeling in Himalayan basin. The SRM uses snow-covered area as input instead of snowfall data, but it does not simulate the base flow component of runoff. In other words, SRM does not consider the contribution to the groundwater reservoir from snowmelt or rainfall, nor its delayed contribution to the stream flow in the form of base flow, which can be an important component of runoff in the Himalayan Rivers, and plays an important role in making these rivers perennial. Almost all the stream flow during winter, when no rainfall or snowmelt occurs, is generated from the base flow (Jain, 2001, Singh and Jain, 2003).

THE STUDY AREA

The four major rivers of Bhutan i.e. Ammochu, Wangchu, Sankosh and Manas all of which flow in north-south direction with numerous small rivers and streams as tributaries, discharge into the Brahmaputra River in the plains of India and Bangladesh. The largest among these is the Manas, which has four major tributaries: the Gamrichu, the Kurichu, the Chamkharchu and the Mangdechu. The Chamkharchu River has its source from the glaciers of Gangkar Punsum and the Monla Karchung ranges. The Chamkharchu emerges from the glaciated terrain south of the water divide separating Tibet from Bhutan's northern territory. It has one western branch and two eastern branches. The western branch has its source from the glaciers of the Gangkar Punsum region and the eastern branches have their sources from the glaciers south of the Monla Karchung La Range. At the source of the Chamkharchu western branch, several glaciers exist. The largest glacier is a valley glacier lying east of Kang Ri Summit (7,239 m from msl) at an elevation of 4,582 m from msl. This glacier occupies an area of 26.71 sq. km and is 8.9 km long. The Chamkharchu eastern branch also has many glaciers at its source, the largest again is a valley glacier—Chubda Glacier. Within this glacier there are several supraglacial lakes which were observed during an expedition in August 1999 (Karma 1999).

DATA USED

In the present study, Terra/Aqua-MODIS snow cover products have been taken. It delivers public domain data in raster format. The MODIS snow cover product can be ordered free of charge through the Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC). The MOD10A1 (MODIS / TERRA SNOW COVER DAILY L3 GLOBAL 500m SIN GRID V005) snow product with 500m spatial was obtained for the study basin for the years of 2004-2009. This data was provided in a Hierarchical Data Format (HDF). This data was re-projected to convert from HDF format into an ERDAS IMAGINE compatible img format for visualization.

To obtain elevation zones for snowmelt runoff study, Digital Elevation Model (DEM) is required. Due to non availability of topographic maps, DEM generated using ASTER has been used. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer sensor) is an imaging instrument that is flying on the TERRA satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER represents a revolution in the remote sensing community because of the availability of its imagery and its superior resolution. ASTER resolution ranges from 15m to 90m, depending on the wavelength. The instrument records in three bands: the Visible and Near Infrared (VNIR), the Shortwave Infrared (SWIR), and the Thermal Infrared (TIR), oriented on the nadir and backward looking. There are 14 spectral bands all together spanning the visible and infrared spectra, so the sensor is susceptible to cloud cover and cannot record images at night. Because of its off-nadir sensor pointing capability, ASTER can collect the stereo pairs necessary to generate high resolution

DEMS (using bands 3N and 3B).The ASTER onboard the Terra satellite has produced 30 m resolution elevation data. There is a fairly complete coverage of world at this high resolution and data are free. Japan's Ministry of Economy, Trade and industry (METI) and NASA announced the release of the ASTER Global Digital Elevation Model (GDEM) on June 29, 2009. The GDEM was created by stereo-correlating the 1.3 million scene ASTER VNIR archive, covering the Earth's land surface between 83N and 83S latitudes. The GDEM is produced with 30 meter postings, and is formatted in 1x1 degree tiles as GeoTIFF files. The GDEM is referenced to the WGS84/EGM96 geoid. The GDEM's pre-production accuracy estimates were 20 meters at 95% confidence for vertical data, and 30 meters at 95% confidence for horizontal data. For this study, grids covering the study area have been obtained from internet and DEM of the study area has been prepared.

Physiographical and hydro-meteorological data are required for computing the streamflow from the basin. Physiographical data represent physical features of the basin, including its total area, its altitudinal distribution through elevation zones and the areas of these zones, and the altitude of precipitation and temperature stations. Hydro-meteorological data include daily precipitation, mean air temperature, snow-covered area and streamflow data. Information on the initial soil moisture status of the basin is needed at the beginning of simulation. In order to simulate the streamflow, the daily rainfall data of five stations and temperature data of four stations were used. Daily mean temperatures were computed by taking the average of available daily maximum and minimum temperatures. In case of snow covered area, snow accumulation starts from the month of October therefore the period October–September was considered as the hydrological year (Clow et al. 2010). In the present study data of five stations for rainfall and four stations for temperature have been used and the details of which are given in table 1.
The rainfall data was available for the stations having altitude 3500, while in this study area the altitude varies up to 6500 m. Therefore to have rainfall data of higher altitudes, Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE's Water Resources) have been downloaded from internet. The APHRODITE project develops state-of-the-art daily precipitation datasets with high-resolution grids for Asia. The datasets are created primarily with data obtained from a rain-gauge-observation network. APHRODITE's Water Resources project has been conducted by the Research Institute for Humanity and Nature (RIHN) and the Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA) since 2006. A daily gridded precipitation dataset for 1961-2007 was created by collecting rain gauge observation data across Asia through the activities of the APHRODITE project. The number of valid stations was between 5000 and 12,000, representing 2.3 to 4.5 times the data available through the Global Telecommunication System network, which were used for most daily grid precipitation products. APHRODITE's daily gridded precipitation (APHRO_V0901R) is the only long-term (1961 onward) continental-scale daily product that contains a dense network of daily rain gauge data for Asia including the Himalayas and mountainous areas in the Middle East. The product contributes to studies such as the evaluation of Asian water resources, diagnosis of climate change, statistical downscaling, and verification of numerical model simulation and high-resolution precipitation estimates using satellites (http://www.chikyu.ac.jp/precip/).

Table 1 Hydrometeorological data and elevation of different stations used in the study: rainfall (*P*), temperature (*T*), discharge (*Q*).

Station	Elevation (m)	Type of data	Period of availability
Kurjey	2600	Q	May 91-Mar-10
Chumey	2850	P	Jan-86 to Dec-98
Chamkhar	2470	P, T	Jan-94 to Mar-10
Gyetsa	2630	P.T	Jan 93 to Dec 08
Ura	3090	P, T	May-85 to Oct-08
Yotongla	3530	P, T	Jan-03 to Oct-08
Tazong	1530	Q	May 2009-Nov. 2010

METHODOLOGY

In the present study SNOWMOD model (Jain, 2001, Singh and Jain, 2003) has been applied for snowmelt runoff modeling. This model is unique as it simulates all components of runoff, i.e. snowmelt runoff, rainfall-induced runoff and base flow, using limited data.The snowmelt model (SNOWMOD) is a temperature index model, which is designed to simulate daily stream flow for mountainous basins having contribution from both snowmelt and rainfall. The generation of stream flow from such basins involves the determination of the input derived from snowmelt and rain, and its transformation into runoff. It is a semi-distributed model and for simulating the stream flow, the basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model achieves three operations at each time step. At first, the available meteorological data are extrapolated at different altitude zones. Then the rate of snowmelt is calculated at each time step. Finally, the snowmelt runoff from SCA and rainfall runoff from SFA (snow-free area) are integrated, and these components are routed separately with proper accounting of base flow to the outlet of the basin. The model optimizes the parameters used in routing of the snowmelt runoff and rainfall runoff. Figure 1 schematically shows the different steps involved in the model.

In order to execute SNOWMOD model, the following input data are required:

- Physical features of the basin which include snow covered area, elevation zones and their areas, altitude of meteorological stations, and other watershed characteristics affecting runoff.
- Time variable data include precipitation, air temperatures, snow-covered area, stream flow data, and other parameters determining the distribution of temperature and precipitation.
- Information on the initial soil moisture status of the basin.
- Miscellaneous job control and time control data, which specify such items as total computation period, routing intervals etc.

SNOWMOD is a semi distributed hydrological model, which allows the basin to be divided into number of zones. The number depends upon the topographic relief of the basin. There are no specified criteria for slicing the basin in different altitudinal, but an altitude difference of about 500 to 600 m is considered appropriate for dividing the basin into different elevation zones.

For the study basin, the daily maximum and minimum air temperature data were available for four meteorological stations. For corresponding zone, the temperature data was interpolated using the air temperature data of different stations and lapse rate data.

CREATION OF DATA BASE FOR SIMULATION OF SNOWMELT RUNOFF

In the present study, ERDAS imagine 9.3 and Arc GIS 9.3 have been used for creation of data base required for simulation of stream flow The catchment map up to Kurjey has been prepared using ASTER DEM. The elevation values ranges from a minimum of 784 m to maximum of 6868 m with in the study area. The study area up to Kurjey is 1361.68 sq. km. The catchment up to Kurjey has been divided into 9 elevation zones. The area covered in each elevation zone for the catchment is given in Table 2.

For the present study, the daily precipitation data were available for five stations within the study area. These stations are located in lower part of the catchment. For upper part of the catchment (higher elevation zones), rainfall data obtained from APHRODITE water resource project have been used. APRODITE data is available for different regions in the Asia and the data of Monsoon Asia (MA) have been downloaded. This data is available in the form of grid of 0.5° and 0.25°. This data was converted into map form using Arc GIS and exported to ERDAS Imagine. Then the rainfall data for the grids falling above 4500 m altitude were obtained and used in this study. The rain gauge has been considered for different elevation zones based on its proximity to the respective elevation zones according to altitude of the station. Similarly temperature data of four stations have been used as per the table 3.

The information on snow cover area (SCA) is determined from the satellite imageries/digital data. MODIS Snow data products have been used to obtain SCA maps. MODIS data were in sinusoidal projection and WGS84 datum. This sinusoidal projection was re-projected to Geographic Lat/Long and WGS84 datum. All the MODIS data products were found to be very accurately geo-referenced with each other (Jain *et al*. 2008). However, it was observed that MODIS data products and ASTER-DEM are not accurately geo-referenced with respect to each other. All the MODIS images and ASTER-DEM were geo-referenced. As many as 12 Ground Control Points (GCPs) were selected in the image. The GCPs were spread throughout the image so that the rectification is more reliable. The Root Mean Square Error (RMSE) value was kept within a pixel. The next step was to convert the source coordinates to rectified coordinates. For this operation second-order, polynomial equation was used. The re-sampling was done using Nearest Neighbor method, which uses the value of the nearest pixel to assign to the output pixel value.

Snow exhibits high reflectance in visible band and strong absorption in SWIR (Short Wave Infrared) band. A spectral band ratio can enhance features, if there are differences in spectral slopes (e.g., Gupta *et al*, 2005). The Normalized Difference Snow Index (NDSI) uses these spectral characteristics of snow and is based on the concept of Normalized Difference Vegetation Index (NDVI) used in vegetation mapping from remote sensing data (Dozier, 1989: Hall *et al*., 1995, Gupta *et al*., 2005). The NDSI is defined as the difference of reflectance observed in a visible band and the short-wave infrared band divided by the sum of the two reflectance (Gupta *et al*., 2005). The MODIS snow cover algorithm is based on the high reflectance of snow in the visible band (band 4, 0.545– 0.565 μm) and low reflectance in the short wave infrared band (band 6, 1.628–1.652 μm). These two bands are used to calculate the normalized difference snow index (NDSI) (Hall *et al*., 1995).The equation is given below:

$$\mathrm{NDSI} = \frac{\text{Visible Band} - \text{SWIR Band}}{\text{Visible Band} + \text{SWIR Band}} \qquad (3)$$

Aqua/Terra-MODIS satellite data products are available from February 2000 till present date. The MODIS snow cover product is a classified image. For development of snow covered products, NDSI approach have been used to compute snow cover area. The images were further classified by clubbing snow and lake ice into snow category and rest of the classes into non-snow category. Thus all the images were classified into snow and non-snow category. SCA from February 2004 to December 2009 have been obtained from MODIS data.

Using the classified snow maps, the total percentage of snow cover in the study area was estimated for different dates. Further, for snowmelt runoff modeling, the SCA are required for different elevation zones. For this purpose, classified DEM and SCA maps have been processed for all the dates. The SCA in each elevation zones were plotted against the elapsed time to construct the SDC (Snow Depletion Curve) for the various elevation zones in the basin for all the years.

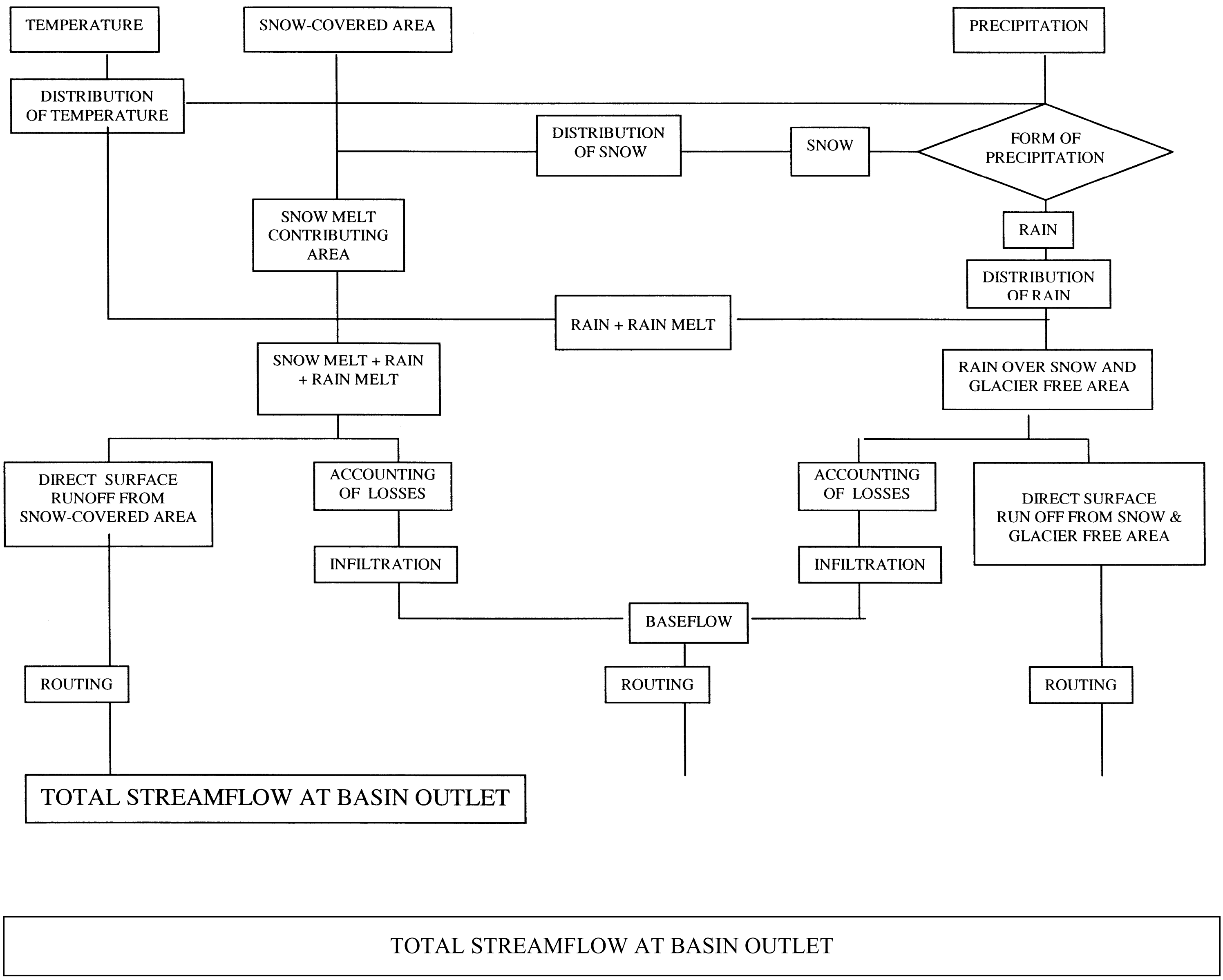


Figure 3.1 Flow chart of the snowmelt runoff model (SNOWMOD)

RESULTS

The runoff from snow covered area consists of: (i) snowmelt caused due to temperature, (ii) under rainy conditions, snow melt due to heat transferred to the snow from rain, and (iii) runoff from rain itself falling over snow covered area. The source of surface runoff from the snow free area is rainfall. Like snowmelt runoff computations, runoff from snow free area was also computed for each zone. The entire data base has been prepared for four years i.e. 2004-2005, 2005-2006, 2006-2007 and 2007-2008. In first phase, the model is calibrated for two years (2004-2005 and 2005-2006) for the catchment up to Kurjey site for two years (2006-2007 and 2007-2008) for this catchment.

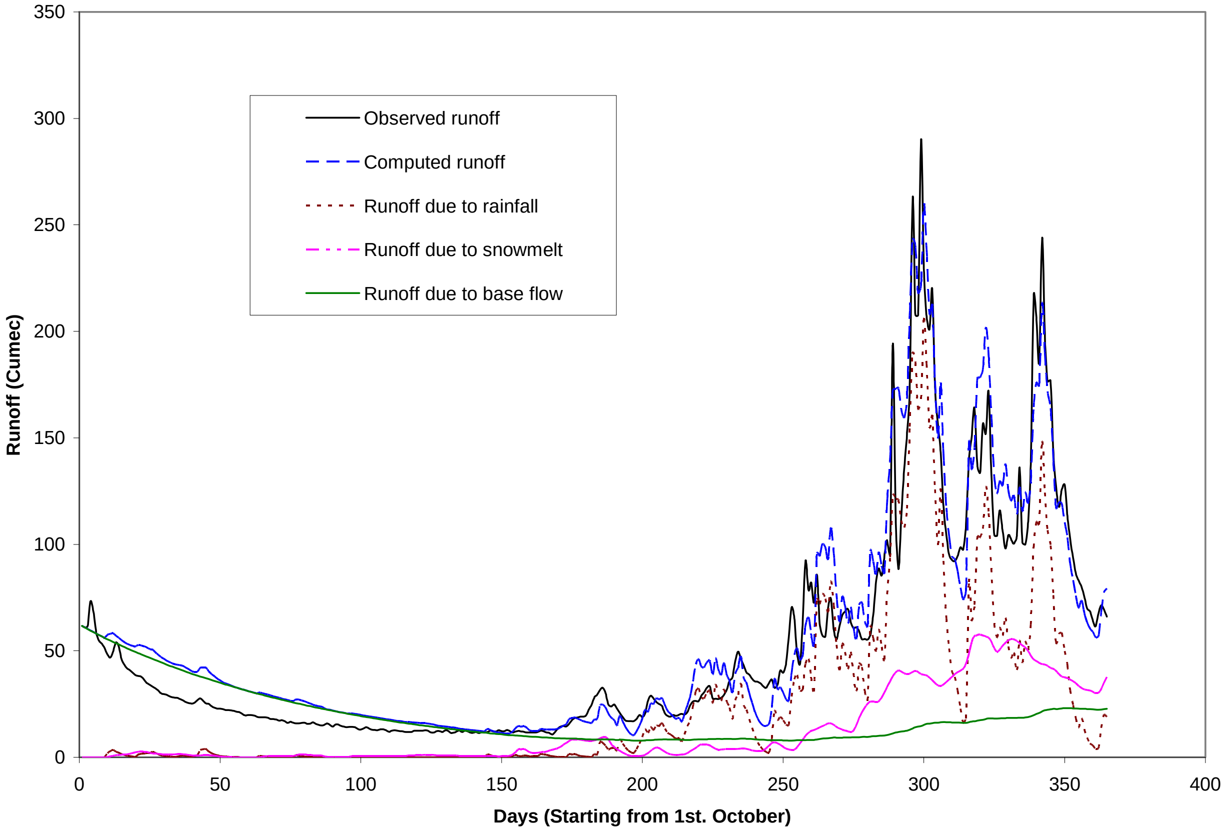
Hydrological models are generally calibrated using computed and observed streamflow records, while the available data set is split into two parts: one being used to calibrate the model and the other being used to validate it, i.e. to check how the model performs in simulation mode (Blackie & Eles, 1985). In the present study, the Rosenbrock optimization technique was used for optimization of parameter values (Kuester & Mize, 1973). A suitable objective function is employed to determine the acceptable degree of agreement between the observed, Q_o and estimated flows, Q_e. The most commonly used objective function, *F,* to be minimized represents a simple summation of the squares of residuals:

$$F = \sum \left(Q_e - Q_o\right)^2 \tag{4}$$

As discussed earlier that discharge is only available for Kurjey site there model was calibrated for the catchment up to this site. The model was calibrated for a period of 2 years (2004-2006) by varying the initial parameters, and optimization of the four model parameters (a_r, b_r, a_s and b_s) was carried out. The calibrated values of the parameters were computed considering the overall performance of the model and reproduction of the flow hydrograph for all the two years. The optimized values of a_r, b_r, a_s and b_s were 0.99, 0.15, 0.959 and 0.15, respectively. For the calibration period of two years, the model simulated daily streamflow with an efficiency, R^2 (Nash & Sutcliffe, 1970), ranging from 0.88 to 0.87 and the difference in volume of observed and computed streamflow was computed to be between 2 and 5%. The results indicate a good performance of the model for all the calibration years.

After successful calibration of the model for a period of two years, the model was run to simulate daily streamflow up to Kurjey site using independent data for two years (2006-2007 and 2007-2008). The comparison of daily observed and simulated streamflow for these two years is shown in Fig. 4. The overall efficiency of the model over the study period of two years was 0.91 and 0.90 for 2006-07 and 2007-08 respectively and the difference in volume of computed and observed streamflow was only 9.17% and 1.62%. The results indicate that the model performed equally well for the simulation years as for the calibration years.

From the figure 4, it is clear that the discharge rises from May onwards and reaches its peak by August and September and than starts reducing from the month of September onwards. In all the years, high flow occurred in the month of July and August. A close observation of rainfall and stream flow data indicates that most of the peaks in the streamflow were because of rainfall. From all the figures, it is clear that the volumes and peaks of streamflow were reproduced well by the model for all the years. The study shows that SNOWMOD, a temperature index based snowmelt runoff model, worked well in the study basin where limited data are available.



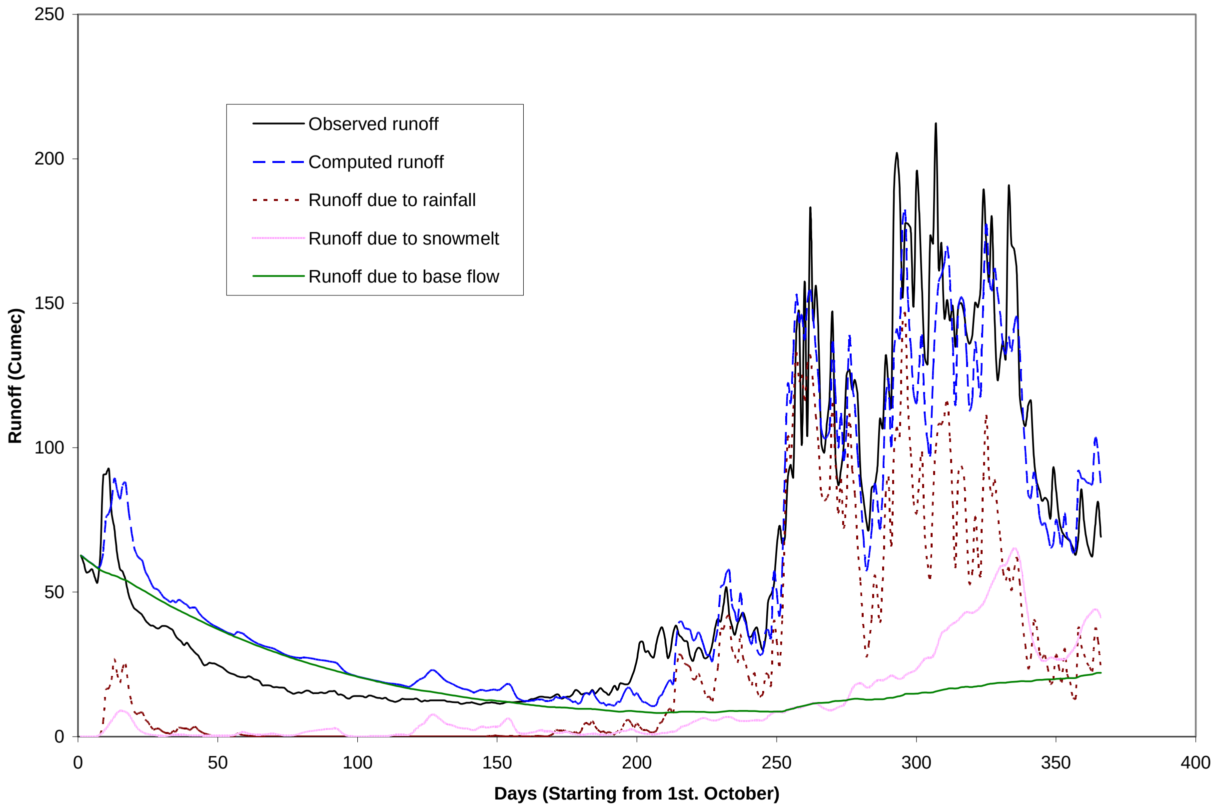


Figure 4.5: Observed and simulated stream flow (at Kurjey site) for the year 2006-2007 and 2007-2008

CONCLUSIONS

The model was calibrated for the catchment up to Kurjey site using data of two years (2004-05 and 2005-2006) and then used for simulating the daily streamflow for an independent data set of two years (2006-07 and 2007-08). The model efficiency (R^2) for the calibration period varied from 0.88 and 0.87, while for the simulation period it varied between 0.91 and 0.90. Keeping in view the size of the basin and limited data availability, the results indicate that the model successfully simulated the streamflow for all the simulation years. It was observed that most of the peaks in the streamflow are generated by rainfall. The model was also applied to estimate the contribution from snowmelt and rainfall at the project site. The analysis suggests that about half of the flow comes from rainfall runoff. From this simulation rainfall runoff, snowmelt runoff and base flow have been computed separately. For the year 2006-2007, average annual runoff comes out to be 106.14 cumec and out of this rainfall runoff, snowmelt runoff and base flow are 50.39%, 23.11%, 26.50%. In this year, minimum runoff and maximum runoff comes out to be 21.34 and 525.05 cumec respectively. For the year 2007-2008 average annual runoff comes out to be 105.6 cumec and out of this rainfall runoff, snowmelt runoff and base flow are 47.27%, 25.46%, and 27.27%. In this year, minimum runoff and maximum runoff comes out to be 22.5 and 364.75 cumec respectively.

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