

SNOWMELT RUNOFF ESTIMATION OF A HIMALIYAN WATERSHED THROUGH REMOTE SENSING, GIS AND SIMULATION MODELING

A. Alam ^{§*}, A. H. Sheikh [§], S. A. Bhat [§], A. M. Shah [§]

[§]Department of Geology & Geophysics University of Kashmir, Srinagar, (India)-190006
E-mail Id: geo_sameer@yahoo.co.in

KEY WORDS: Snowmelt, Runoff, SRM, Remote Sensing, GIS.

Abstract:

The snowmelt runoff is bedrock to various resource-based economies vis-à-vis Agriculture, Tourism, Horticulture and Hydropower and contributes predominantly to the GDP of the Jammu & Kashmir state. The glaciers in the Kashmir Himalayas have been reported to be receding rapidly due to the Global climatic change. In light of the economic and scientific importance of these glaciers, it is imperative to assess these resources and their water potential periodically. In the mountainous and inaccessible areas the satellite images accompanied with GIS tools such as Digital Elevation Model (DEM) and simulation models have proved to be of great importance to determine and establish a link between theoretical principles and ground situations. The present study integrates different geo-spatial tools vis-à-vis Remote Sensing (RS), Geographical Information System (GIS) and SRM (Snowmelt-Runoff Model) for estimation of snowmelt runoff in the Kolahai catchment of western Himalayas. Estimation of snowmelt runoff and resulting stream flow from various catchments is of considerable importance for resource management. Hydro-meteorological data of the year 2001 was used for running the SRM. The results obtained revealed that there is not much variation between measured runoff (79.160) and computed runoff (72.909). The analysis of results proves that the SRM model is best tool for computing the snowmelt runoff in the mountainous areas.

1.0 Introduction:

Knowledge of the hydrological behavior is a crucial step in water resources management of large-scale catchments. Estimation and prediction of snowmelt runoff and resulting stream flow from various catchments is of considerable importance for planning, operation of river valley projects and for understanding various hydro-meteorological processes. Besides accurate estimation of runoff volumes is needed for water supply forecasting, flood predictions and warnings, navigation, and water resource management works. Snowmelt-Runoff Model (SRM; also referred to in the literature as the "Martinec Model" or "Martinec-Rango Model") is designed to simulate and forecast daily stream-flow in mountain basins where snowmelt is a major runoff factor. SRM can be applied in mountain basins of almost any size (so far from 0.76 to 120,000 km²) and any elevation range (for example 305-7690 m a.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. The required input to the Snowmelt Runoff Model (SRM) for different elevation zones is snow-covered area (S), temperature (T) and precipitation (P) values. One of the important tools in acquiring spatial and temporal information of large-scale catchments is remote sensing.

Monitoring of snow-covered area with satellite images, as quantitative data, improves the standard methods and hydrological tools by using spatial analysis. Snow cover is an important input variable for SRM therefore multi-temporal Landsat-MSS and Landsat-ETM images were processed using appropriate enhancement techniques and geo-processing algorithms including supervised classification for land use / land cover and snowcover extraction. It is a typical feature of mountainous basins that the areal extent of the seasonal snow cover gradually decreases during the snowmelt season. Depletion curves of the snow coverage can be interpolated from periodical snow cover mapping so that the daily values can be read off as an important input variable to SRM.

2.0 Study Area:

Pahalgam Valley, a famous pilgrimage and tourist destination, located in the southeastern part of the of Jammu & Kashmir state, has been selected for the present research.



Figure 1: Location Map of the Study Area

* Corresponding Author.

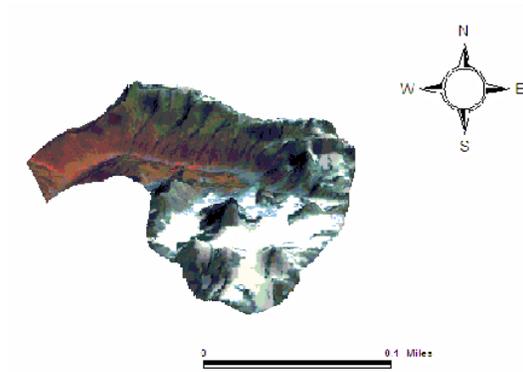


Figure 2: 3D View of the Selected Watershed

As snowmelt runoff is one of the main factors in the water budget of the river, a special attention and recognition of the runoff processes is needed. The area falls approximately between $75^{\circ} 30'$ to $75^{\circ} 45'$ longitude and $34^{\circ} 15'$ to $34^{\circ} 30'$ latitude. The catchment spreads over an elevation range of 1600-5500 meters above mean sea level. The catchment remains under the snow cover throughout the year especially in winter and is one of the main sources of water in the state. Climate of a particular place is the net result of the combination of several factors like latitude, altitude, terrain, distance from the sea and the prevailing winds. Kashmir province of Jammu and Kashmir has cold moist winters and a mild temperature in the summers. The cold and moist Siberian anticyclones affect this area when the west winds from the Mediterranean Sea are dominant.

3.0 Material used:

The research involved the usage of historical hydro-meteorological data, S.O.I topographic maps of 1:50000 scale with 40m contour interval, Digital Elevation Model (DEM), multi-temporal Landsat-MSS and Landsat-ETM satellite images, numerical modeling and field surveys.

4.0 Methodology:

The methodology adopted for the present research involved following steps:

-Analyses of hydrological and meteorological data (daily, monthly) from the stations located outside the study area and calculating the model parameters for SRM, such as rainfall and temperature.

-Using topographical maps for creating DEM and the area elevation curve of the basin. It is required for the physiographic studies. The physical characteristics of the basin are necessary for the determination of model parameters, such as extrapolation of temperature and rainfall data for different zones.

-Computation of degree-days from temperature data. This is used in the model for the calculation of daily snowmelt depth.

-The precipitation data is required at stations outside the study area. This is to be used for the calculation of precipitation-altitude relationship.

-The SRM model requires the monitoring snow cover in the selected catchment during the snow season. A series of Landsat TM & MSS sensor images was used for monitoring the snow cover extent.

-Simulations of runoff using SRM, the following variables are needed: daily data of precipitation, temperature and discharge. The model parameters are: degree-day factor, runoff coefficient for snow and rain, temperature lapse rate, critical temperature, rainfall contributing area, recession coefficient and time lag.

-Assessment of model accuracy: the SRM computer program includes a comparison display of the computed runoff and measured runoff. A visual inspection of the graph shows at the first glance whether the simulation is successful or not.

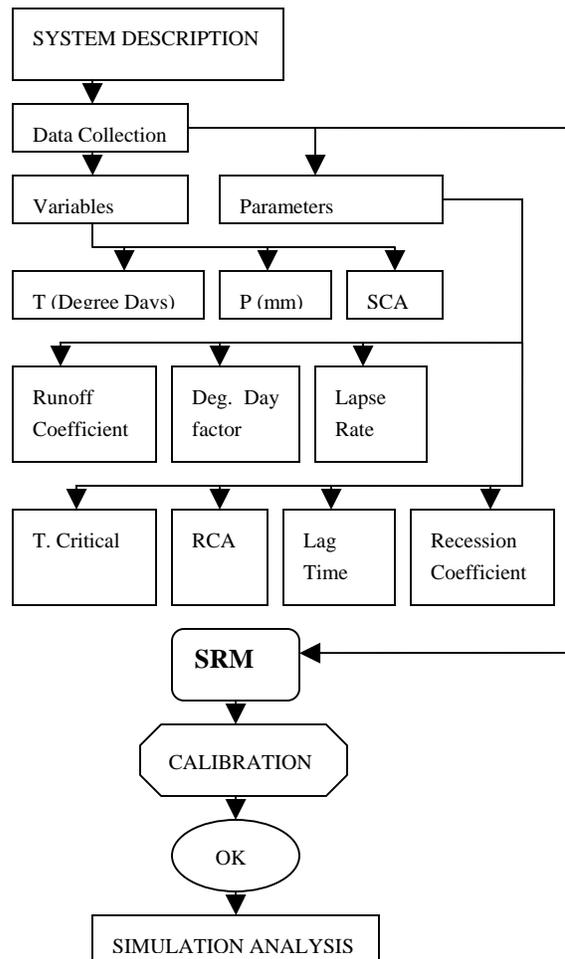


Figure 3: Work Flow of the research

4.1 Elevation Zonation /Reclassification:

For snowmelt runoff modeling using SRM, the watershed had to be reclassified/subdivided into elevation zones. For that matter Erdas Imagine's (8.4) "Modeler" module was used with "Conditional" and "Relational" functions. Based on the elevation range between lowest (3500m) and highest (5500m) point in the watershed, 10 elevation zones have been delineated with the varying altitude and spatial extent using DEM of the catchment.

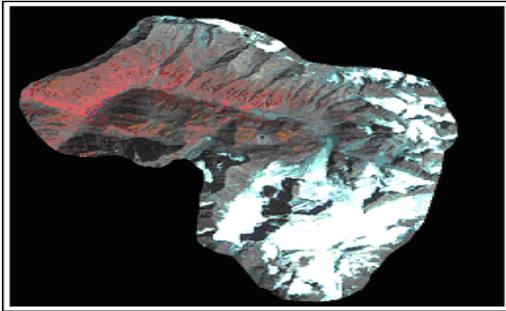


Figure: 4 Landsat-ETM Scene of the Watershed (2001)

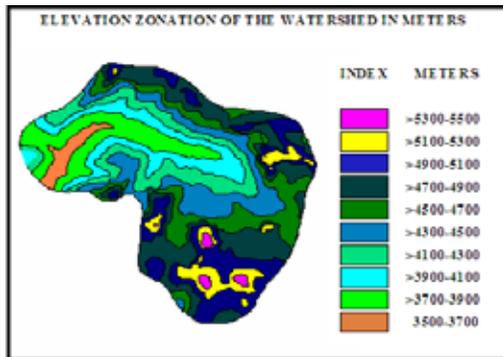


Figure: 5 Elevation Zonation Map of the Watershed

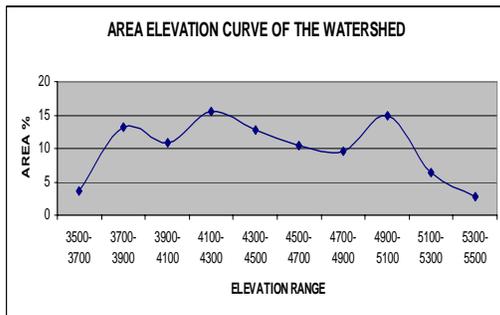


Figure: 6 Area Elevation Curve of the Watershed

ZONE NUMBER	ELEVATION RANGE	AREA Sq. MILES	% AREA
1	3500-3700	0.9	3.60
2	3700-3900	3.3	13.2
3	3900-4100	2.7	10.8
4	4100-4300	3.9	15.6
5	4300-4500	3.2	12.8
6	4500-4700	2.6	10.4
7	4700-4900	2.4	9.60
8	4900-5100	3.7	14.8
9	5100-5300	1.6	6.40
10	5300-5500	0.7	2.80
TOTAL	3500-5500	25	100.0

Table: 1 Showing Area Under Each Elevation Zone

These zones form the basis of the calculations in snowmelt runoff model (SRM). For the calculation of snowmelt runoff, various variables and parameters were defined and extrapolated to each elevation zone separately because all these variables vary with the variation in elevation.

4.2 Hydro-meteorological Analyses:

In order to predict hydrological behavior of a catchment it is necessary to analyze the historical hydrometeorological data of the catchment. Analyses of hydrological and meteorological data (daily, monthly) from the various stations located inside and outside the study area is necessary for calculating the model parameters for SRM, such as temperature, rainfall and runoff.

4.2.1 Variables:

Variables basically describe the actual meteorological conditions for the simulated period. These data have to be obtained preferably from in situ measurements, but snow cover; can be defined by remote sensing.

4.2.2 Temperature (T):

The SRM accepts either the daily mean temperature or two temperature values on each day T_{Max} , T_{Min} .

Temperature data are extrapolated to the hypsometric mean elevations of all zones using the lapse rate. If temperature stations at different altitudes are available, the lapse rate can be predetermined from historical data. Otherwise it must be evaluated by analogy from other basins or with regard to climatic conditions. In SRM simulations, a lapse rate of 0.65°C per 100 m is usually employed. The altitude adjustment ΔT in Equation (1) is computed as follows:

$$\Delta T = \gamma \cdot (h_{st} - \bar{h}) \cdot \frac{1}{100} \dots\dots(1)$$

Where γ = Temperature lapse rate [°C per 100 m]

h_{st} = Altitude of the temperature station [m]

\bar{h} = Hypsometric mean elevation of a zone [m]

Whenever the degree-day numbers ($T + \Delta T$) become negative, they are automatically set to zero so that no negative snowmelt is computed.

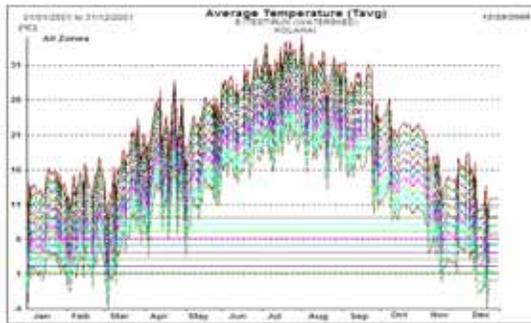


Figure: 7 Graph Showing Average Temperature of 10 Elevation Zones in Kolahai Catchment 2001

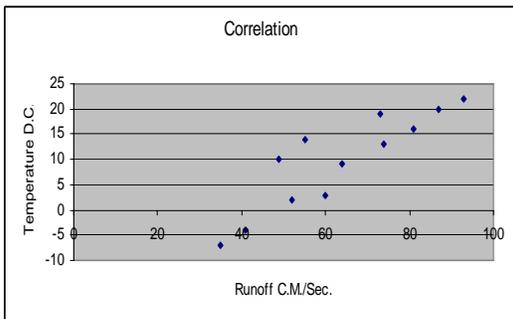


Figure: 8 Graph Showing Response of Runoff to Temperature in the watershed 2001

4.2.3 Precipitation (P):

The evaluation of representative areal precipitation is particularly difficult in mountain basins. The SRM accepts 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.

In basins with a great elevation range, the precipitation input may be underestimated if only low altitude precipitation stations are available. It is recommended to extrapolate precipitation data to the mean hypsometric altitudes of the respective zones by an altitude gradient, for example 3 % or 4 % per 100 m. If two stations at different altitudes are available, it is possible to assign the averaged data to the average elevation of both stations and to extrapolate by an altitude gradient from this reference level to the elevation zones. It should be noted that the increase of precipitation amounts with altitude does not continue indefinitely but stops at a certain altitude, especially in very high elevation mountain ranges.

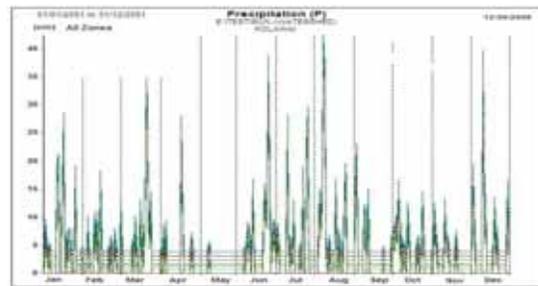


Figure: 9 Graph Showing Average Precipitation of 10 Elevation Zones in Kolahai Watershed 2001

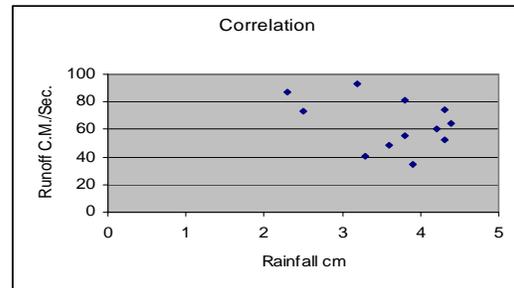


Figure: 10 Graph Showing Response of Mean Monthly Runoff to Mean Monthly rainfall 2001

4.2.4 Snow Covered Area (S):

It is a typical feature of mountain basins that the areal extent of the seasonal snow cover gradually decreases during the snowmelt season. Depletion curves of the snow coverage can be interpolated from periodical snow cover mapping so that the daily values can be read off as an important input variable to SRM. The

snow cover can be mapped by terrestrial observations (in very small basins), by aircraft photography (especially in a flood emergency) and, most efficiently, by satellites. The minimum area, which can be mapped with an adequate accuracy, depends on the spatial resolution of the remote sensor (Martinec and Rango 1998).

4.2.5 Parameters:

The SRM parameters are not calibrated or optimized by historical data. They can be either derived from measurement or estimated by hydrological judgment taking into account the basin characteristics, physical laws and theoretical relations or empirical regression relations. Occasional subsequent adjustments should never exceed the range of physically and hydrologically acceptable values (Martinec and Rango 1998). These include, Runoff Coefficient (C), Degree-day factor, (a) Temperature lapse Rate (γ), Critical Temperature (T_{CRIT}), Rainfall Contributing area (RCA) Recession Coefficient (k), Time Lag (L)

5.0 Results and Discussion:

The runoff simulation of Kolahoi watershed was done using Snowmelt Runoff Model for the hydrological year of 2001. Hydrometeorological data of Odur station was used for running the model. Reliability and situation of this station is important in using its data for simulation.

5.1 Assessment of the Model Accuracy:

SRM uses two well-established accuracy criteria, namely, the coefficient of determination, R^2 , and the volume difference, D_v . (Martinec and Rango 1998).

The coefficient of determination is computed as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Q_i - Q'_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \dots\dots\dots(3)$$

Where:

- Q_i is the measured daily discharge.
- Q'_i is the computed daily discharge.
- \bar{Q} is the average measured discharge of the given year or snowmelt season
- n is the number of daily discharge values. The deviation of the runoff volumes, D_v , is computed as follows:

Simulation Statistics	Run Results
Measured Runoff Volume (10^6 m ³)	79.160
Average Measured Runoff (m ³ /s)	5.988
Computed Runoff Volume (10^6 m ³)	72.909
Average Computed Runoff (m ³ /s)	5.515
Volume Difference (%)	7.8969
Coefficient of Determination (R^2)	0.0296

Table 2 Simulation Results of Kolahai Watershed (2001)

$$D_v [\%] = \frac{V_R - V'_R}{V_R} \cdot 100 \dots\dots\dots(2)$$

Where:

- V_R Is the measured yearly or seasonal runoff volume.
- V'_R Is the computed yearly or seasonal runoff volume

The results obtained reveal that there is not much difference between computed and measured runoff

and the simulation of Kolahai catchment for the hydrological year of (2001) is successful.

Conclusion:

The snowmelt runoff for the hydrological year of (2001) was simulated using SRM model. The obtained results show that, the SRM model is best tool for computing the snowmelt runoff in the mountainous areas and it is recommended for other catchments.

SRM model is very sensitive to input data especially temperature and precipitation and simulates the runoff with correct delay related to the causing event. Since the meteorological stations are located in very low altitude range, it is recommended that the catchment should be

equipped with temperature monitoring and rain gauge stations at as high altitudes as possible. Since snow density and snow pack thickness are important in snowmelt, it is recommended to equip these stations with the instruments. Since critical temperature and degree-day factor are two main parameters in snowmelt runoff forecasting and snow studies, it is recommended to determine them for different places and times by research centers and meteorological organization. Creating scenarios of wet and dry years for all the important sub catchments of the Pahalgam Valley will give a more detailed and accurate insight into the potentials and limitations of the water resources in the state of Jammu & Kashmir.

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