TRAINING COURSE
ON

HYDROLOGICAL MODELING AND GIS

(MAY 26 TO JUNE 06, 2014)

FOR

UNFAO & Ministry of Energy and Water, Afghanistan

LECTURE NOTE
ON

SNOW COVER MAPPING AND SNOWMELT RUNOFF MODELLING

By

SANJAY K. JAIN
NIH ROORKEE

NATIONAL INSTITUTE OF HYDROLOGY
AND
INDIAN ASSOCIATION OF HYDROLOGISTS

ROORKEE – 247 667 (UTTARAKHAND)

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Snow cover is an important component of the hydrologic cycle. A significant part of the earth is covered by snow for at least a portion of the year, producing a substantial change in surface characteristics from those exhibited when snow is absent. About 10% of the earth's surface, 15×10^6 km^2, is covered by polar ice caps and glaciers. The upper catchment of the Himalayan basins is covered by seasonal snow during winters. For example average snow and glacier contribution in the annual flows of Chenab River at Akhnoor was estimated to be 50%, Ganga at Devprayag was about 30%, Beas at Manali was about 54% and Parvati at Bhunter is about 50% (in press). The accumulated snow in the Himalayan basin becomes an important source of streamflow during the summer time.

The majority of rivers originating from the Himalayas have their upper catchment in the snow covered areas. The solid precipitation results in temporary storage and the melt water reach the river in the melt season. The snow accumulation in Himalayas is generally from November to March, while snowmelt is from April to June. During April to June, snowmelt is the predominant source of runoff and during July to September it forms a significant constituent of melt. The Himalayan river system is shown in Figure 1. The snowmelt runoff modelling is of vital importance in forecasting water yield. Snow and glacier melt runoff is very important particularly in the lean season and it plays a vital role in making perennial nearly all the rivers originating in Himalayas perennial. The contribution of the snow and glacier melt in annual flows of Himalayan Rivers at potential project site is not available. Further, the extent of snow cover and its distribution with time is not available for the Himalayan region. Such information is necessary to solve the hydrologic problems of this region.

REMOTE SENSING OF SNOW COVER

Distributed hydrological models, which can account for the spatial variability of basin physiography and meteorological inputs, have the potential to exploit detailed snow cover data, including distributed snow cover area. Conventional snow cover data, such as snow surveys, provide detailed information on such snow pack properties but their site specific nature and infrequent occurrence limit their potential for use in distributed models. In order to provide distributed information characterizing the snow cover of a watershed, snow survey measurements must be extended to regions where no snow survey data are available. Remote sensing offers a significant potential for collecting this data in cost effective manner. Because of difficult access, harsh weather conditions and expensive operation of hydrological stations, radar or satellite data are particularly appropriate. However, ground truth data are indispensable in the calibration and verification of remotely sensed data. Aerial and satellite surveys are useful in mapping snow lines. The wealth of observational material obtained by remote sensing can be integrated into models, such as snowmelt runoff models, considerably improving the forecast accuracy.

Remote sensing technology makes use of the wide range of the electro-magnetic spectrum (EMS). Most of the commercially available remote-sensing data are acquired in the visible, infrared, and microwave wavelength portion of the EMS. Satellite data are digital records of the spectral reflectance of the Earth's surface features. These digital values of spectral reflectance are used for image processing and image interpretations. Snow was first observed by satellite in eastern Canada from the TIROS-1 satellite in April 1960. Since then, the potential for operational satellite based snow cover mapping has been improved by the development of higher temporal frequency satellites such as GOES (Geostationary Operational Environmental Satellite), Landsat, SPOT and IRS series, and NOAA-AVHRR, NIMBUS-SMMR and DMSP SSM/I satellites. Snow has a high albedo in the visible region of the electromagnetic spectrum compared to most natural surface cover. For this reason snow covered area maps were one of the first satellite remote sensing applications.

Figure 1 shows the electromagnetic spectrum and its intervals. Furthermore, the behaviour of snow in Visible, Near Infrared, Thermal Infrared and Microwave intervals is described.

Visible and Near Infrared

Fresh dry snow appears white to the human eye. That is to say, it is highly reflective, with little variation over the range of wavelengths (approximately 0.4 to 0.65 μm) to which the eye is sensitive . The reflectivity of new snow decreases as it ages in both visible and infrared region of spectrum, however the decrease is more pronounced in the curves of snow and ice Infrared. Decreasing reflectivity in the visible region can be attributed to the contaminants such as dust, pollen and aerosols. An advantage of using visible and near infrared data is the easy interpretation of the image. Even though, snow extent can be easily extracted, no information regarding the snow water content can be derived.

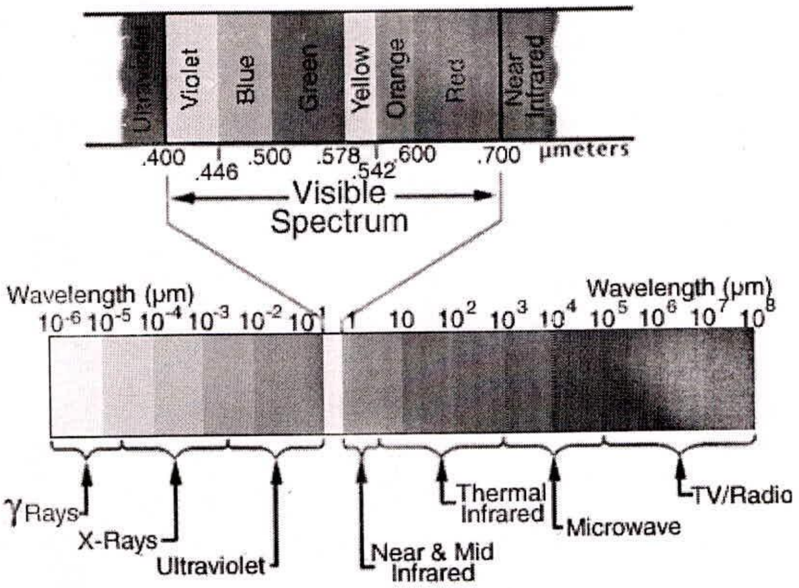

Figure 1: Electromagnetic spectrum and its intervals

Thermal Infrared

Thermal data have been used less than other remote sensing data for measuring snow characteristics since we should recognize snow radiation spectrum to determine temperature of snow. Despite all these limitations, thermal data are of great use to recognize the boundary between snowy zones and no-snowy zones. Like visible and near infrared images, clouds limit the usability of thermal infrared images. If there are clouds, the temperature above them will be measured.

Microwave

Microwave regions and microwave's sensors can have most application attentive to climatological conditions. Actually the physical characteristics of the snowpack determine its Microwave properties. Properties affecting microwave response from a snowpack include: depth and water equivalent, liquid water content, density, grain size and shape, temperature, stratification as well as snow state and land cover. The regular and frequent mapping of snow cover is possible using a sensor independent of time and weather. Depending on wavelength, microwave radiation will penetrate clouds and most precipitation, thus providing an all-weather observational capability, which is very significant in snow regions where clouds frequently obscure the surface. There are two types of microwave sensors: active and passive. Passive radiometers include NIMBUS-7 Scanning Multi-channel Microwave Radiometer (SMMR) and the DMSP SS/I satellites and measure surface brightness temperatures. Active satellite sensors contain synthetic aperture radar (SAR) and emit microwave radiation at a specific frequency and polarization and measure the return backscatter in the form of the backscatter coefficient.

Microwaves have unique capabilities for snow cover modelling:

1. They can penetrate cloud cover , providing reliable data;
2. They can penetrate through various snow depths depending on wavelength therefore potentially capable of determining internal snowpack properties such as snow depth and water equivalent;

Active microwave sensor was there on the First European Remote Sensing Satellite (ERS-1) and Canadian RADARSAT offer the possibility to observe seasonal snow cover characteristics in detail over the entire snow-cover season. In one simulation of RADARSAT data, snow-cover classification accuracy was 80%, comparable to aircraft Synthetic Aperture Radar (SAR). Comparing a classification of snow-covered area based on SAR with that done using TM suggests that a SAR-based classification is sufficiently accurate to substitute for visible-and-near-IR based estimates when such data are not available, for example due to cloudiness.

Passive microwave signals are also sensitive to the liquid-water content of snow, thus offering the potential to develop snow wetness estimates. The sensitivity of passive microwave signals to snow wetness aids in determining the onset of spring melt and the occurrence of multiple melt events during the winter. In passive mode, microwave emission is strongly dependent on the condition of the snow in terms of humidity, metamorphism and water equivalence. Microwave penetration depth of dry snow is much larger and dry snow cover less than 2.5 cm depth is transparent to the microwaves and ignored even though it is thick enough to reflect incoming short-wave radiation. The interaction of microwaves with snow strongly depends on the snow wetness, size and structure of snow grains. The dielectric constants of water and snow are so drastically different that even a little melting will cause a strong microwave response.

Reflectance pattern from different form of snow and ice is given in Figure 2.

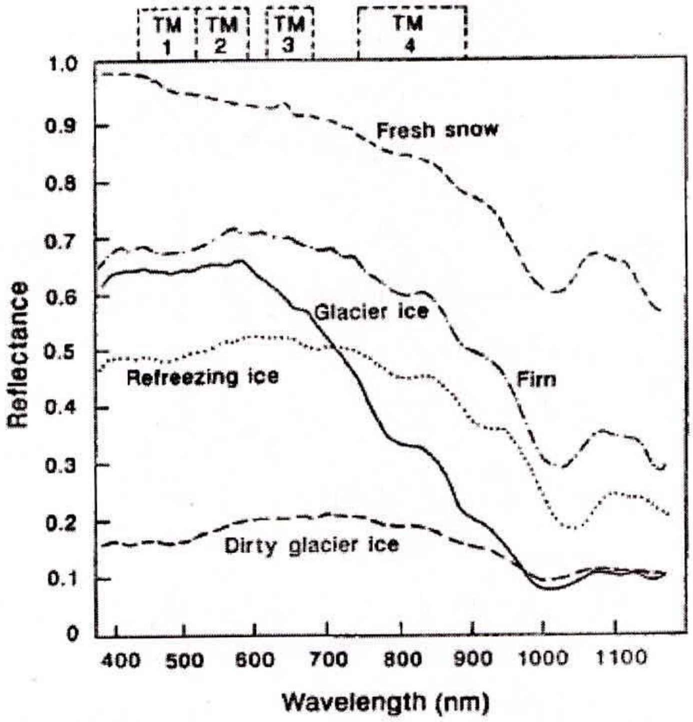

Figure 2: Reflectance curves from snow/ice

SNOW COVER MAPPING

Early work with satellite data indicated that snow and ice could not be reliably mapped because of the similarity in spectral response between snow and clouds due to limitations in the then available data set. It is now possible to differentiate snow and cloud easily in the middle infrared portion of the spectrum, particularly in the 1.55 - 1.75μm and 2.10 - 2.35μm wavelength bands (bands 5 and 7 of LANDSAT TM or band 4 of IRS). In the visible, near infrared, and thermal infrared bands, spectral discrimination between snow and clouds is not possible, while in the middle infrared it is. The reflectance of snow is generally very high in the visible portions and decreases throughout the reflective infrared portions of the spectrum. The reflectance of old snow and ice is always lower than that of fresh snow and clean/fresh glacier in all the visible and reflective infrared portions of the spectrum. Compared to clean glacier and snow (fresh as well as old), debris covered glacier and very old/dirty snow have much lower reflectance in the visible portions of the spectrum and higher in the middle infrared portions of spectrum.

Cloud-cover is considered as a hindrance for operational monitoring of snowcover using remote sensing data in the optical region of electromagnetic spectrum. Thus, SCA is obtained for the cloud-free days and information about snowcover during cloudy days is lost. There is not a globally accepted method to fill out SCA values of missing dates required for simulation and forecasting of snowmelt runoff . Snow maps derived from satellite data are a pixel-based representation of a snow-covered area. With spatial resolution of a few hundred meters up to one kilometer, a pixel, either classified as 'snow' or 'no-snow', often consists of snow-covered and snow-free parts. In theory, the snow line defines the line separating snow-covered from snow-free areas. However, because of the patchiness of the edge of the snowcover, no distinct line can be drawn. Instead, a more or less narrow belt has to be defined as the snow line, which represents a zone of approximately 50% snow coverage.

The Normalized Difference Snow Index (NDSI) uses the above spectral characteristics of snow and is based on the concept of Normalized Difference Vegetation Index (NDVI) used in vegetation mapping from remote sensing data. The NDVI 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 reflectances. The equation is given below:

$$\mathrm{NDSI} = \frac{\text{Visible Band} - \text{SWIR Band}}{\text{Visible Band} + \text{SWIR Band}}$$

The NDSI map can be classified into two classes: (a) snow and (b) snow-free area based on threshold value of 0.4. This type of classification provided an advantage of SCA estimation under mountain shadow condition and discrimination between snow and cloud.

Mapping the snow cover with in situ measurements is impossible for large catchments, mainly because of the extremely high cost and manpower required. Since the mid-1960s a variety of coarse and medium spatial resolution remote sensing data has been used to map several parameters of the earth. Remote sensing offers a powerful alternative for obtaining environmental data worldwide. Nowadays, many different instruments on satellites provide continuous information about the earth's actual state. The Moderate Resolution Imaging Spectroradiometer (MODIS) is one such instrument installed on the Terra and Aqua satellites. The MODIS instruments installed on the Terra and Aqua satellites collect data as part of NASA's Earth Observing System (EOS) program. The first MODIS instrument on the Terra satellite was launched in December 1999 and began to deliver data in February 2000. The second MODIS instrument on the Aqua satellite was launched in May 2002 and started to deliver data in July

2002. The Terra satellite crosses the equator from south to north at about 10:30 a.m. and the Aqua satellite from north to south at about 1:30 p.m. The Normalized Difference Snow Index (NDSI) method was used as the MODIS snow mapping algorithm with a set of thresholds. The MODIS snow cover product is partly distributed as tiles of about 10_by 10_ worldwide. There are a total of 36 horizontal (H) and 18 vertical (V) tiles covering the entire globe. The H23V05 tile that covers complete study area was used for this study. 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 and daily temporal resolution was obtained for the Kokcha basin for the whole year of 2003. This data was provided in an Hierarchical Data Format (HDF). The MODIS Reprojection Tool (MRT) was used in this study to convert from HDF format into an ArcGIS compatible GEOTIF format for visualization. The estimation of cloudy pixels was done in the ASCII format. Additionally, the Hole-filled seamless Shuttle Radar Topography Mission (SRTM) digital elevation data with 90m spatial resolution was obtained from the International Centre for Tropical Agriculture (CIAT) and this was also used as ASCII format in this methodology.

Accurate information concerning ice cover has long been required in many scientific disciplines. Studies of glaciers are needed for water resources development and water management, present climate and past climate, and the history of upheaval of mountains. They involve a glacier inventory in the regions of interest. A glacier inventory contains data on the number, location elevation, length, width, thickness and fluctuation patterns. Inaccessibility to glaciers located in remote areas in the rugged terrain restricts data collection in the normal course. Due to blocking of high passes in winter and limited time available in summer the study of these glaciers is not possible. Satellite remote sensing imageries for such areas are of immense value for identifying various features of glaciers. The information extracted from satellite data may include number and areal extent of glaciers, determination of the equilibrium line and its relationship with mass balance of the glacier, accumulation area ratio (AAR) and its relationship with mass balance of the glacier, and determination of the various metamorphic processes taking place in the different zones of the glacier which can be related to the dynamics of the glacier. The inventory of Himalayan glaciers using remote sensing data has also been initiated.

SNOWMELT RUNOFF MODELLING

Modelling of streamflow from a basin is based on transformation of incoming precipitation to outgoing streamflow by considering losses to the atmosphere, temporary storage, lag and attenuation. Hydrological models use for simulation or forecasting of streamflow are generally categorized as simple regression models, black-box models, conceptual models and physically based models. Black-box models are generally lumped in nature by treating a basin as a single spatial unit. Physically based models use appropriate physical equations contain equations for all the processes involved. These models are invariably distributed and involve desegregation of basin into zones or grid cells. Conceptual models may be either lumped or distributed with one or more storage represented by conceptual units and connected by incoming and outgoing fluxes representing different hydrological pathways.

Remotely sensed data play an important role in monitoring the progress of snow melt and modeling the quantity of water produced as runoff. The simplest model of snow melt uses a ‘‘degree–day coefficient’’ of typically 0.5 cm, i.e., one degree–day of thaw, without rainfall, can melt 0.5 cm of water from the snow pack. More sophisticated models include the effect of precipitation, and also the time lag between melting of snow and the appearance of the resulting meltwater at the gauging station. The snowmelt runoff model (SRM) of is widely used. The Snowmelt-Runoff Model is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Most recently, it has also been applied to evaluate the effect of climate change simulation.

It can be written as

$$Q_{n+1} = [c_{Sn} \cdot a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] \frac{A \cdot 10000}{86400} (1-k_{n+1}) + Q_n k_{n+1} \qquad (1)$$

where: Q = average daily discharge [$m^3 s^{-1}$]

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation), with cS referring to snowmelt and c_R to rain

a = degree-day factor [cm $^{o}C^{-1} d^{-1}$] indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days [^{o}C d]

Δ T = the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [^{o}C d]

S = ratio of the snow covered area to the total area

P = precipitation contributing to runoff [cm]. A preselected threshold temperature, TCRIT, determines whether this contribution is rainfall and immediate. If precipitation is determined by TCRIT to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km^2]

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:

$k = Q_{m+1}/Q_m$ (m, m + 1 are the sequence of days during a true recession flow period).

n = sequence of days during the discharge computation period. Equation (1) is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponds to the discharge on the n + 1 day. Various lag times can be introduced by a subroutine.

10000/ 86400 = conversion from $cm^{-1}km^2d^{-1}$ to $m^3\ s^{-1}$

It is clear from equation 1 that the application of the SRM requires both the area of snow cover, which can be obtained from remotely sensed imagery and ancillary data such as temperature, precipitation, and runoff, which cannot be obtained in this way. The SRM is essentially a form of geographic information system in which data from different sources are fused. The ability to distinguish between frozen and melting snow cover can enhance the performance of the model.

When precipitation falls as snow it accumulates in the basin and snowpack is developed. Conceptually snowmelt runoff models are rainfall-runoff models with additional component or routines added to store and subsequently melt precipitation that falls as snow. Some snowmelt runoff models are purpose built and are not intended for use in non snowy environments, though they have to make some allowance for precipitation which falls as rain during the melt season. In general, the part of the model which deals with snowmelt, has to achieve three operations at each time step.

- extrapolate available meteorological data to the snowpack at different altitude zones
- calculate rates of snowmelt at different points, and
- integrate snowmelt over the concerned effective area of the basin and estimate the total volume of new melt water.

The melt water and rainfall, if any, is then routed to the basin outlet. In the next time step the model has to take into account of changes in snow-covered area because there is general depletion of snow covered area with time. A snowmelt runoff model (SNOWMOD) has been developed at NIH for Himalayan basins. The structure of the model and algorithms used are discussed in brief in the following sections.

The snowmelt model is designed to simulate daily streamflow in mountainous basin where snowmelt is major runoff component. The process of generation of streamflow from snow covered areas involves primarily the determination of the amount of basin input derived from snowmelt alongwith some contribution from glacier melt and rain. Most of the Himalayan basins experience runoff from the snowmelt as well as rain. The contribution of rain comes from the lower part of the basin having elevation less than 2000 m, the middle part between 2000m to 4000m contributes runoff from the combination of rain and snowmelt while in the high altitude region having elevation more than 4000 m, runoff computation comes from the glacier melt. The contribution from snow and glacier is controlled by the climatic conditions and therefore, varies from year to year.

Himalayan basins are complex in nature in terms of input to the basin and have contributions from all the three sources, i.e., rain, snow and glacier. For these types of basins, situation becomes more complex because contribution from each component is not known or could not be observed separately. The observed flow consists of the contribution from all these three sources in addition to the base flow/ground water contribution. For the Himalayan basins, most important factor influencing the development of model and the approach to be adopted, is the limited availability of data. There is very sparse network of measurement stations in the high altitude region of the Himalayas. Data collected at most of the measurement stations consist of mostly temperature and precipitation data. Most of the meteorological data required for the application of energy balance approach is hardly available. Therefore, development of a conceptual model with an index approach for calculating the snow and glacier melt runoff is the suitable choice for snowmelt runoff in the Himalayan basins. Keeping in view the limited data availability, the structure of the present model has been kept simple so that all suitable/available data is properly utilised.

MODEL STRUCTURE

The flow chart of the model structure is shown in Figure 2. Specific major considerations in the design of the model components are as follows:

(a) The model computes or simulates the snow melting and runoff processes on a daily basis. The basin is divided into snow covered and snow free part and modelling of runoff is carried out separately from these two parts.

(b) Use of practical yet theoretically sound methods for subdividing the basin in evaluating the various physical and hydrologic processes relevant to snow melt and its appearance as streamflow at the outlet.

(c) The model has ability to perform simulation computations over any specified time interval according to the availability of input data

(d) Capability of the model to adjust itself to specified or observed conditions of streamflow from the previously computed amounts, and maintaining continuity of functions in further processing.

(e) Optimisation of parameters used in routing of the rainfall-runoff and snowmelt runoff.

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

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

ASSESSMENT OF MELTWATER CONTRIBUTIONS

The Indus, Ganga, and Brahmaputra receive substantial amount of melt water from the Himalayas and are, therefore, considered as the lifeline of the Indian sub-continent. Most of the rivers have their upper catchments in the snow-covered areas and flow through steep mountains. Rainfall during the monsoon season adds more potential to be exploited from the glacier. NIH has carried out some studies to estimate snow and glacier contribution into the annual flows of few Himalayan rivers. Table 1 gives snow and glacier contribution into annual flows of Himalayan rivers alongwith maximum and minimum snow covered area. It may be seen that all three rivers at these sites receive significant contribution from snow and glacier melt into their stream flows.

Table 1: Snow and glacier melt contributions in some Himalayan rivers

River	Catchment area up to a specific site (km^2)	Snow cover area (km^2)		Snow and glacier contribution in the annual flow (%)
		Maximum	Minimum	
Ganga	19700 (Deoprayag)	9080 (40.9%)	3800 (19.3%)	28.7
Chenab	22200 (Akhnoor)	15590 (70.2%)	5400 (24.3%)	49.1
Satluj (Indian Part)	22305 (Bhakra Dam)	14498 (65.0%)	4528 (20.3%)	61.0
Beas River (Manali)	361 (Manali)	344 (95%)	88 (24%)	54
Parvati River (Bhunter) (in Press)	1782 (Bhunter)	1580 (88%)	478 (26%)	50

It has also been observed that the river discharge of Himalayan snow-fed rivers per unit area is roughly twice to that of peninsular rivers of South India. This is mainly due to perennial contribution from snow melting and glacial drainage.

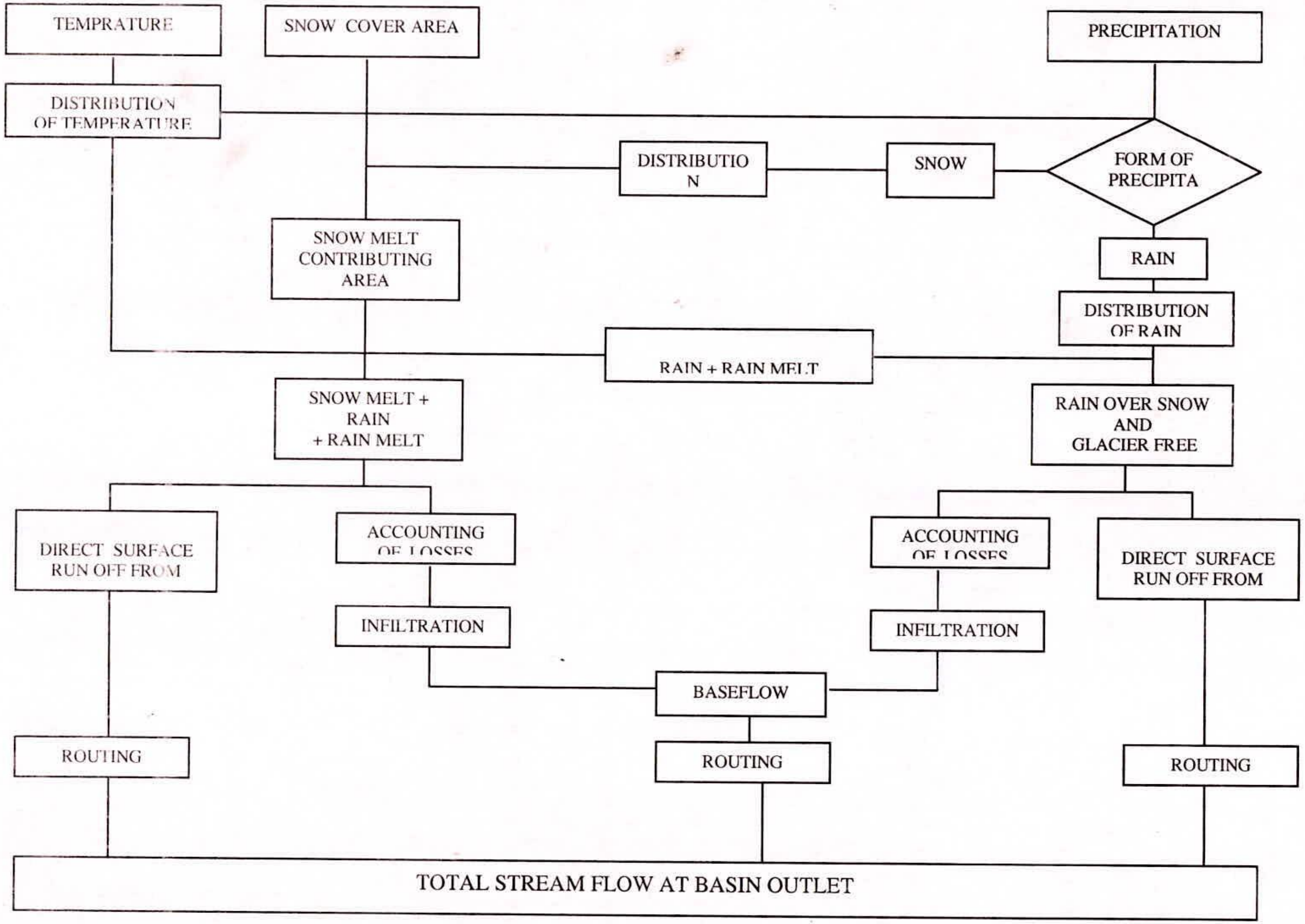

Figure 2: Structure of the snowmelt model