MODELLING OF SNOWMELT RUNOFF

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Abstract *The Himalayas play a very significant role in the country's economy. They are vast reservoirs of snow and glaciated ice and occupy a unique position in the Indian perspective if development of water resources. The major river systems of North India, namely, the Indus, the Ganges, the Brahmaputra and their tributaries originate in the Himalaya. The contribution of the snow and glacier and glacier melt to these snow fed rivers of India is well recognised and most of it is received in the summer months of April to June, when there is heavy demand for water Proper estimation and prediction of volume of water contained in the snow pack and rate of release of this water are therefore needed for efficient management of water resources. In spite of substantial contribution from the Himalayan Rivers, at present there is no hydrological model available in our country, which can be, applied for snowmelt forecast for reservoir operation and planning and management of various water resources projects on the Himalayan Rivers. A conceptual model based on simple approach and minimum data requirement is required to be developed to the Himalayan basins. The paper briefly describes various models available and summarises the studies carried out by Central Water Commission for estimation of snowmelt runoff from the experimental watershed at Sundlinala using various available models. The conclusions derived by the above studies and recommendations are discussed.*

INTRODUCTION

In the context of our country, Himalayas are the reservoirs of snow and glaciated ice regulating the annual water distribution and providing substantial contribution in form of melt water to the major river systems of India namely the Indus, the Ganga and the Brahmaputra. The water flowing in the Himalayan rivers is a combined drainage from rainfall, snowmelt and glacier melt. Snow and glacier melt runoff play a vital role in making all the northern rivers of India perennial, as about 30% to 50% of the total annual water yield of major rivers of Northern India is provided by the snow and glacier melt runoff particularly during the months of summer when the demand is particularly high.

With the increase in population, urbanization and industrialization, the water demands for irrigation, municipal and industrial uses have increased considerably. Assessment of the snowmelt have importance in harnessing the Himalayan river systems for hydroelectric power generation and irrigation, and lead to other benefits such as reservoir operation, watershed management, water supply and design of hydraulic structures. With the increasing exploitation of water for irrigation, municipal and industrial purposes and hydro-power, there would be increasing demand for more scientific information for snow cover and glacial hydrology of Himalayan streams in order that future planners are able to plan more efficient water resource management system. Although the economy of this region in dependent on melt water flow from the snow fields and glaciers very limited have been carried out to understand the melt process and other hydrological characteristics for understanding the relationships between meteorological variables and the snow and glacier melt processes.

In recent years, the condition of data network has been improved and continuous efforts are being made to develop the snow and glacial runoff-forecasting model for the Himalayan region and the study of glaciers and snow has gained momentum in recent years. Systematic studies of the Himalayan glaciers in Himachal Pradesh, Jammu and Kashmir, Uttar Pradesh and Sikkim are being carried out by the different agencies like Bhakra Beas Management Board (BBMB), Snow and Avalanche Research Establishment (SASE), National Institute of Hydrology (NIH), Roorkee, and Central Water Commission (CWC) etc. with the help of snow cover survey by manual and Remote Sensing Technique for prediction of snow melt.

PHYSICS OF SNOWPACK

The physics of snowfall is simple a special case of precipitation formation in that the meteorological conditions producing snowfall are the same as those, which generate other forms of precipitation. Although the formation of snow in the atmosphere depends on many variables the most important are the presence of super cooled water and an ambient temperature lesser than $0^{\circ}C$.

At a temperature of about $-5^{\circ}C$, ice forming nuclei present in the atmosphere form tiny crystals through the process of nucleation. The vapour pressure at the ice surface being lesser than that of the above water surface result in transfer of water vapour from the droplets to the surface of ice crystals thereby increasing their mass and subsequent fall. During its fall, the crystal grows through riming process and it passes through a layer of atmosphere where temperature is greater than $0^{\circ}C$ it melts and falls as rain. The raining process affects the velocity of fall and motion of crystals. The aggregation of these snow crystals followed by their adhesion results in formation of snowflakes.

The formation of snowpack begins with the deposit of new fallen snow in the form of snowflakes. The density of snowpack is usually very low which increased with time and called as ripening of snowpack. When liquid-water holding capacity of ripe snowpack is reached, it becomes ready to produce run off. At this stage, the storage effect of the snowpack is transitory in nature resulting in temporary delay of liquid water in transit through the pack. There is no restriction that the snowpack would yield runoff only in spring season. Mid winter rainfall or snowmelt may satisfy the cold content and liquid water holding capacity to the snowpack. When this condition is reached, any further input of liquid water would simply pass through the snowpack under gravity. The changes that take place within the snowpack are caused by several physically processes, such as:

i. Heat exchange at the snow surface
ii. Percolations of melt or rain water through the snowpack
iii. Internal pressure due to weight of the snow

iv. Wind
v. Temperature and vapour pressure variation within the snowpack
vi. Heat exchange at the ground surface.

SNOWMELT RUNOFF MODELLING

The snowmelt evaluation is a highly complex and variable phenomena depending on various meteorological parameters. It is a process utilizing various natural sources of heat transfer like absorbed solar radiation, net long wave radiation, convection heat transfer from air, latent heat of vaporization by condensation from air, conduction of heat form the ground and heat content of rain water etc. The use of stream flow simulation models has expanded significantly during the last 3 decades. The main use of use of these models includes forecasts of flood levels. Inflows for reservoir operation ascertaining water availability for navigation and the likely range of future inflows both in terms of volume and timing for water supply, irrigation power generation and management studies of water resources.

The areal snow cover models are broadly classified either as 'lumped' or 'distributed' type. The distributed models are further classified into models distributed by elevation zones or by some other basic characteristics such as soil type, of land use. Either of the above models mostly uses either an energy balance approach or an index method to compute the surface energy exchange. Energy balance approach, though more accurate, requires a lot of information on radiant energy, sensible and latent heat, energy transferred through the rainfall over the snow and heat conduction from ground to snowpack. Several meteorological parameters are to be monitored to obtain this information over the snowpack. The index method uses one or more variable in an empirical equation to estimate snow cover energy exchange. Many variable like air temperature, net radiation, wind speed, vapour pressure and solar radiation can be used as index. The degree-day approach uses air temperature as index and is widely popular as temperature represents reasonably the energy flux and at the same time it is easy to measure, extrapolate and forecast and give reasonably accurate results. However, snowmelt prediction can be significantly improved by using vapour pressure, net radiation and wind rather that the temperature variable alone.

Over the period of their use, a general set of principles has evolved concerning the model structure, data input, method of calibration, and the operational use of the models in the snow cover areas. These principles are briefly described as under.

a. For a simulation model to be widely applicable the basic model should require only data that can be readily obtained on real time basis wherever the model is to be used. This gives the advantage of the input data, which can be forecasted with reasonable degree of accuracy. Thus the basic snowmelt-precipitation, air temperature and snow cover as input for wider acceptability.

b. The parameters, which have a unique effect on the output of the model, should only be included in the input. Two or more parameters having the same effect on the model response should not be included. The need for subdividing the watershed should only arise when the parameters have a distinct and unique effect on the each sub area.
c. The model should have a structure in which all unit processes having a significant effect on the volume of timing of snow cover runoff should be represented. The inclusion of all unit process result in a modular model, which can be changed as better representations of unit processes as the available data change.

SELECTION OF A MODEL

The selection of a model varies according to various factors related with climatic and physiographic characteristics and availability of the data for the specific region. A brief description of these factors is given below.

Atmospheric Conditions

Under less variable climatic conditions, especially during snowmelt period, index snowmelt models tend to work best. If only one meteorological variable is available for snowmelt prediction, average temperature is the best predictor. When meteorological conditions vary widely during a melt season or from year to year, an energy balance model is considered more suitable.

Physiographic Factors

A considerable variation in the slope, aspect, elevation and the forest cover affects the areal and time distribution of melt. This could lead to the need to subdivide the basin into more homogeneous sub basins/elevation zones in the heavily forested basins, the wind speed and solar radiation have a small effect on the energy balance and thus index models give good results. In open areas, where there is much greater chance or variability in meteorological conditions, all terms in the energy balance are likely to be important and energy balance models are more suitable.

Availability of Data

An energy balance model requires much more data than an index model and offers more reliable means of extrapolating to determine behaviour under extreme conditions. A logical minimum data requirement for using an energy balance model would be solar radiation, wind and vapour pressure in addition to air temperature.

Application of the Model

The application of the model also influences the selection of a model. For design applications where only extreme conditions are of interest, an energy balance model is more suitable. When all type of conditions are of interest, as in river and water supply forecasting, the selection of a snow model should be based on other factors like climatic conditions, physiographic features and available data, affecting the model performance. The accuracy of forecast vis-à-vis cost benefit ration should also be given due consideration.

AVAILABLE MODELS

Most models for snowmelt runoff consist of two components, a snowmelt model, which simulates the process of snow accumulation and melting and a transformation model, which takes the snowmelt, and where appropriate the rainfall as input data, and yields the hydrograph of basin runoff as output. These models are distinguished from each other by the manner of handling of meteorological data and their structure. Precipitation and temperature are basically the two major inputs influencing the functioning of most of these models. An understanding of the distribution of precipitation and temperature in a basin both with elevation and across the catchment is essential for the success of the model. These problems are approached by taking into account temperature lapse rate and orographic precipitation gradients. Another important factor is the determination of the form of precipitation, which is solved by using a critical tèmperature in a particular elevation zone to distinguish between precipitation as rain and as snow. Few popular Snowmelt Runoff Models, their data requirements and uses are listed in Table 1. Based on trials conducted on different models, CWC adopted the Martinec's Snowmelt Runoff Model for its studies.

MARTINEC'S SNOWMELT RUNOFF MODEL

The SRM model makes use of degree-day approach in considering surface energy exchange. The simplicity of the mode lies in the use of very few externally derived parameters, which are:

i. Basin characteristics: Area-Elevation curve
ii. Externally derived parameters: Degree-day factor, recession coefficient, time lag, and critical temperature for snow/rain
iii. Calibrated parameters: recession coefficient and time lag, if not externally derived.

The SRM simulates the process of snow accumulation and ablation. The input factor is in the form of a hydrograph. The only operational data needs are temperature, precipitation, snow coverage by elevation zones, recession coefficient and Snow Water Equivalent (SWE). The model calculates the daily discharge during snowmelt from temperature and depletion curves of snow cover. The discharge data serves only to evaluate the accuracy of the simulation. If the discharge data is available, the model provides an option for updating on a periodic basis with actual discharge.

Table 1 Commonly used snow runoff models.

Model	Input data	Output	Application
SSARR	Daily- • Rainfall • Temperature • Insolation • Snow Line • Regulation & Stream flow	• Input Summary • Simulated Daily Flow Hydrograph	• Flow Forecasting • Reservoir Design and Operation
UBC	• Daily Precipitation • Daily Temperature • Monthly Evaporation • Various parameters for calibration	• Input Summary • Simulated Daily Flow Hydrograph	• Flow Forecasting in snow/Rain catchments
SRM	• No. of days • Snow Covered Area • Temperature • Lapse rate • Precipitation • Stream flow Lag • No. of Zones • Mean Elevation of each Zone • Elevation of stations	• Input Summary • Simulated Daily Flow • Computed Total volume • Average Computed Discharge • Measured Total volume • Average Measured Discharge • Goodness of Fit	• Simulate & Forecast Daily Streamflow in basins where snowmelt is a major factor
HBV	• Daily Precipitation • Air Temperature • Potential Evapo-Transpiration	• Input Summary • Lumped Response Function	• Flood estimation • Forecasting for regions with or without snow
NAM	• Precipitation • Potential Evapo-Transpiration • Temperature at any sampling interval	• Input Summary • Simulated Discharge Hydrograph at specified sampling interval	• Flood estimation and forecasting for regions with or without snow
HEC-I	• Precipitation and discharge data for each event at sampling interval • Lapse Rate • Snowmelt Coefficient • Melt Temperature	• Input Summary • Optimised Parameters • Simulated Discharge Hydrograph at specified sampling interval	• Design Flood Estimation Flood Routing • Snowmelt Runoff Unit Hydrograph Analysis • Precipitation • Depth area Simulation

SNOW HYDROLOGY STUDIES BY CWC

In view of the increasing demands upon water resources of the country resulting in an urgent need for better understanding of the natural process which govern their flow, the CWC undertook a pilot project. It was realised that forecasts based solely on rainfall data could prove to be erroneous especially during spring season due to substantial contribution of the snowmelt runoff. The main aim of the project was collection of meteorological and hydrological data, ascertain applicability of available snowmelt runoff models and to develop an indigenous Snowmelt Runoff Model for short and long range river forecasting using state of the art techniques.

A research watershed was selected at Sundlinala, near Jubbal, under guidance of experts from U.S. The Snow Hydrology Observatories were equipped with state of the art equipment to measure various hydro-meteorological parameters. A V-Notch weir was constructed for measurement of outflow from the pilot catchment. Data was collected from 1984 onwards. The modelling exercise was conducted on the research watershed using different snow runoff models.

Comments on Simulation Results

The continuous studies carried out in the pilot catchment using various models available have established the applicability of the Martinec's Snowmelt Runoff Model in the Himalayan catchment. The comparison of the simulated and measured volume and discharge in the pilot catchment of Sundli Nala for various years have been depicted in Tables 2 and 3, respectively.

Table 2 Comparison of simulated and measured volume in the pilot catchment of Sundli Nala for different years.

Snow Season	Volume in MCM	
	Measured	Simulated
94-95	0.45	0.45
95-96	0.82	0.78
96-97	1.09	1.04
97-98	1.14	1.01

Table 3 Comparison of simulated and measured discharge in the pilot catchment of Sundli Nala for different years.

Snow Season	Average discharge in cumec	
	Measured	Simulated
94-95	0.06	0.06
95-96	0.10	0.09
96-97	0.14	0.13
97-98	0.13	0.11

The simulated and actual hydrograph is also depicted in Fig. 1. The simulation results generally agree with the measured discharge. It is observed that the SRM is very sensitive to the small changes in the value of the inputs and therefore, it is very important to collect consistent and reliable data over a much larger area. The success of the simulation will greatly depend on the accuracy with which the model variables are determined.

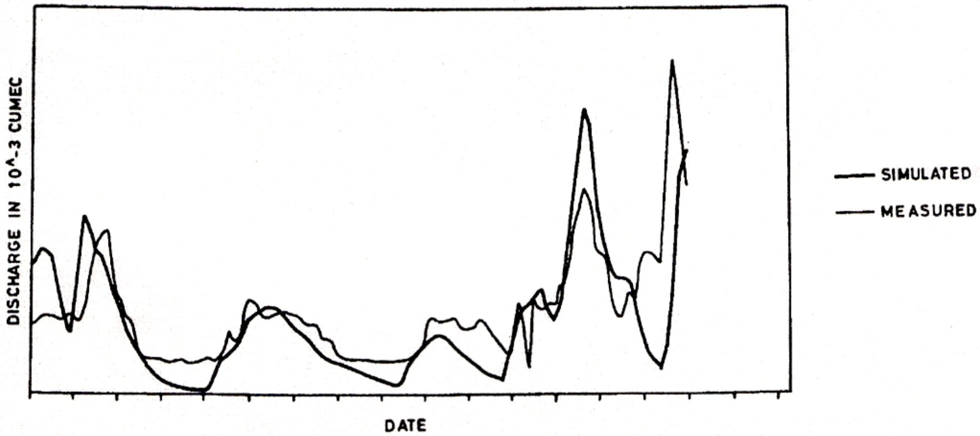

Fig. 1 Comparison of simulated and actual discharge at Sundli Nala watershed.

CONCLUSIONS AND RECOMMENDATIONS

i. Preliminary exercises on snowmelt runoff modelling for the experimental watershed have indicated that Martinec's SRM Model can be successfully used for simulation and forecast of snowmelt in Yamuna Catchment. This model appears to be best suited for the Himalayan regions. During the modelling exercise, it was realised that the model is very sensitive to the data input requirements particularly regarding spread and depletion of snow cover in the watershed, the recession coefficient, runoff coefficient and the melt factor. NHPC, SASE and CWC have tried SRM model for small catchments. There is a need to extend the studies to larger areas of various river basins.

ii. Special efforts are needed to extend the data collection activity with a view to fully cover the areas related to snow cover area, its build up and depletion, the range of recession and runoff coefficients, the degree day factor and its variation etc. a realistic estimate of snow cover variation etc. a realistic estimate of snow cover area is essential for the success of the model. Studies for developing temperature elevation, precipitation elevation relationship should continue, as these will be very useful in studies on the Yamuna basin as a whole. For the sake of reliability, long standing data be studied to determine recession coefficients and runoff coefficients.

iii. While considering the total basin, since snow covered area and its depletion are major inputs for the SRM model, NRSA's collaboration be sought in monitoring the snow cover and in preparing a digital terrain model for the basin. To start with, previous years data could be analysed and a rough simulation can be tried straightaway after making some assumptions on the precipitations/temperature regime at high elevations. Since the area of the basin is quite large for purpose of simulating snowmelt runoff, it can be divided into two or three sub-basins with identifiable stream discharge stations and of a sufficiently large area to be located in LANDSAT/IRS imagery.

iv. An efficient data collection system has to be supported by state of the art working equipment. Keeping in view the importance and awareness of snow hydrology and its impact on water resources management, especially in Himalayan region, there is a basic necessity develop the instrumentation for snow measurements, snow surveys and other hydrological elements including stream flow. Automated instrumentation or instrumentation with remote control and access is desirable to minimise the human errors and ensuring the observation of data even at remotest place and at odd hours.

v. Training is another important aspect for overall improvement of data collection system and prediction of snow melt, imparting phased training to the field staff for data collection and snow surveys, at least within the country will help them to handle their job more effectively. The training programmes should be formulated to utilize the expertise available on the latest technological developments in this field and for further research and development to optimise the utilization of Water Resources and improving water management.

vi. Most of these equipments are used specifically for snow hydrology activities only. Obviously there is a lack of demand for these instruments in our country. Thus, the facilities, either for repairs calibrations, or for the procurement spares is not easily available in India, rendering them in operational for considerable time, even for the small defects. Thus their repairs not only have the financial implications in terms of foreign exchange, but in the process, precious data is lost. In view of the above, it is the need of the time to encourage the development of technology in India itself through transfer or indigenously so as to promote large-scale use in management of vast water resources that nature has bestowed upon our country.

vii. Simultaneously, a plan of action should be chalked out to develop snowmelt runoff model for different rivers basins for future optimisation of available water resources. The data being collected by various organisations involved can be pooled together and kept in a computerised database and be made available to the users through information network. This may facilitate wider applications of the existing database created by various agencies for development of Snow Runoff Model for the Himalayan catchment. The collaboration of various agencies in this field like NRSA, SASE, NIH can go a long way in developing of an indigenous Snowmelt Runoff Model for forecasting of snowmelt in Himalayan rivers.

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BIBLIOGRAPHY

Anderson, E. (1978) Stream flow Simulation Models for use in snow-covered watersheds. In: Proc. Modelling of Snow Cover Runoff Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Martinec, D. Snowmelt Runoff Model, Fedeıal Institute of Snow and Avalanches Research Switzerland.

Singh, Pratap (1997) Development of a Conceptual Model for Snow, Glacier and Rainfed Catchments. National Institute of Hydrology, Roorkee.

Singh, R.N.P. (1994) Data Observation for Snowmelt Runoff Assessment. In: Proc. Symp. on Snow and Related Manifestations, SASE, Manali.

Sud, S.C. (1999) Snowmelt Estimation Models. In: Proc. Symp. on Snow, Ice and Glaciers. Geological Survey of India, Lucknow.