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A Test of Snowmelt-Runoff Model for a Major River Basin in Western Himalayas

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In the Snowmelt-Runoff Model (SRM), the estimate of discharge volume is based on temperature condition in the form of degree days which are used to melt the snowpack in the area of the basin covered by snow as observed from satellites. Precipitation input is used to add any rainfall runoff to the snowmelt component. When SRM was applied to the large, international Kabul River basin, initial simulations were much above the observed stream flow values. Close inspection revealed several problems in the application of SRM to the Kabul Basin that were easily corrected. Foremost among the corrections were determination of an appropriate lapse rate, substitution of a more representative mean elevation for extrapolation of temperature data, and use of an automatic streamflow updating procedure. These improvements led to a simulation for 1976 that was comparable to other simulations on large, inaccessible basins. As SRM is applied to more basins similar to the Kabul River, the determination of suitable parameters for new basin will be enhanced. Additional improvements in simulations would result from installation of climate stations at the mean elevation of basins and work to assure delivery of timely and reliable satellite snow cover data.

Introduction

Remotely-sensed observations of snow cover extent provide a useful input for reliable estimates of snowmelt runoff in mountain watersheds, particulary those with a paucity of groundbased data. A number of models predicting seasonal and short-term discharge from snow cover data have been proposed. Hawley *et al.* (1980) have made a comparative study of selected models that are widely used for simulating discharge from snow-covered watersheds.

Snowmelt runoff varies with day-to-day hydrometeorological conditions. Therefore, models structured for the forecast of snowmelt on a short-term basis become most useful in efficient management and planning of water resources. The snowmelt models for short-term forecasts determine the amount of snow that will be melted by the transfer of energy through radiation, convection, and conduction in a given time period rather than depending on the estimates of the total volume of water held in the snowpack (Hawley *et al.* 1980). Some complex energy balance models in this category require data on the thermal quality and albedo of snow, solar radiation, cloud cover, and convective heat transfer as input variables for snowmelt forecasts. All such variables are difficult to obtain, but particulary so for remote areas with difficult access.

The Snowmelt-Runoff Model (SRM) (Martinec *et al.* 1983) is a relatively simple conceptual process-response model developed for daily simulation or forecast of streamflow in mountain watersheds contributes substantially to the mean annual flow. SRM was developed by Martinec (1975) originally for small mountain watersheds in Europe. With the widespread application of satellite data for monitoring snow accumulations, the model has been refined over a period of time for applications on large basins – some in inaccessible terrain – for simulation periods of only a few days to the entire year (Martinec *et al.* 1983). Daily temperature and precipitation data, along with daily snow cover extent are the three basic input variables required for the operation of the model. Whereas temperature and precipitation are routine meteorological observations within and/or outside drainage basins, the extent of snowpack may be accurately determined from satellite observations. In SRM discharge for consecutive days is determined from the equation

$$Q_{n+1} = c_n [a_n (T+\Delta T_n) S_n + P_n] \frac{2323200}{86400} (1-k_{n+1}) + Q_n k_{n+1}$$

where

- Q – average daily discharge in $ft^3 s^{-1}$;
- c – runoff coefficient, expressing the loss of runoff to precipitation as a ratio;
- a – degree-day factor (in, °F^{-1} d^{-1}) indicating the snowmelt depth resulting from 1 degree-day;
- T – number of degree-days (°F);
- ΔT – the adjustment by temperature lapse rate in °F due to altitudinal difference between the temperature station at the base and the mean hypsometric elevation of the catchment;
- S – ratio of snow-covered area to the total area of the catchment;
- P – precipitation in inches (in.) contributing to runoff;

A – area of catchment in square miles;
2323200/86400 = conversion factor from in $mi^2\ d^{-1}$ to $ft^3\ s^{-1}$;

k – recession coefficient. It indicates the decline of discharge in a period without snowmelt or rainfall, such that

$$k = \frac{Q_{m+1}}{Q_m}$$

The subscripts m, $m+1$ represent the sequence of days during which a true recession flow occurs. The recession coefficient is determined from the auto-correlation of daily discharges;

n – sequence of days. In the above equation, a time lag of 18 hours is assumed between the daily temperature cycle and the resulting runoff. Thus, the number of degree-days measured on the n^{th} day correspond to the discharge on the $n+1$ day.

Martinec and Rango (1986) noted that the model performs well for basins ranging in size from 0.3 to 1,544 sq mi (0.77 to 4,000 sq km), and the accuracy of prediction is generally not limited by the basin relief and climatic characteristics. However, the model simulation accuracy is observed to decrease with increasing basin size (Rango 1980). Similarly, Hawley *et al.* (1980) also conclude that SRM is most effective for basins of smaller rather than larger size. In this model, calibration of parameters is not necessary, and they do not require frequent adjustments. Furthermore, the model can function without reference to the historical records of streamflow.

The model has been developed and tested so far on small temperate watersheds. Major basins with areas in excess of 965 sq mi (2,500 sq km) are characterized by tremendous variations in snow cover and in the factors that govern melting and runoff. SRM has been applied here for the first time on a watershed an order of magnitude larger than those previously tested, and where snowmelt hydrology is largely governed by a hot-dry subtropical climate. The purpose of this study is to assess the accuracy of model simulation in a subtropical environment and its performance on a daily basis for the snowmelt season.

Study Area

Located between latitudes 33°36′ N and 36°55′ N and longitudes 67°36′ E to 73°54′ E, the catchment of the Kabul River drains an area of 24,578 sq mi (63,657 sq km) (Fig. 1). Except for a small stretch of crystalline massif in the west, the catchment as a whole has developed almost entirely on the folded and faulted Alpine-Karakoram System of the Hindukush Mountain ranges. The elevation in the basin varies from 1,000 ft (305 m) at Nowshera, the gauging station, to 25,230 ft (7,690

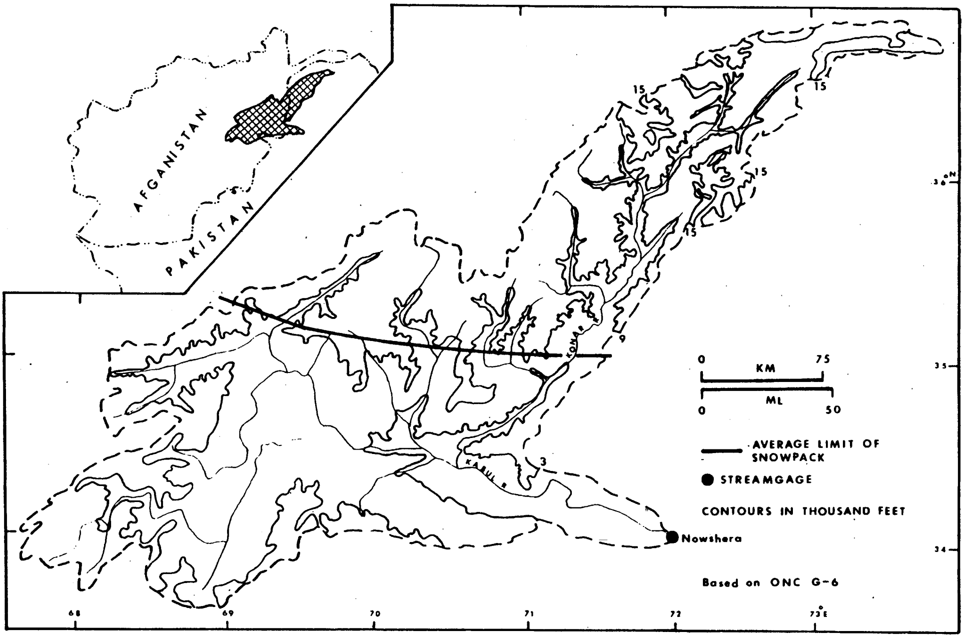

Fig. 1. The Kabul River Basin.

m) in the valley of Konar – a principal tributary of the Kabul River. The Konar drains through a relatively higher and more rugged topographic relief from the north than the Kabul River, which has a roughly east to west orientation. Nearly all the glaciers in the catchment are situated above 13,000 ft (3,962 m) in the Konar valley. They occupy some 260 sq mi (673 sq km) or 1.06 per cent of the total area of the Kabul basin. Thus, the glacial meltwater discharge apparently constitutes a minor fraction of the river discharge. The total cumulative observed discharge of 4,314,400 cf (122,170 m^3) for the 82-day period from April 4 through June 24, 1976, representing a major part of the snowmelt season of 1976, may be compared with a total of 3.61 in (9.17 cm) of rainfall spread over 13 days. During the same period, the extent of snowcover varied from 72.5 to 27.6 per cent. The period of snowmelt is one of high thermal efficiency during which time the maximum and minimum temperatures at the Mardan climate station (655 ft; 200 m) respectively ranged between 108°F and 50°F (42°C and 10°C). The Himalayan watersheds are characteristic of seasonally heavy snowmelt discharges, and in some cases snowmelt may provide up to 70 per cent of the total flow volume (Tarar 1982). Thus, snowmelt is a major factor controlling the hydrologic response of the watershed.

With the mean hypsometric elevation of 7,700 ft (2,347 m), the basin is distinctly asymmetrical in the distribution of relief (Fig. 2). The area elevation curve suggests that only about 4 per cent of the basin's area lies above 15,000 ft (4,572 m), the

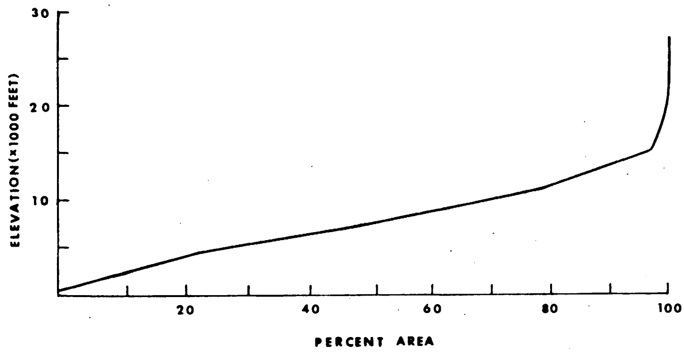

Fig. 2. Area-elevation relation for the Kabul Basin.

major source area of snow accumulation. The average limit of the 1976 melt season snow cover generally descends to below 6,000 ft (1,829 m) in the Konar valley, due primarily to the high and very steep valley side slopes (see Fig. 1). The snowpack, with an average elevation of 11,250 ft (3,429 m), covers some 42 per cent of the total area, mostly in the Konar subbasin. Therefore, it is the extent of snowpack and its thaw in the Konar basin that principally contributes to the meltwater yield in the Kabul River basin.

Procedure

A daily snow cover in the catchment has been extrapolated for a part of the snowmelt season (April 4 through June 24, 1976) from NOAA-4 satellite pictures. The daily temperature data for the same period recorded at Mardan, about 20 miles (32 km) from Nowshera, Pakistan, has been used as an index of the thermal efficiency of the basin. In order to determine the degree-day values for snowmelt and whether a particular event is rain or snow, the Mardan temperatures were extrapolated to the mean hypsometric elevation of 7,700 ft (2,347 m) for the Kabul catchment using lapse rates of 3.3°F/1,000 ft (0.6°C/100 m) and 5.0 °F/1,000 ft (0.98°C/100 m). Specifically, it was thought that the higher lapse rate would probably best describe the decline of temperature with elevation in this area of high thermal regime.

Some reasonable assumptions are also necessary to determine the parameters of the basin. The runoff coefficients for snowmelt and rainfall are taken to vary between 0.2-1.0. The recession coefficient factors, x and y, for the catchment have been assessed from the serial correlation of daily discharges recorded at Nowshera (Fig. 3). These are given as: $x = 1.342$ and $y = -0.0309597$. The degree-day factor, a, can be computed from measurement of snow density through a simple empirical

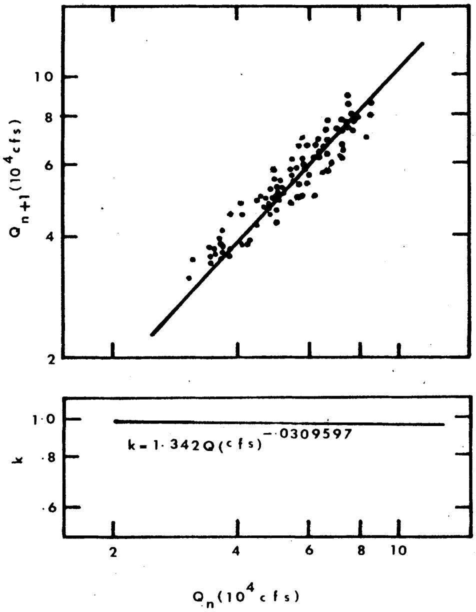

Fig. 3. Regression flow plot Q_n versus Q_{n+1}, and relation of k and Q for the Kabul Basin.

relationship proposed by Martinec (1975). The degree-days are extrapolated to the mean elevation by the equation

$$\Delta T \equiv \delta\,(hST - \bar{h})$$

where

T – temperature lapse rate correction factor in °F,
δ – normal lapse rate in °F/1,000 ft,
hST – altitude of the base station in feet,
$\bar{h}$ – mean elevation of the basin or elevation zone and snowpack in feet.

The daily discharges simulated by SRM have been compared against the observed sequence of daily discharges. Two goodness-of-fit statistics are used to evaluate model performance. The volumetric difference Dv compares the computed and observed discharge for the entire simulation period and is a measure of the seasonal streamflow simulation accuracy and may be expressed as

$$D_v = \frac{V_c - V_o}{V_o} \times 100$$

where, D_v is the volumetric difference between observed V_o and computed V_c seasonal runoff.

The model performance on a daily basis is evaluated by using the nondimensional Nash-Sutcliffe R^2 value (Nash and Sutcliffe 1970). The R^2 value is a measure of model efficiency that expresses the proportion of variance between the observed

Q_0 and computed Q_c runoff on consecutive days of snowmelt period n in the following way

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_o - Q_c)^2}{\sum_{i=1}^{n} (Q_o - \bar{Q})}$$

where, $\bar{Q}$ denotes the average observed discharge.

Results and Discussion

In the past, SRM has provided accurate simulations of daily discharges for small to large mountainous watersheds in temperate climates where meltwater discharge is the major component of streamflow (Martinec and Rango 1986). Even in cases where SRM was applied to Himalayan basins, the simulation results were acceptable but somewhat less accurate than average because the input data set quality was low. The inaccessibility of the characteristically large basins of the region and the sparseness of the climate observations are the primary reasons for simulation problems encountered by SRM or any model.

The initial SRM simulations on the Kabul resulted in runoff values much in excess of observed values and not indicative of prior SRM results (see Fig. 4). The large simulated streamflow amounts indicated the possibility of major flooding, however, the reasons for this became evident after close inspection. The first runs were performed by a first time user of SRM not familar with the model or the

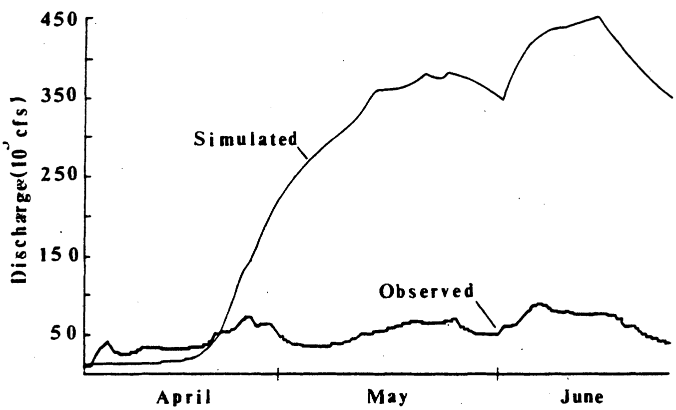

Fig. 4. Comparison of initial model results between observed and simulated yield for the Kabul Basin 3.3°F/1,000 ft (0.650°C/100 m) normal lapse rate and 7,700 ft (2,347 m) mean elevation of the watershed.

characteristics values of certain model parameters. After the close inspection it was evident that several factors were responsible for the poor simulation, namely, an unrepresentative lapse rate, extremely marginal climate data, and a large difference between the mean elevation of the entire Kabul basin and the mean elevation of the Konar basin where most of the snow covered area is located.

Martinec and Rango (1981) state that the most accurate simulation are provided by SRM when the climate station is located at the hypsometric mean elevation of the basin or elevation zone and inside the basin boundaries. In the case of the Kabul, the climate station at Mardan is not able to meet any of the guidelines. It is situated some 20 mi (32 km) outside the basin near the Nowshera gauging station and about 125 mi (200 km) from the major snow covered area in the Konar tributary. Mardan is also located at an elevation of 655 ft (200 m). This is some 7,005 ft (2,147 m) difference in vertical elevation than the mean elevation of the basin and some 10,595 ft (3,229 m) difference from the mean elevation of the snowpack. The hot, dry continental climate of Mardan is considerably different than mountains climate of the upper snow covered regions of the Kabul. Temperature extrapolation to the snow covered region of the Kabul would be very difficult under ideal conditions.

Any error in temperature lapse rate would result in major errors in snowmelt because of the vast elevation difference between the base station and the snowmelt area. It was noted from prior experience with applying temperature lapse rates and extrapolating temperature to elevation zones with SRM that a 3.3°F/1,000 ft (0.65°C/100 m) lapse rate is not indicative for this dry region. The first change was to use only a lapse rate of 5.0°F/1,000 ft (0.98°C/100 m).

Because the hypsometric means elevation (7,700 ft; 2,347 m) of the Kabul basin is seldom covered by snow, the elevation for temperature extrapolation was changed to the approximate mean elevation of the Konar tributary where the vast majority of snowmelt is generated. This value of 8,500 ft (2,591 m) was thus used as the target elevation for the temperature extrapolation. This provides a more realistic amount of energy for melting the snowpack. The final change involved minor modification of the other SRM parameters such as the degree day coefficient, snowmelt runoff coefficent and the rainfall runoff coefficent to make them more indicative of a large snowmelt basin. Table 1 lists the major SRM parameter values used in the revised simulation of flow for the Kabul basin.

After these changes, the results of simulation were significantly different. In addition, the automatic updating of SRM with actual streamflow values every seven days was employed. Fig. 5 provides the new SRM simulation for the Kabul with the above improvements. The goodness of fit values ($D_v = -6.05\,\%$; $R^2 = 0.66$) are now in line with the prior work on Himalayan basins. The results are still not good because of the unrepresentativeness of the Mardan climate station, but they can be used to gain information on the snowmelt runoff process.

Additional improvements are still needed. The easiest improvement involves use

Table 1 – SRM parameter values used in revised simulation for the Kabul River basin.

Time Period	a	C_S	C_R	γ
April 1-15	0.07	1.0	0.1	5.0
April 16-30	0.07	0.8	0.5	5.0
May 1-15	0.08	0.6	0.4	5.0
May 16-31	0.08	0.4	0.3	5.0
June 1-15	0.09	0.3	0.2	5.0
June 16-30	0.10	0.2	0.2	5.0

a = degree day factor (in °F^{-1} d^{-1})
C_S = snowmelt-runoff coeffecient
C_R = rainfall-runoff coeffecient
γ = temperature lapse rate (°F/1,000 ft)

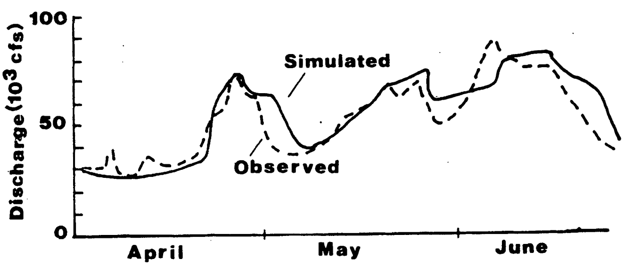

Fig. 5. Comparison of modified model results between observed and simulated yields for the Kabul basin 5°F/1,000 ft (0.98°C/100 m) normal lapse rate and 8,500 ft (2,591 m) mean elevation of the watershed.

of multiple elevation zones which allows temperature extrapolation to the mean elevation of smaller areas and thus the generation of more appropriate snowmelt amounts. An alternative method would employ a one zone approach especially useful for use with lower resolution satellite data as developed by Rango and van Katwijk (1988). In this method the temperature data are extrapolated to a changing mean elevation of the snow covered area. Of course, the most positive changes would result from the location of a climate station at or near the mean elevation of the major snow zone in the basin, thereby reducing any errors due to assumption and use of an incorrect lapse rate. This would be an extremely important and productive investment of resources for any country to make for data sparse snow basins.

Finally, the increasing availability of satellite snow cover data has to be continued. It is especially critical to make these data available to countries with data sparse regions. A reliable source of satellite snow cover data will allow new possibilities for predicting flow from large, remote snowmelt basins.

Conclusions

The Snowmelt-Runoff Model (SRM) was employed to simulate runoff during the snowmelt season from the large, data sparse Kabul River basin in the Himalayas. Certain factors can lead to simulation problems on such basins, and they include: new users unfamilar with SRM; climate stations located vertically and horizontally at a great distance from the snowmelt contributing area; unrepresentative lapse rates and other SRM parameter values; too large a basin area with too few elevation zones; and inadequate snow cover data. These problems can be resolved by: training of new users; specific placement of climate stations at the mean elevation of the snow covered area; analysis of representative lapse rates and other parameters used in prior SRM simulations on other basins; use of multiple elevation zones or a one zone approach with a varying mean elevation of the snow covered area; and commitment of resources to assure regular and timely delivery of satellite snow cover data.

When the initial SRM simulation for the Kabul basin was analyzed, several potential modifications were implemented which drastically improved the simulation. More representative parameters, including lapse rate, were used, and temperature was extrapolated to a mean elevation representative of the tributary supplying the vast majority of snowmelt runoff. These new values produced a much improved simulation that was comparable to prior results in the region. Little could be done to solve the problem of unrepresentative climate data.

SRM will work in such remote and data sparse regions. The performance of SRM or any model will be limited by the quality of the input data. Large gains in simulation accuracy will be achieved by improving the quality of climate and snow cover input data.

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