Snow Cover, Snowmelt and Runoff in the Himalayan River Basins

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July 1988

FOFWARD

This is the final report on "Snow Cover, Snowmelt and Runoff in the Himalayan River Basins" submitted to the National Aeronautics And Space Administration (NASA), the funding agency. The research was conducted at Howard University, Washington, D.C. 20059. The results presented herein are in no way final and may be subject to alteration for improvement as and when more refined snowcover and meteorological data are available for many other watersheds in future. Further, some of these results have been published in research journals by the principal investigator and his associates.

PREFACE

Not withstanding the seasonal vagaries of both rainfall amount and snowcover extent, the Himalayan rivers retain their basic perennial character. However, it is the component of snowmelt yield that accounts for some 60 to 70 per cent of the total annual flow volumes from Himalayan watersheds. On this large hydropotential predominantly depends the temporal performance of hydropower generation and major irrigation projects – the two infrastructural facilities basic to socio-economic realm of both India and Pakistan. Further, year-round successful operation of multiple projects requires judicious planning of water levels in reservoirs so that the inflows from seasonal snowmelt and rainfall can be effectively accomodated. More often than not, the more unpredictable summer monsoon in India upsets the normal operation of reservoirs, with a devastating effect on the economy.

This project was undertaken to study the large-scale effects of Himalayan snowcover on the hydrologic responses of a few selected catchments in western Himalayas. The antecedent effects of snowcover area on long-and short term meltwater yields can best be analyzed by developing appropriate hydrologic models forecasting the pattern of snowmelt as a function of variations in snowcover area. It is hoped that these models would be of practical value in the management of water resources. The project examined the following aspects:

(a) The predictability of meltwater yield for the entire snowmelt season from remotely-sensed observations of an early three-week, April 1 through April 20, snowcover extent over the selected watersheds;

(b) The concurrent flow variations in adjacent watersheds, and their hydrologic significance; and

(c) The applicability of the Snowmelt-Runoff Model for real-time forecast of daily discharges during the major part of the snowmelt season for mega-sized Himalayan watersheds.

ACKNOWLEDGEMENTS

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ABSTRACT

The hydrologic attributes of watersheds, such as in the high energy Himalayan environment, reflect the large-scale effects of snowcover. The spatio-temporal variations in snowcover account not only for the seasonal drought of low flows and floods, but also strongly affect the composition of daily flows during the entire snowmelt season. Therefore, data on the extent and depth of snowpack in watersheds, and snowmelt intensity as governed by physiographic parameters of watersheds and climatological variables become indispensable for evaluating the hydrologic response of watersheds. However, practical difficulties in quantitative observations of the above parameters in the largely inaccessible Himalayan physiographic province preclude any possibility of developing relationships between the snowcover and the resulting flow characteristics. As an alternative to field observations, remotely-observed data through satellites have recently been successfully employed for modelling the snowcover area-runoff relationships. To this end, snowcover data as depicted on NOAA and TIROS imageries have been used in the present study of snowcover and meltwater yield for selected watersheds in western Himalayas. As variables other than the extent of snowpack cannot be studied on the above referred satellite imagery, some constraints become obvious while examining the dependence of observed flow on the remotely sensed snow covered extent in watersheds.

The objectives of this research have been to provide quantitative estimates of seasonal and daily discharges from spatial and temporal variations in snowcover area. Explanations, such as these, invariably lead to the development of hydrologic models that best describe the observed pattern of streamflow. Generally, two basic types of hydrologic models as empirical and conceptual can be considered. The empirical or regression models that approximate seasonal meltwater discharge from snowcover area do not, however, provide the explanation of the principles that govern snowmelt. A number of conceptual snowmelt-runoff models that have been developed in the past treat the meltwater yield in terms of parameters that respond directly to the hydrologic characteristics of watersheds. Such models are ideally suited for short-term or daily forecast of snowmelt volume. In this study, a number of linear and nonlinear regression models for the Indus and Kabul rivers, and concurrent runoff correlation models for the Sutlej, Indus, Kabul and Chenab rivers of western Himalayas have been suggested. The snowmelt-runoff model has been applied to the mega-sized Kabul River basin for day-to-day simulation of snowmelt discharge.

For the period 1974-79, the linear regression models expressing the dependence of seasonal runoff on the early snow accumulation between April 1 through April 20 explain 73 and 82 per cent of the variability of flow respectively in the Indus and Kabul river basins. Such a relationship for 1969-79 period, however, provides for only 60 per cent of the variability in the seasonal flow of Indus, but improves the account of seasonal variability in the Kabul River to 90 per cent. The analyses of variance test for the equality of regression coefficients of snowcover area-runoff curves, and the confidence intervals around the intercepts of the regression equations suggest that the regression equations are remarkably similar despite the differences in the covariance as noted above. This variation, therefore, remains largely unexplained.

Multiple regression models incorporating the concurrent runoff as an additional variable have also been developed for the two watersheds. The use of concurrent runoff as additional independent variable in the model is justified since the Himalayan watersheds have experienced a similar geomorphic evolution, and similar cycles of snow and glacier melts. For the 11-year period under consideration, the multiple regression model has explained 79 per cent of the variability of flow as against the 60 per cent for the Indus River given by bivariate model.

The study notes that the adjacent Himalayan catchments are characteristic of concurrent meltwater discharges. Hence, concurrent flow models for pairs of rivers, such as the Kabul and Sutlej, the Chenab and Indus, and the Sutlej and Kabul were also developed. The models show that the variability in flow of one river against the other in the same pair can be statistically significantly explained. However the concurrent flow models can best be used for providing missing discharge data-links, and not for operational forecastings.

Three nonlinear regression models have also been developed for describing the covariance between the April 1 - 20 snowpack and the attendant flow volume for the entire snowmelt season during the 1969-79 period. The nonlinear models deviate from the assumption of linearity inherent in the linear or bivariate models. The three nonlinear models are developed by assuming log-normal distribution of discharge and snowcover area, log variation of discharge relative to the basin's snowcover area, and the relation of the square-root of seasonal discharge with snowcover area in the basin. Further, confidence limits for discharge within a given range of snowcover area are also suggested. The statistical analysis shows that the log-normal distribution explains 77.64 per cent of the variability of flow

in the Indus River as against the 60 per cent given by the linear regression model. However, for uncertain reasons the Kabul basin does not obey the condition of log-normal distribution between the two variables. For this basin, the condition of linearity seems to hold. The other two nonlinear models do not, however, appear to contribute towards a better prediction of seasonal runoff due primarily to a lower accountability of variability in the flow regime of the Indus and Kabul rivers.

An understanding of daily outputs of meltwater yield in relation to temporal variations in snowcover extent has specific significance in watershed management. The Snowmelt-Runoff Model, or the Martinec-Rango Model as it is sometimes called, is structurally reputed to accurately simulate daily snowmelt discharges in small temperate watersheds. This model was applied to the exceptionally large-sized Kabul basin in the hot-dry subtropical environment of a part of Afganistan and Pakistan for assessing its accuracy in predicting daily meltwater yields, and for its potential use in other major Himalayan basins. The study shows that the model computed daily snowmelt volumes for a greater part of the snowmelt season are "flood-like". The anomaly in observed and computed discharges is thought to result from the accentric position of the temperature station relative to the mean elevation of the basin. Since major Himalayan catchments do not presently have representative climatic and streamgage data in respect of the requirements of the model, its use in large-sized Himalayan basins is to be recommended with caution.

SNOW COVER, SNOWMELT AND RUNOFF IN THE HIMALAYAN RIVER BASINS

1. Introduction

Spatio-temporal variations in the snowcover and the ensuing meltwater discharge from the seasonal snowpack and glaciers are the major parameters that modulate the hydrologic characteristics of the Himalayan catchments in both India and Pakistan. According to one estimate (Tarar, 1982), the seasonal snowmelt contributes to about 70 per cent of the mean annual water yield in the catchments of western Himalayas.

Snow is a valuable resource. Seasonal snow accumulation is known to be significantly important with respect to its small and large-scale effects. The small-scale effects of snow are individual events localized in areas of less than 19 sq mi (50 sq km). Such effects may usually be observed in snow avalanches. The large-scale effects of snow are multidimensional with impact area of 965 sq mi (2500 sq km) cr more. These are summarized by Rango (1985), and may be listed as

1. effects of seasonal snowcover on regulation of weather and climate,

2. the impact of seasonal snowcover on the general global wind circulation pattern,

3. hydrologic response and response characteristics of river basins in relaticn to seasonal snow accumulation,

4. the role of snowcovers in agriculture and,

5. acid snow and its impact on the ecological system.

Of these attributes, only the large-scale hydrologic role of seasonal snowcover is of concern in the present investigation. This study is an attempt to understand the relation of meltwater yield to seasonal snowcover variations in selected river basins in the western Himalayas for which supporting data were readily available during the course of preparation of this report.

Quantitative estimates of long (seasonal)-and short-term (daily) discharges from a given data-set require modelling. Hydrologic models that provide model discharges approximating the actual are most ideal in their application to the time-based estimation of flow volumes. The hydrologic models in general can be subsumed into two broad categories as empirical and conceptual. Regression models for approximating seasonal

meltwater yield from snowcover area are basically empirical in character and are also deficient in the explanation of physical rationale of snowmelt. A variety of conceptual snowmelt-runoff models have been developed in the past. These simulation models are structured around the parameters that relate directly with the response, and response characteristics of the hydrologic system. Such models, to quote Dawdy (1969), summarize the hydrology of the given basin.

Early prediction of snowmelt allows efficient planning and management of water resources for irrigation, hydropower generation, regulation of discharge through reservoirs for flood-control, and industrial and domestic water-supply. In the Himalayan basins which for the most part are inaccessible and where snowcover data from conventional methods are nonexistent, satellite remote-sensed observations provide the only viable alternative for aquiring snowcover data necessary for hydrologic forecasting of snowmelt runoff.

In the present study, a number of empirical models for estimating meltwater yield from snowcover area in the Indus and Kabul rivers, and regression models for explanation of concurrent discharge variations in selected pairs of Indus, Sutlej, Kabul and Chenab rivers in western Himalayas have been developed. The Snowmelt-Runoff Model (Martinec, 1975) for simulation and estimation of daily discharges has been applied to the Kabul basin for assessing its suitability of application to other major drainage basins in the Himalayan environment.

For this study, the basin snowcover areas are estimated from NOAA/TIROS images mapped for weekly snow and ice charts, and from NOAA-4 satellite imagery. Daily river discharges, and temperature and rainfall statistics, where applicable in this research, were provided by the Pakistan Water and Power Management Authority. The body of the text is divided into three major sections. These are (1) introduction to and methodological treatment of the subject matter at the beginning of the text for the models discussed, (2) presentation and interpretation of results, and (3) a summary and conclusions.

2. Meltwater-Snowcover Area Models

Several types of regression models have been developed to forecast seasonal meltwater yield, but they fall short of the physical bases that govern streamflow. Another category of models that are structured around the major physical processes as forecast parameters of runoff are ideally suited for short-term simulation of meltwater yield on day-to-day bases. This report

examines here a few regression models for estimation of seasonal runoff in selected river basins in western Himalayas, and one conceptual model for simulation and estimation of daily discharges in a major western Himalayas watershed.

2.1 Regression Models

Whether seasonal meltwater yield can be predicted within a reasonable accuracy from observation of early spring snow accumulation in watersheds may be examined by developing linear and nonlinear relationships between the two variables. Rango et al. (1977) developed a linear regression model for estimating seasonal runoff in the Kabul River basin from satellite-observed snowcover data in this western Himalayan basin. Later, Tarar (1982) also found a significant correlation between the variations in March or April snowcover and the summer-season runoff for several basins of the Indus system in the Himalayas. Dey et al. (1983) have examined such a relationship for the data on the Indus and Kabul rivers from the standpoint of improving prediction of seasonal meltwater yield from remotely-observed variations in the snowpack area.

2.2 Linear Regression Models

A linear regression model expressing the seasonal runoff as a function of April snowcover is developed in parts by Dey et al. (1983) for the periods 1974-79, and 1969-79. The latter period with an extended time-base incorporates the 1969-73 data from Rango et al. (1977). These data on snowcover and runoff in the Indus and Kabul basins are given in Table 1. Plots of

Table 1: Early Spring Snowcover and Seasonal Runoff in the Indus and Kabul Rivers, 1969-79

	Indus River Above Besham		Kabul River above Nowshera	
Year	April 1-20 Snowcover (%)	April-July Runoff ($10^9 m^3$)	April 1-20 Snowcover (%)	April-July Runoff ($10^9 m^3$)
1969	79.5	40.71	41.5	18.96
1970	55.5	32.20	28.5	11.70
1971	62.0	38.19	34.0	11.40
1972	71.0	39.15	44.0	20.15
1973	90.0	57.90	54.5	23.70
1974	65.0	33.04	31.5	12.20
1975	75.7	37.37	42.3	16.30
1976	86.6	40.41	38.5	15.75
1977	90.8	42.40	34.6	13.46
1978	92.3	52.28	42.5	18.28
1979	88.0	42.43	38.5	17.41

Sources: A. Rango, V. V. Solomonson and J. L. Foster (1977), and
B. Dey, D.C. Goswami and A. Rango, 1983.

snowcover for the first twenty days of April 1974 through 1979 as
independent or predictor variable, and the April to July snowmelt
of the corresponding years as dependent or regression variable,
with the regression lines drawn, are shown for the Indus River
above Besham, and for the Kabul River above Nowshera in Figure 1.
The regression equations describing the best-fit lines, and
their statistical significance are given in Table 2.
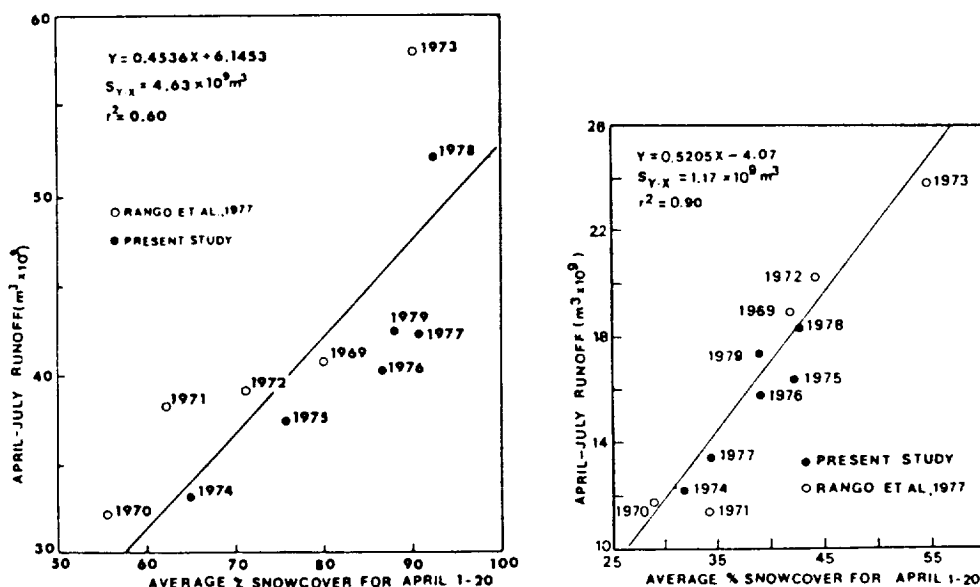
Fig. 1: Linear regression models depicting the
covariance between the snowcover and
meltwater yield for Indus (left) and
Kabul (right) river basins

Table 2: Regression Equations for Seasonal Runoff as a Function
of Early Spring Snowcover in Indus and Kabul Basins for
Different Time-periods During 1969-79

Period	Indus River Estimating Equation	r^2	Kabul River Estimating Equation	r^2	Source
1969-73	Y=0.64 x -3.88	0.82	Y=0.52 x -3.99	0.92	Rango et al., 1977
1974-79	Y=0.52 x -1.57	0.73	Y=0.49 x -2.98	0.82	Dey et al., 1983
1969-79	Y=0.45 x +6.14	0.60	Y=0.52 x -4.07	0.92	Dey et al., 1983

X = Average basin snowcover (%)
Y = April-July runoff ($10^9 m^3$)

The statistical analysis for the period 1974-79 suggests that the correlation between April 1-20 snowcover area and April-July runoff is significant at 97 per cent for the Indus River (r = 0.73) and at 99 per cent for the Kabul River (r = 0.82). The linear regression model explains about 73% of the variability in the seasonal flow of the Indus River. The standard error of estimate in this case is determined to be 7.5% of the mean seasonal yield. For the Kabul River, a similar model with the standard error of estimate of 6.4% of the mean annual flow explains 82% of the variability in the flow. Standard error of estimate is the amount of dispersion in the dependent variable. Stated simply, the extent of early April snowcover in these two basins can be effectively used to predict the volume of meltwater flow that will accrue in the Indus and Kabul rivers from April through July months.

The linear regression model for the extended data-base of 1969-79 shows that for certain undetermined reasons, the model now explains only 60% of the variability in the seasonal flow of the Indus as against the 73% variability previously determined from the shorter time-frame. However, the model improves the account of seasonal variability of flow in the Kabul River from 82 to 90% of the mean seasonal yield. Perhaps, the diffrence in the satellite image resolution from 4 km during 1969-73 to 0.9 km in 1974-79 may have had an unexplained degrading effect on the linear regression model for the Indus River.

In order to determine whether or not the distribution of sample data about the regression lines has affected the above relationship, analysis of variance test was applied for comparing the coefficients 'b' or slopes of the regression lines in each of the three regression equations representing the three periods of data base. A null hypothesis that there is no statistical significant difference in the slopes of the three regression lines is first set-up. The analysis, presented in Table 3, suggests that the computed F .05 (2,16) is less than the critical tabulated value of F = 0.32 at 2 and 16 degrees of freedom. Thus, the null hypothesis that the slopes of the regression lines do not differ statistically is accepted.

Table 3: Analysis of Variance Test for the Equality of Regression Coefficients of Snowcover Area-Runoff Curves for the Indus River at Besham, 1969-79, 969-73, and 1974-79 Periods

Source of variation	d.f.	SS	MS	F	Remarks
Deviation from hypothesis (Variation among regressions)	2	14.4	7.2		The critical value of F at 0.05 is F .05 (2,16) = 3.634
Separate regressions (Variation within regression)	16	64.44	22.78	0.32	Null hypothesis is accepted

The intercepts of the three regression lines may also be compared for determining the statistical differences in the distribution of data about the regression lines. The statistical procedure adopted is that by Draper and Smith (1966). The two-tailed t-test at 95% confidence intervals around the intercepts is given in Table 4.

Table 4: Confidence Intervals around the Intercepts b_0, of the Regression Equations for Different Periods

Period	Confidence Intervals
1969-79	$-16.17 \leq b_0 \leq 28.45$
1969-73	$-44.07 \leq b^0 \leq 36.31$
1976-79	$-38.66 \leq b_0 \leq 35.52$

It may be noted that the intercepts (viz. 6.14, -3.88 and -1.57) for the three periods lie within the confidence limits estimated above. Therefore, these may be accepted as being statistically not different from one another at 0.5 significance level. As the confidence limits for the intercepts contain zero, graphically this means that regression lines possibly pass through the origin.

The inference from the statistical analysis presented in Tables 3 and 4 may be briefly summarized. For the three periods of data-base, the slopes as also the intercepts of the estimating equations are statistically similar at 95% confidence level. Furthermore, the three regression lines for the Kabul River are also found to be statistically similar in their regression coefficients at 0.05 level of significance. It is, therefore, implied that the three sample data on snowcover and snowmelt are distributed around their regression lines in a like-manner. The remarkable similarities in the regression equations for the Indus and Kabul rivers should normally provide comparable correlations between the snowcover and snowmelt. For certain undetermined reasons, however, the linear regression model explains the covariance better for the Kabul than the Indus river. For improving the prediction of snowmelt discharge in the Indus basin, some other suitable linear regression models may, therefore, be developed.

2.3 Multiple Regression Model

The principles of multiple regression are similar to those of the linear regression. The statistical technique, however, involves the use of additional independent variable(s). Such variable(s) should directly relate to the characteristics of snowmelt, and be preferably from the same basin. In the present case, covariance is shown for snowmelt yield and remotely observed basin snowpack area, and no other characteristics of the basin that affect meltwater yield are known in quantitative terms. Such limitations may be overcome by using derived properties of the basin that may be significantly correlated with snowmelt runoff. In the present study, the concurrent runoff in the Kabul River estimated from the bivariate model relating snowmelt runoff to basin snowcover area is used as an additional parameter along with the snowcover in the Indus basin for improving the Indus relationship. These variables form the basis of a multiple regression model described below. The acceptance of concurrent snowmelt runoff as one of the input variables in the model in justified since the concurrent snowmelt runoff in the adjoining Himalayan basins are correlated (Dey and Goswami, 1984). Such a correlation is not surprising since the basins studied by Dey and Goswami (1984) share a similar genetic history and climatic regimes and experience similar cycles of snowmelt and glacier runoff.

For each year of the study period from 1969-79, a separate multiple regression is developed by dropping from the data-base the data for the year in question, and using only those for the remaining years. The snowcover area and the concurrent runoff data are then used to estimate the snowmelt runoff for that year. The multiple regression model thus obtained is given as

$$Y = 2.693 + 0.263 \, X_1 + 1.119 \, X_2$$

where, Y = April-July runoff in $10^9 m^3$

X_1 = Early April per cent snowcover area over the Indus basin

X_2 = Runoff, $10^9 m^3$, in the Kabul basin estimated from the bivariate regression model in Table 2.

In the above equation, the coefficient of determination, r, is given as 0.79. Thus, the multiple regression model explains 79% of the variability of flow as against 60% in the earlier bivariate equation. Moreover, the standard error of estimate is also reduced by 27%, giving an average difference of 10% between the estimated and observed snowmelt discharge over a period of 11 years.

Further, the two-tailed, 95% confidence intervals around the partial slopes, b_1 and b_2, of the multiple regression equations are

$$0.182 \leq b_1 \leq 0.345$$
$$0.401 \leq b_2 \leq 1.839$$

Since zero is not captured between the confidence limits, the null hypothesis ($Ho: \beta = 0$) is rejected. Hence, the partial slopes of the multiple regression equation tend to be significantly different from one another.

The linear regression model for the combined period of 1969-79 was earlier shown to give results inconsistent with the observation on a shorter run of time from 1974-79. This apparent shift of regression lines may perhaps be explained in terms of the differences in the satellite image resolution from 4 km to 0.9 km that may have caused an unexplained degrading effect on the Indus relationship. Inclusion of the estimated current discharge of the Kabul River in the Indus regression provides an additional point of reference that improves the relationship.

2.4 Concurrent Flow Models

Concurrent flow models are yet another illustration of linear regression. In the present study, they express the covariance of snowmelt discharges in adjacent river basins, albeit of different sizes, but epitomized by similarity of flow regime. Potential of concurrent flow models lies mainly in simulating flows, filling missing data points, and extending flow records for evaluating and upgrading the snowcover-runoff linear models. The usefulness of concurrent flow as additional parameter in improving the forecast of seasonal flow in the Indus flow has been demonstrated in the previous section of this report.

Dey and Goswami (1984) have shown that meltwater discharge in the adjacent Himalayan basins are concurrent. In other words, streamflow in one river basin can be effectively used as a parameter for predicting streamflow for the same period in the other basin in which concurrent flow correlation has been established. In the present study, these models demonstrate that the April through June 1975-79 mean monthly flows in pair of rivers – Sutlej, Indus, Kabul, and Chenab – in western Himalayas are correlated with each other.

The pair of rivers which suggest a high degree of correlation are selected and linear regression equations defining the flow in one river as a function of concurrent flow in the other are derived. The regressions from the snowcover-runoff

relationship are used to compare the results of concurrent flow correlation and those derived from the snowcover-runoff model (Table 5). The concurrent flows are best matched for the Kabul and Sutlej rivers, Chenab and Indus rivers, and Sutej and Kabul rivers (Figs. 2a, b, and c).

The concurrent flow in the Kabul River explains about 97% of the variability in the flow of the Sutlej River. The standard error of estimate in this case is given as 5.6% of the mean seasonal flow. The snowcover area-runoff relationship expressing

Table 5: Comparison of Snowcover Area-Runoff and Concurrent Runoff Correlation Models for the Sutlej, Indus, Kabul, and Chenab Rivers of Western Himalayas

River/ Year	Snowcover Area- Runoff Relationship	r^2	S.E.	Flow in the River as a Function of the Flow in							
				Sutlej		Indus		Kabul		Chenab	
				r^2	S.E.	r^2	S.E.	r^2	S.E.	r^2	S.E.
Sutlej 1975-79	Y = −0.363 + 0.065X	0.91	9.7			0.84	20.8	0.97	5.6	0.95	9.4
Indus 1971-79	Y = 4.739 + 0.472X	0.52	11.9					0.71	27.1		
Indus 1975-79	Y = −13.308 + 0.649X	0.57	7.6	0.84	22.6			0.86	21.4	0.90	15.7
Kabul 1971-79	Y = −5.242 + 0.543X	0.91	6.8			0.71	19.6				
Kabul 1975-79	Y = −1.488 + 0.451X	0.64	6.0	0.97	2.6	0.86	9.4			0.94	5.0

Explanation: Y = Seasonal runoff, April-July, $10^9 m^3$; X = Average percent snowcover in the basin; r^2 = coefficient of determination; S.E. = standard error of estimate.

Sources: Dey et al., 1983; Dey and Subba Rao, 1984; Dey and Goswami, 1984.

variation in the flow of Indus as a function of the flow in Kabul River predicts 91% of the variability of flow with a standard error of estimate of 9.7%.

The variability in the flow of Indus River is best explained by the concurrent flow in the Chenab River. The concurrent flow model explains 90% of the variability in flow, while the flow variability given by the snowcover area-runoff model in only 57% of the average seasonal flow. However, as shown in Table 5, the standard error of estimate from the snowcover-runoff model is lower than that obtained from the present model. As may be noted in Table 5, the concurrent flow model explains the variability of flow in the Indus River better than that given by the bivariate snowcover area-runoff model.
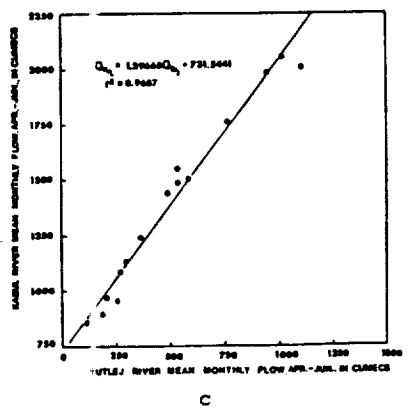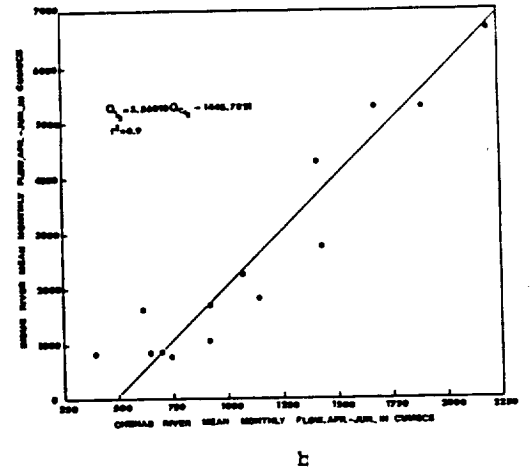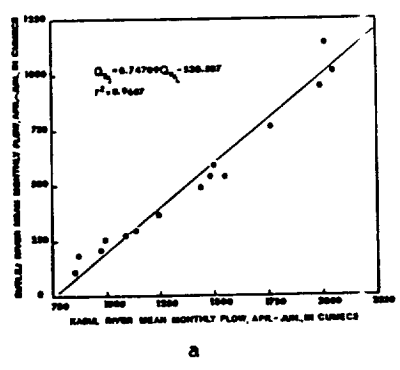
Fig.2: Concurrent flow models

a- Mean monthly flow in the Sutlej
   as a function of the mean monthly
   flow in the Kabul River

b- Mean monthly flow in the Indus
   as a function of the mean monthly
   flow in the Chenab River

c- Mean monthly flow in the Kabul as
   a function of the mean monthly
   flow in the Sutlej River

The concurrent flow model between the Kabul and Sutlej rivers explained 97% of the flow variability. This is a distinct improvement over the 64% explained variability suggested by the linear snowcover area-runoff model. The standard error for the concurrent flow model is also lower (2.6%) than the one for the snowcover area-runoff model (6%). However, for the period 1971-79, the snowcover area-runoff model explained 91% of flow variability as against 71% given by the concurrent flow correlation with the Indus River.

As a snowcover-runoff model is not available for the Chenab River, similar comparisons with other selected rivers could not be suggested. However, as shown in Table 5, the concurrent flow correlation of the Chenab with the Sutlej, Indus and Kabul rivers respectively explains 95, 90 and 94 per cent of the variability in its flow.

In all the basins under reference, the concurrent flow model explains the variability in flow better than that given by the bivariate snowcover area-runoff model. However, in view of the inadequate data base, the strength and weakness of the models, as revealed by the comparison, are to be accepted with caution. With improvement in the size and diversity of data-base, more rigorous and elaborate statistical techniques could be used to compare the efficiency of such models. It is, however, to be remembered that unlike the snowcover area-runoff model, the concurrent flow model cannot be used for operational forecasting procedures.

2.5 Nonlinear Regression Models

Previous investigations referred to above have suggested a strong linear correlation between the early April snowcover and the subsequent summer-season snowmelt discharge in some of the Himalayan watersheds. These catchments are also characteristic of concurrent discharge variations during the snowmelt season. This section examines some nonlinear relationships for improving the prediction of meltwater yield from early-spring snow accumulation in the Indus and Kabul basins in the western Himalayas, and compares the results with those of the previously described linear regression models.

The linear regression models assume that basin discharge, the dependent variable, increases by a constant amount with a unit increase in the value of basin snowcover area, the independent variable. This assumption of linearity is, however, not always satisfied. The dependence of meltwater yield on snowcover area in the Beas watershed and its subbasins in the western Himalayas is, to quote Gupta et al. (1982), explained by a logarithmic relationship. Such a covariance reportedly holds on account of progressive slight increases in the snowcover area

that subsequently promotes higher meltwater yield. Dey and
Sharma (in press) have, therefore, developed three nonlinear
regression models, each for the Indus and Kabul basins , for
describing the covariance between the April through July flow
volume and April 1-20 per cent snowcover area. The data for the
period 1969-79 used in the development of nonlinear regression
equations are given in Table 1. Three nonlinear regression
models assuming log-normal distribution of discharge with
snowpack area, log variation of discharge with snowcover area,
and relation of the square root of discharge with basin
snowcovered area are developed. The methods of computation and
analysis can be found in standard textbooks on statistics. The
equations best describing the relationship are further analyzed
to predict the limits of population from expected sample
discharges at selected values of snowpack area.

The results of three nonlinear regression methods, and
those derived previously by the linear regression method are
given in Table 6. For the Indus River, the log-normal

Table 6: Comparison of Nonlinear and Linear Relationships for
Reduction of Seasonal Snowmelt (Y) and Percent Snowcover
Area (X) in the Indus and Kabul Basins, 1969-79

Relationship

Log Y, Log X

1. Estimating equation: $Y = 0.1382 X^{0.7801}$ $Y = 0.0016 X^{1.2617}$
2. Coefficient of
   determination: $r^2 = 0.7764$ $r^2 = 0.8752$
3. Standard error of
   estimate: S log Y.log X = 3.3166   S log Y.log X = 3.3166

Log Y, X

1. Estimating equation: log Y = 1.2445 + 0.0047X   log Y = 0.6822 + 0.0132X
2. Coefficient of
   determination: $r^2 = 0.6250$ $r^2 = 0.5494$
3. Standard error of
   estimate: S log Y.X = 3.3170   S log Y.X = 3.3167

$\sqrt{Y}$, X

1. Estimating equation: $\sqrt{Y}$ = 3.6913 + 0.0349X $\sqrt{Y}$ = 1.5018 + 0.0641X
2. Coefficient of
   determination: $r^2 = 0.4623$ $r^2 = 0.7951$
3. Standard error of
   estimate: S$\sqrt{Y}$.X = 3.3166   S$\sqrt{Y}$.X = 3.3166

Linear*

1. Estimating equation: Y = 6.14 + 0.45X   Y = -4.0660 + 0.52X
2. Coefficient of
   determination: $r^2 = 0.60$ $r^2 = 0.90$
3. Standard error of
   estimate: S Y.X = 4.63   S Y.X = 1.32

*Source: Dey et al., 1983

distribution explains 77.64% of the variability of flow as against 62.50% and 46.23% given respectively by the log Y, X and $\sqrt{Y}$, X relationships. The linear regression equation explains only 60% of the variation in the observed and predicted discharges. The standard error of estimate is, however, remarkably similar to within the two decimal points for the nonlinear regression models as against a much larger unexplained variability of flow given by the linear regression model. Therefore, the log-linear relationship is best suited for the prediction of seasonal flow in the Indus River than the linear regression or the two other nonlinear regression models discussed above.

For the Kabul River also, the standard error of estimate given by the three nonlinear models is similar to within the two decimal points. The linear regression model, however, shows a slightly larger deviation between the observed and predicted flows as is evident from the standard error of estimate (1.32). The log-normal model has the effect of slightly minimizing the difference between the observed and predicted flows, but it explains only 87.52% of the variability in the Kabul flow as against the 90% account for by the linear regression equation. Therefore, both linear and log-linear regression methods, in that order of suitability, can be used for seasonal flow estimation in the Kabul River. The bivariate linear regression model is simplest to compute however, and may be adopted for the Kabul basin.

The discharge variations with respect to the basin snowcover area should normally conform to a given regression model for basins, such as the Indus and Kabul, that have developed in almost similar physiographic and climatic provinces. The Indus discharge and snowcover area closely follow a log-normal relationship, while the Kabul basin tends to obey a linear relationship between the seasonal meltwater discharge and early-spring snow accumulation. The basin to basin deviations from the assumptions of regression are, however, not understood. Perhaps, differences in the size or drainage order of the basins, and variations in the propotion of basin areas in south and north-facing slopes may have profound influence on the relationship between snowcover area and meltwater yield (see Gupta et al., 1982).

On the basis of estimating regression equations, it is possible to state the limits within which the population value of discharge being estimated can be expected to lie for any given value of the snowcover area. The difference between the computed value of discharge from the sample and its actual population value may be attributed to sampling fluctuations, error in measurement, and deviation from the assumption of regression.

Given in Table 7 are the confidence limits fitted to the log-normal regressions of the Indus and Kabul rivers. The

Table 7: Confidence Limits for Predicted Runoff
Volume ($10^9 m^3$)

Confidence Level	Percent Snowcover Area					
	Indus River			Kabul River		
	50	60	70	30	40	50
95%	± 17.06	± 14.27	± 9.78	± 32.23	± 26.32	± 20.69
99%	± 13.81	± 11.55	± 9.58	± 26.09	± 21.31	± 16.76

regression coefficient limits have been derived from the two-tailed critical values of t with n-2 degrees of freedom at 0.5 and 0.1 significance levels. As an illustration of the table, the population value of predicted discharge for the Indus River is expected to lie somewhere between 21.95 ($10^9 m^3$) and 46.85 ($10^9 m^3$) for the snowmelt volume of 34.40 ($10^9 m^3$) at 62 per cent snowcover area.

2.6 Snowmelt-Runoff Model

The Snowmelt-Runoff Model or the Martinec-Rango Model is a simple conceptual deterministic model for simulation and forecast of streamflow in mountain watersheds where snowmelt contributes substantially to the mean annual flow. The Snowmelt-Runoff Model was developed by Martinec (1975) initially for small watewrsheds in Europe. With its widespread applications, the model has been refined over a period of time for simulation of daily discharges in large basins over a part, a season or the entire year (Martinec et al., 1983).

Discharges for consecutive days are determined from the equation:

$$Q_{n+1} = cn \left[an \left(Tn + \Delta Tn \right) Sn + Pn \right] \frac{23232000A}{86400} (1-k_{n+1}) + Q_n k_{n+1}$$

in which 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 ($^\circ$F-32).d^{-1}, indicating the snowmelt depth resulting from 1 degree-day;

T = number of degree-days ($^\circ$F-32).d^{-1};

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;

P = precipitation in inches contributing to runoff;

S = ratio of snow-covered area to the total area of the catchment;

A = area of the catchment in sq ft.;

$\dfrac{2323200}{86400}$ = conversion factor from $ft^2\ d^{-1}$ to $ft^3\ s^{-1}$;

k = recession coefficient. It indicates the decline of discharge in a period without snowmelt or rainfall, such that $k = \dfrac{Q_{m+1}}{Q_m}$

represent the sequence of days during which a true recession flow occurs. The recession coefficient is determined from the auto-correlation of daily discharges; and

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, during the discharge computation period the number of degree days measured on the nth day correspond to the discharge on the n+1 day.

Martinec and Rango (1986) noted that the model performs well for basins as large as 1544 sq mi (4000 sq km) in area, and the accuracy of prediction is generally not limited by the basin relief and climatic characteristics. However, the accuracy of model simulation reportedly decreases with increasing basin size (Rango, 1980; Hawley et al., 1980). Calibration and frequent adjustment of basin parameters is not necessary in this model, and it 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 of more than 965 sq mi (2500 sq km) are characteristic of tremendous variations in snowcover, and in the factors that govern melting and runoff. Dey and Sharma (in press) applied the Snowmelt-Runoff Model on the Kabul basin with an area of 24587 sq mi (63675 sq km) in the western Himalayas to access the accuracy of model simulation and its performance on daily basis for the snowmelt season.

2.6.1 Kabul Basin

The Kabul basin is located between latitudes $33^{\circ}36'$ to $36^{\circ}55'$ north and longitudes $67^{\circ}36'$ to $73^{\circ}54'$ east, and drains an area of 24578 sq mi (63675 sq km) in parts of Afganistan and Pakistan (Fig.3). The basin experiences a hot-dry steppe and highland type of climate in the subtropical environment. Except for a small stretch of crystalline massif in the east, the watershed as a whole has developed almost entirely on the folded and faulted

Alpine-Karakoram System of Hindukush Mountain ranges. The
elevation in the basin varies from 1000 ft (305 m) at Nowshera,
the gaging station to 25230 ft (7581 m) in the valley of Konar-
a principal tributary of the Kabul River. The Konar drains
through a relatively higher and rugged topography from the north
than the Kabul River which has a roughly west to east
orientation. Nearly all the glaciers in the catchment are
situated above 13000 ft (3962 m) in the Konar valley, and these
occupy some 260 sq mi (675 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 Himalayan watersheds are characterized by seasonally heavy
snowmelt discharges, and in some cases the meltwater yield 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 watersheds. Some other hydrometeorological
characteristics of the basin may be briefly stated here. During
the major part of snowmelt season from April 4 through June 24,
1976, a cumulative discharge of 431.44 x 10^4 cfs (1221.84 x 10^2
cms) was observed. During this 82-day period of snowmelt, the
extent of snowcover varied from 27.6 to 72.5 per cent of the
basin area, and a cumulative rainfall of 3.61 in (9.02 cm) was
experienced. This period is one of the high thermal efficiency
during which time the maximum and minimum temperatures
respectively ranged between 108°F and 50°F (42°C and 10°C).

   With the mean hypsometric elevation of 7700 ft (2347 m), the
basin is distinctly asymmetrical in the distribution of relief
(Fig.4). The area-elevation curve suggests that only 4 per cent
of the basin's area lies above 15000 ft (4572 m), the major area
of snow accumulation. On the average, the snowpack generally
descends to below 6000 ft (1828 m) in the Konar valley, due
primarily to the high and very steep valley-side slopes. The
snowpack, with an average elevation of 11250 ft (3429 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 principally
in the Konar basin that contributes to the meltwater yield in the
Kabul River basin.

2.6.2 Procedure

   A daily snowcover in the catchment has been extrapolated for
a major part of the snowmelt season from April 4 through June 24,
1976, from NOAA-4 satellite imagery. The daily temperature data
for the same period recorded at Mardan, about 20 mi (35 km) from
Nowshera, Pakistan have been used as an index of the thermal
efficiency of the basin, and approximately extrapolated to the
mean hypsometric elevation of 7700 ft (2347 m) for the Kabul
catchment by assuming normal lapse rates respectively of 3.3°
F/1000 ft and 5.0° F/1000 ft. It was thought that the higher
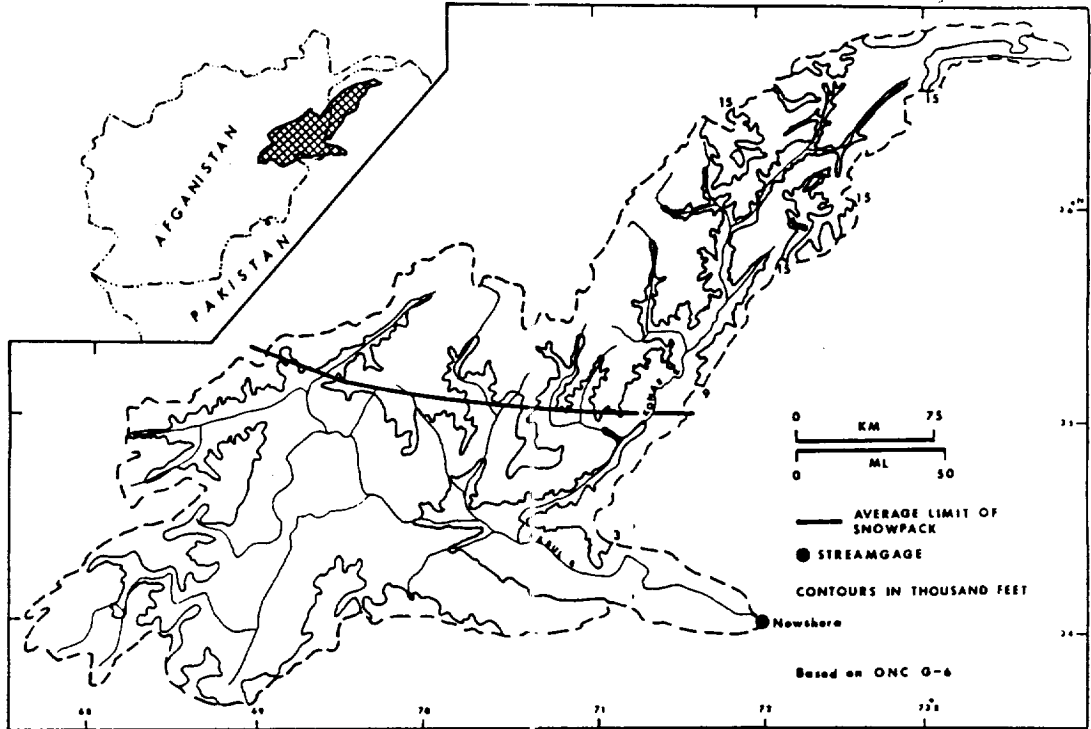normal lapse rate of 5.0°F/1000 ft would probably best describe
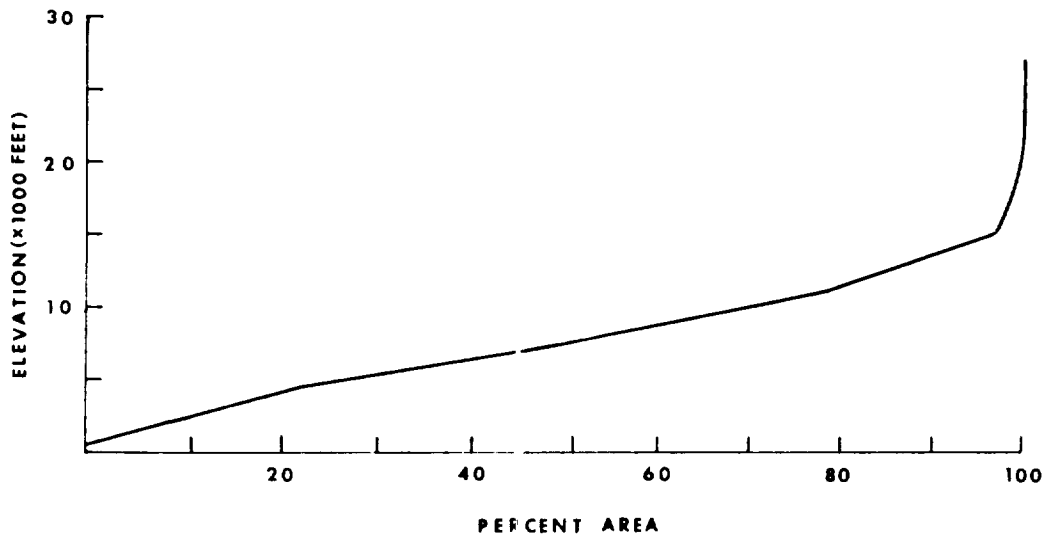
Fig. 3:   The Kabul River basin

Fig. 4:   Area-elevation relation for the Kabul basin

the vertical decline of temperature in this area of high thermal regime. Keeping in view the asymmetric distribution of elevation, and restriction of average snowpack to 42 per cent of the basin area, similar computations were also obtained for the average elevation of 11250 ft (3429 m) for the snowpack. It was determined that for the assumed critical temperature of 34° F $(1.2^\circ$ C), the rainfall recorded at Mardan, and applied to the basin as uniformly distributed, is always available for immediate runoff for the normal lapse rates of 3.3° and 5°F/1000ft.

Some reasonable assumptions are also necessary to determine the parameters of the basin. As a result of variations in snowmelt and receipts from rainfall, the runoff coeffients may vary on day-to-day basis. The runoff coeffients for snowmelt and rainfall are taken to vary respectively between 0.50-0.85 and 0.40-0.80. The recession coefficient factors, x and y, for the catchment have been assessed from the serial correlation of daily discharges (Fig. 5). These are given as x = 1.342 and y =
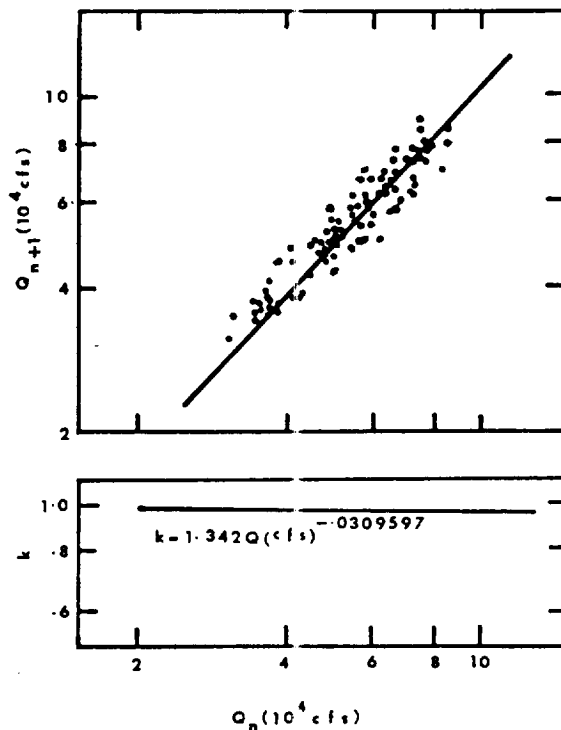

Fig. 5: Regression flow plot, Q_n vrs. Q_{n+1}, and relation of k and Q for the Kabul basin

-0.0309597. The degree-day factor (a) has been computed from the relationship (Martinec, 1975)

$$a = 1.1 \rho r$$

in which ρr if the density of snow relative to water. In the snowmelt computation process, the density of snow was taken to progressively increase from 0.05 at the beginning of the melt-season to 0.11 as its close. The degree-days are extrapolated to the mean elevation by the equation

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

where, ΔT = temperature lapse-rate correction factor in $^{\circ}F$, δ = normal lapse rate in $^{\circ}F/1000$ ft, hST = attitude of the base station (ft), and $\bar{h}$ = mean elevation of the basin and snowpack in feet.

The daily discharges simulated by the Martinec-Rango model have been compared against the observed sequence of daily discharges. The volumetric difference between the computed and observed discharge values is a measure of the accuracy of model simulation. The model performance is evaluated by a non-dimensional Nash-Sutcliffe value.

2.6.3 Results and Discussion

The accuracy of model simulation is determined by the goodness of fit between the observed and computed runoff volumes, and may be expressed as

$$Vd = \frac{Vc - Vo}{Vo} \times 100$$

where, Vd is the volumetric difference between the computed (Vc) and observed (Vo) seasonal runoff.

The model performance on daily basis is evaluated by using the non-dimensional Nash-Sutcliffe R^2 values (Nash and Sutcliffe, 1970). The R^2-value is a measure of model efficiency that expresses the proportion of variance between the observed (Qo) and computed (Qc) runoff on consecutive days of snowmelt period (n) in the following way

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

in this equation, $\bar{Q}$ denotes the average observed discharge.

The goodness of fit and R^2 values computed for 7700 ft and 11250 ft mean elevations of the watershed and snowpack area respectively at 3.3° and 5°F/1000 ft of assumed normal lapse rates are given in Table 8.

Table 8: Goodness of Fit and R^2 Values for Given Mean Elevation and Assumed Lapse Rates

#	Mean Elevation (ft)	Assumed Lapse Rate (°F/1000')	Total Flow Volume (cfs)		Goodness of Fit Measures	
			Observed	Computed	Simulation Efficiency (% Seasonal Difference)	Model Efficiency (Nash-Sutcliff R^2)
1	7,700	3.3	4314400	36024696	- 734.98	- 331.33
2	7,700	5.0	4314400	21823500	- 405.97	- 233.52
3	11,250	3.3	4314400	9033106	- 109.51	- 78.09
4	11,250	5.0	4314400	1093592	74.54	- 5.42

A comparison between the predicted and observed daily discharges shows that the three of the four simulations represent a "flood-like" stage as the meltwater season gradually gets underway. Figure 6 is an illustration of the anomaly in computed and observed discharges. These curves also show a temporal near-similar pattern of discharge computation. For the 5°F/1000 ft normal lapse rate and the 11250 ft mean elevation of the snowpack a base flow is, however, generated. These bad simulations can result from inadequacy of any one or all of the input variables used in this model, or from the structural limitations of the Snowmelt-Runoff Model itself. To answer these two-fold questions, a procedure of selective elimination of the variables one-by-one was adopted for examining the role of each parameter in computing abnormal daily discharges. If, none of the variables contributed to the collapse of the model it would follow that the model is not structurally suitable for tropical environment.

Rango and Martinec (1981) have demonstrated that accuracy of model simulation depends entirely upon the quality of input data. Weakness in the data of following types usually provide for discrepancy in computation of discharges: (i) Scanty temperature and rainfall coverage for relatively large-sized watersheds, and when the vertical distance between the temperature station and the mean elevation of the basin tends to be sufficient; (ii)
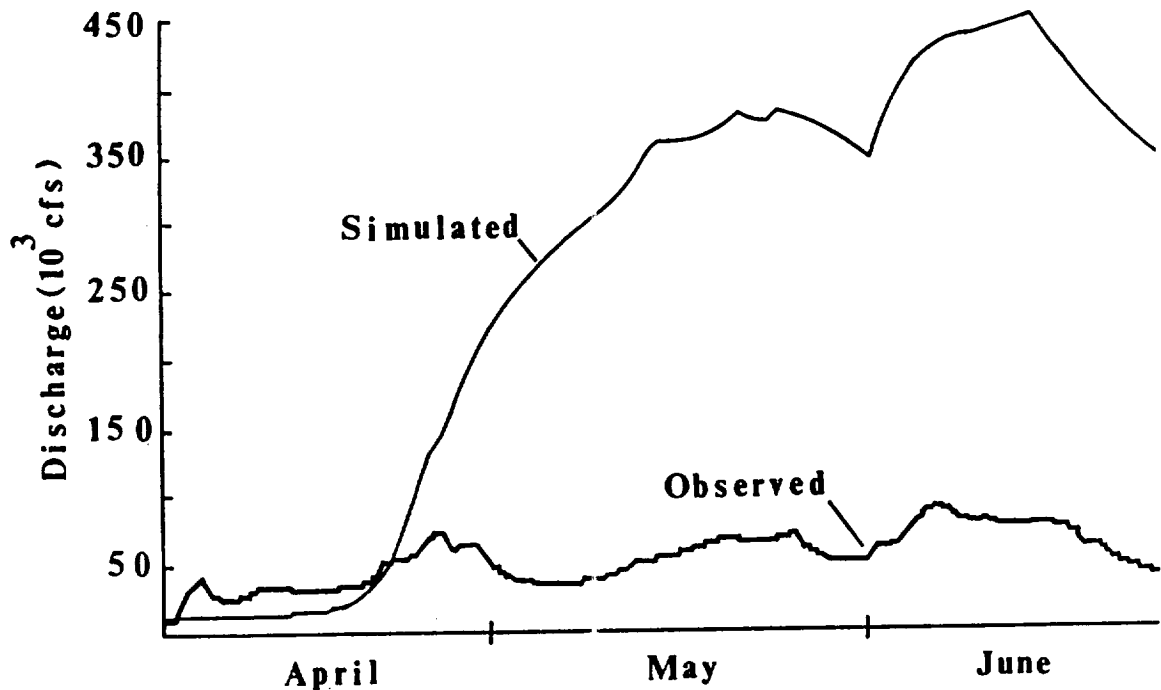
Fig. 6: Comparison of observed and simulated yield for the Kabul River basin at 3.3 degrees F normal lapse rate and 7700 ft mean elevation of the watershed

Errors in the determination of snowcover extent due to cloud cover in tropical environment and inadequate information on its short-term random variations; (iii) Error in computation of regression coefficients; (iv) Decrease in the simulation accuracy perhaps with increasing size of the watershed. To these observations, it may also be added that discrepancy in observed and computed discharges become real when substantial subterranean waterloss takes place in the watersheds. Further, slope aspect in a rugged terrain can delay or enhance the snowmelt, and effect the duration of snowmelt period.

The use of personal computer for snowmelt simulation in the Kabul basin allowed a greater freedom of judgement of errors in the input data causing the discrepancy in the computation discharges. By the process of selective elimination of basin's parameters, it become apparent that the pattern of computed daily discharges may be explained by the size of the basin, and the accentric position of the temperature station. The effect

of basin size on simulation results can neither be independently verified nor conclusively suggested as the study considers only one available streamgage station and, consequently, treats the entire mega-sized basin as one hydrologic unit for computation of snow depletion over a period of time. The position of temperature station, however, appears to have affected the computation of discharges on daily basis. The station is situated some 25 mi (35 km) outside the watershed where seasonal heating in the continental environment causes the temperatures to rise abruptly to high levels during the snowmelt season. The major part of the watershed, however, experiences a mountainous temperate climate. Further, a large altitudinal differences of about 24230 ft (3657 m) exists between the temperature station and the absolute elevation of the Kabul basin. Extrapolation of temperature by lapse rate to the mean elevation of the watershed may lead to unrealistic values of extrapolated temperatures. It may be pointed out that air drainage and gravity winds on rugged and steep mountain slopes can greatly upset the principle on which extrapolation of temperature by lapse-rate is based. The study by Rango and Martinec (1981), referred to above, notes that the most appropriate simulations are generated by the model when the temperature station is situated at the mean elevation of the basin. Further, the error in simulation bears a direct relation to this altitudinal difference. It may, therefore, be concluded that bad simulations for the Kabul basin are most likely caused by the accentric position of the climatic station, and not by a structural deficiency in the Snowmelt-Runoff Model.

Major Himalayan watersheds do not have adequate density of raingage and climatic stations. Therefore, application of model to such watersheds will have to wait till such time representative input basin parameters are available for real-time forecasting of snowmelt discharges on daily basis.

Another model of snowmelt forecast on short-term basis developed by the Corps of Engineers (1973) is based on empirical relationships of snowmelt to meteorological parameters. Singh and Mathur (1976) applied this hydrological model to the simulation of daily snowmelt discharges in the Beas basin, northwestern Himalayas, and found a close agreement between the observed and model predicted runoff pattern. For the Kabul basin, however, the Corps of Engineers' model could not be considered for want of appropriate meteorological data, such as air temperature and solar radiation at the snowpack surface, air temperature 3 m above the snow surface, dewpoint temperatures, and wind speed 15 m above the snowpack area.

3. Summary and Conclusions

This preliminary study on the relationship between the Himalayan snowcover and streamflow has shown that carefully

selected regression models can be effectively used for forecasting of long-term meltwater yields in the Indus, Kabul, Sutlej and Chenab basins draining the slopes of western Himalayas. In these basins of rugged topography, limitations of access, and inadequate hydro-meteorological data-base, the remotely-observed snowcover information provides the best available input data in empirical snowmelt prediction techniques. This investigation highlights that the early-spring basin snowpack area can be reliably used for estimating cumulative meltwater yield in the summer months. These estimates should provide useful guidelines in the management of water resources in the basins studied.

Utilizing the 1969-79 data-base for the April 1-20 snowcover area and April through July meltwater yield, linear and nonlinear models for the Indus and Kabul rivers are developed. On the bases of estimating equations, coefficients of determination and standard errors of estimate, it is suggested that the relationship for the Kabul basin is better explained by the bivariate linear regression model that accounts for 90 per cent of the variability in the river flow. However, a log-normal relationship accounting for 77.4 per cent of the flow variability in the Indus River is an improvement over the explained variability of 60 per cent given by the linear regression model. For these rivers, the other - logarithmic and fractional nonlinear models provide a lower prediction ratings, and are not recommended for use in these river basins.

Concurrent flow models are yet another illustration of linear regression models. In the present study, they are developed to express the covariance of snowmelt discharge in adjacent river basins of different sizes but with similarity of flow regimes. These models demonstrate that the April through June 1975-79 mean monthly flow in pairs of rivers - Sutlej, Indus, Kabul and Chenab are correlated with each other. In other words, flow variations in the one river can be used to predict the variation of flow in the other adjacent river with which concurrent flow relation has been established. The concurrent flow characteristics in related basins can be used for explaining intra-basin flow-variabilities and punching-in the missing discharge data links.

The multiple regression technique, which in based on the same principles as the linear regression model, can be used for improving the empirical relationship between the meltwater yield and snowcover area. This model for the Indus explains 79.00 per cent of the flow variability in the river, and may be compared with the explained variabilities respectively of 60.00 and 77.64 per cent suggested by the linear and log-normal models. The multiple regression model, however, involves the use of

additional input variable(s) which in this case has been the concurrent runoff in the Kabul basin estimated from the bivariate model.

Real-time forecast of daily discharges from watersheds is as important as estimation of seasonal meltwater yield from the basin snowcover area. The Snowmelt-Runoff Model, or sometimes referred to as the Martinec-Rango model, reportedly provides estimates consistent with the observed daily discharges in temperate basins. This model was applied to the Kabul basin for assessing its performance and suitability of application to the Himalayan watersheds of exceptionally large size. The study shows that the model computed daily snowmelt volumes for a greater part of the snowmelt season are "flood-like". This anomaly in observed and computed discharges is suggested to result from the accentric position of the temperature station relative to the mean elevation of the Kabul basin. Since major Himalayan watersheds do not presently have representative climatic and streamgage data in respect of the requirement of the model, its potential use for forecasting meltwater yields in large-sized Himalayan basins is to be recommended with caution.

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