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Utilization of Satellite Snow-Cover Observations for Seasonal Streamflow Estimates in the Western Himalayas

B. Dey and D. C. Goswami
Howard University, Washington, DC 20059, U.S.A.

A. Rango
Agricultural Research Service, Beltsville, MD 20705

The results presented in this study indicate the possibility of seasonal runoff prediction when satellite-derived basin snow-cover data are related to point source river discharge data for a number of years. NOAA-VHRR satellite images have been used to delineate the areal extent of snow cover for early April over the Indus and Kabul River basins in Pakistan. Simple photo-interpretation techniques, using a zoom transfer scope, were employed in transferring satellite snow-cover boundaries onto base map overlays. A linear regression model with April 1 through July 31 seasonal runoff (1974-1979) as a function of early April snow cover explains 73% and 82% of the variance, respectively, of the measured flow in the Indus and Kabul Rivers. The correlation between seasonal runoff and snow cover is significant at the 97% level for the Indus River and at the 99% level for the Kabul River. Combining Rango et al.'s (1977) data for 1969-73 with the above period, the April snow cover explains 60% and 90% of the variance, respectively, of the measured flow in the Indus and Kabul Rivers. In an attempt to improve the Indus relationship, a multiple regression model, with April 1 through July 31, 1969-79, seasonal runoff in the Indus River as a function of early April snow-covered area of the basin and concurrent runoff in the adjoining Kabul River, explains 79% of the variability in flow. Moreover, a significant reduction (27%) in the standard error of estimate results from using the multi-variate model. For each year of the study period, 1969-79, a separate multiple regression equation is developed dropping the data for the year in question from the data-base and using those for the rest of the years. The snow cover area and concurrent runoff data are then used to estimate the snowmelt runoff for that particular year. The difference between the estimated and observed dircharge values averaged over the 11 year study period is 10%. Satellite derived snow-covered area is the best available input for snowmelt-runoff estimation in remote, data sparse basins like the Indus and Kabul Rivers. The study has operational relevance to water resource planning and management in the Himalayan region.

Introduction

The potential of satellite remote sensing as an effective snow monitoring tool and the applications of satellite-derived snow-cover data in hydrologic modelling of snowmelt runoff have been demonstrated in various studies since the launch of the first meteorological satellite TIROS in April, 1960 (Leaf 1971; Rango et al. 1977; Dey et al. 1979a, 1979b; Rango and Martinec 1979; Hawley et al. 1980; Barnes and Bowley 1981). In the early years, the results were less promising due to limitations of sensors and poor ground resolution. Today, a wide variety of environmental and resource satellites equipped with high resolution and more versatile sensors continue to generate snow-cover data at an unprecedented rate. However, in spite of the numerous present applications of satellite observed snow-cover data to streamflow estimation in diverse environmental settings, such investigations are extremely limited for remote river basins such as those in the Himalayas.

Satellite-derived snow-cover mapping of the Himalayan region for estimation of snowmelt runoff was first conducted by Salomonson and MacLeod (1972), then by Rango et al. (1975, 1977). Using Nimbus 3 and 4 meteorological satellite images, Salomonson and MacLeod (1972) delineated the snow-covered area over the Indus Basin for 1969 and 1970 and correlated it to mean monthly runoff in the river. Although the data-base was very limited, the study indicated the usefulness of satellite observed snow-cover data for streamflow estimation in the Himalayan basins. Rango et al. (1977) mapped early spring snow covered area over the Indus and Kabul Basins using low resolution (4 km) ESSA and NOAA satellite images and obtained, in each case, a significant relationship between early April snow-covered area and April 1 through July 31 measured streamflow for the period 1967-73. Based on the regression equations obtained for the two rivers, the 1974 seasonal streamflow was predicted within 7% of the measured flow. Since 1973, high resolution (1 km) satellite snow-cover data over the Indus and Kabul Basins have been available. The purposes of the present study are to extend the earlier work of Rango et al. (1977) using more recent years of snow cover and runoff and to compare the empirical relationships between snow-cover data and runoff data over different time periods and with higher resolution sensors.

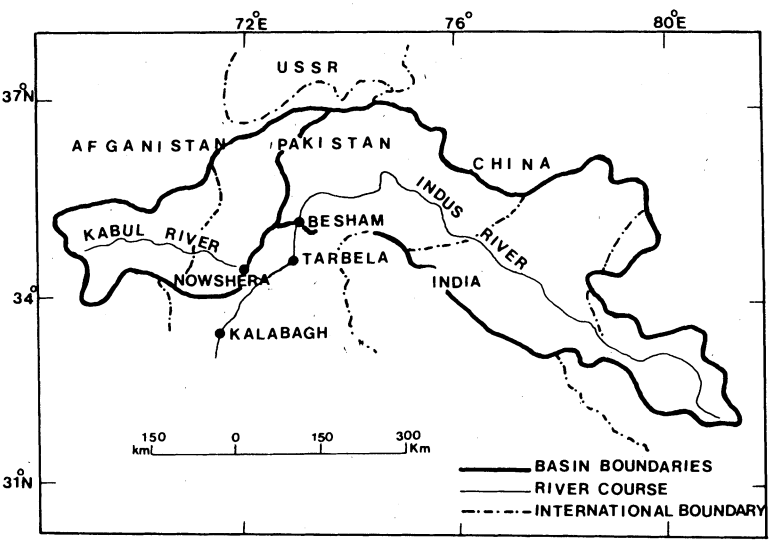

Fig. 1. The Indus River and Kabul River Basins.

Study Area

The study focuses on the Indus River basin above Besham, Pakistan, and the Kabul River basin above Nowshera, Pakistan (Fig. 1). Runoff regimes of both these rivers are significantly influenced by snowmelt. The Indus basin rivers rise in the Hindukush, Karakoram and Himalayan mountains at elevations ranging between 4,500 and 8,500 m. The gaging stations at Besham, located at an elevation of 1,200 m, defines a drainage area of 162,100 km^2 in northern Pakistan, India and extreme western China. Snowmelt, starting in March or April and continuing through summer, contributes about 70% of the annual river flow (Tarar 1982). The Indus at Besham provides the main artery for inflows to the Tarbela reservoir which is located in the immediate downstream section. The Kabul River basin above Nowshera, covering an area of about 88,600 km^2 in eastern Afghanistan and northern Pakistan, varies in elevation from 7,620 m in the Hindukush mountains down to 305 m at the gaging station near Nowshera. Joining the Indus River below Tarbela, the Kabul River is the primary source of water for the proposed dam at Kalabagh, about 200 km downstream from Tarbela. In view of the strategic location of the two gaging stations, prediction of snowmelt runoff at these sites will aid the decision-making process for reservoir operation and water resources planning in Pakistan. In fact, the operational aspect had been underscored in the study by Rango et al. (1977).

Methodology

NOAA/TIROS images that provide daily coverage over the Indus and Kabul basins were used in the analysis. NOAA satellites collecting Very High Resolution Radiometer (VHRR) data, with one visible (0.6-0.7 μm) and one thermal infrared (10.5-12.5 μm) spectral bands, have a ground resolution of 0.9 km. The imagery covers at swath 2,350 km wide. Two major limitations of NOAA images are low resolution and inherent geometric distortion. To overcome the distortion a Bausch and Lomb zoom transfer scope was employed. This instrument reduces image distortion by superimposing the images onto a base map through a system of mirrors and lenses. For the large basins being tested, the VHRR resolution was completely adequate.

Simple photo-interpretation techniques using the zoom transfer scope were employed to extract early April snow-cover area data for the period 1974-79. Basin snow-covered areas delineated on base map overlays, were measured with a digital planimeter. The average percent snow cover for early April was obtained by comparing the snow-covered area with the area of the entire basin. The Indus basin, located at a higher average elevation, has higher average percent snow-covered area compared to the Kabul basin. Streamflow data for the Indus River at Besham and the Kabul River at Nowshera during the months April through July for the period 1974-79 were obtained from the Pakistan Water and Power Development Authority (WAPDA). The estimated snow cover and measured runoff data used in this study are presented in Table 1.

Results

In order to estimate seasonal snowmelt runoff, least square regression analyses were performed relating average percent snow cover for early April and seasonal runoff from April through July for the period 1974-79. The scatter of the plotted points and the regression equations defining the best-fit-lines for the Indus and the Kabul Rivers are shown in Figs. 2 and 3 respectively. The correlation between snow-covered area and seasonal runoff is significant at 97% level for the Indus River and at 99% level for the Kabul River. The linear regression model explains about 73% of the variability in seasonal flow of the Indus River and the standard error of the estimate equals 7.5% of the mean seasonal yield. For the Kabul River, a similar model explains 82% of the variability in the flow and the standard error in this case is 6.4% of the mean seasonal yield.

Incorporating the snow-cover and runoff data for 1969-73 from the study by Rango et al. (1977), regression analyses with regard to the above two variables were performed on the enlarged data base, 1969-79, for both the Indus and the Kabul Rivers. Regression equations pertaining to different data-bases and

Table 1 – Snow Cover (April 1-20) and Runoff (April 1 – July 31) Data for the Indus River above Besham and the Kabul River above Nowshera in Pakistan for the period 1969-79.

	Indus River above Besham		Kabul River above Nowshera	
Year	Snow Cover (%)	Runoff ($10^9 m^3$)	Snow Cover (%)	Runoff ($10^9 m^3$)
1969	79.5	40.71	41.5	18.96 (17.54)
1970	55.5	32.20	28.5	11.70 (10.77)
1971	62.0	38.19	34.0	11.40 (13.63)
1972	71.0	39.15	44.0	20.15 (18.84)
1973	90.0	57.90	54.5	23.70 (24.30)
1974	65.0	33.04	31.5	12.20 (12.33)
1975	75.7	37.37	42.3	16.30 (17.95)
1976	86.6	40.41	38.5	15.75 (15.97)
1977	90.8	42.40	34.6	13.46 (13.94)
1978	92.3	52.28	42.5	18.28 (18.06)
1979	88.0	42.43	38.5	17.41 (15.97)

Remark: Figures within parenthesis denote runoff values for the Kabul River estimated from the snow-covered area-runoff relationship. Data for 1969-73 from Rango et al. (1977).

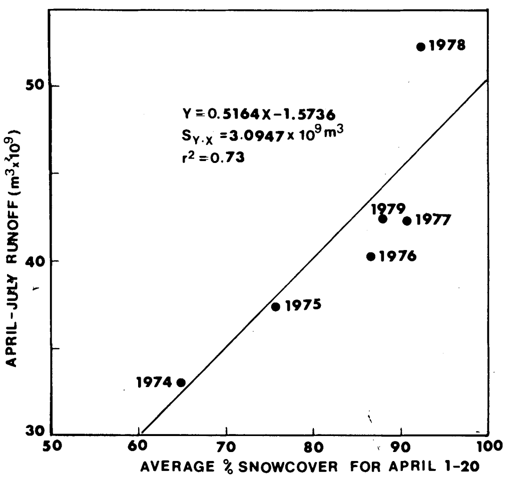

Fig. 2. Satellite-derived snow cover estimates versus measured runoff for the Indus River, above Besham, Pakistan, 1974-79.

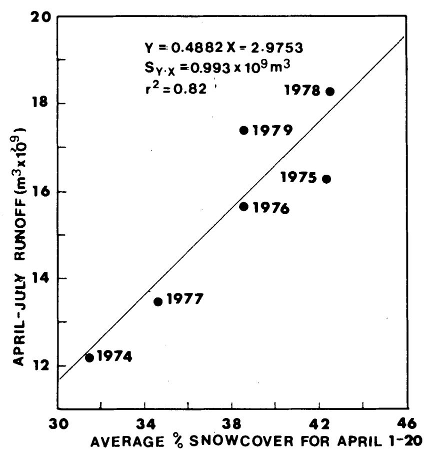

Fig. 3. Satellite-derived snow cover estimates versus measured runoff for the Kabul River above Nowshera, Pakistan, 1974-79.

Table 2 – Regression Equations showing Seasonal Runoff as a Function of early Spring Snow Cover for the Indus and Kabul River Basins in different Time-Periods during 1969-79.

	Indus River above Besham		Kabul River above Nowshera		
Period	Regression Equation X = Av. % of snow cover Y = April-July runoff $10^9 m^3$	r^2	Regression Equation X = Av. % of snow cover Y = April-July runoff $10^9 m^3$	r^2	Remark
1969-73	$Y = 0.64X - 3.88$	0.82	$Y = 0.52X - 3.99$	0.92	Data from Rango et al., 1977
1974-79	$Y = 0.52X - 1.57$	0.73	$Y = 0.49X - 2.98$	0.82	Present study
1969-79	$Y = 0.45X + 6.14$	0.60	$Y = 0.52X - 4.066$	0.90	Combined data

variability in the flow data each of these equations explains (given as r^2 values) are presented in Table 2 and the scatter of the plotted points is shown in Figs. 4 (a) and (b). For the Indus River, the slopes of the regression equations, b_i, representing different time-periods are compared using an analysis of variance test (Table 3). The test statistic for testing the hypothesis that regression coefficients are equal is $F = 0.32$ at d.f.2 and 16. The critical value of F for $\alpha = 0.05$ is $F_{.05(2,16)} = 3.634$. Since the computed value of F is less than the critical F value, the null hypothesis regarding equality of regression coefficients is not rejected. Thus, there is no statistically significant difference in the slopes of the regression lines. Following the procedure suggested by Draper and Smith (1966), two tailed, 95% confidence intervals around the intercepts, b_o, of the regression equations for different periods are estimated to be

$$-16.17 \leq b_0 \leq 28.45 \text{ (1969-79 curve)}$$
$$-44.07 \leq b_0 \leq 36.31 \text{ (1969-73 curve)}$$
$$-38.66 \leq b_0 \leq 35.52 \text{ (1974-79 curve)}$$

Since the intercepts of the regression lines for the above three periods (viz. 6.14, – 3.88 and – 1.57) lie within the confidence bands estimated above, these may be accepted as being statistically not different from one another at the 0.05 significance level. As the confidence bands for the intercept contain zero, graphically this means that we do not reject the possibility that the regression lines cut the origin. A similar examination indicates that the regression coefficients of the Kabul River snow-covered area-runoff curves for 1969-79, 1969-73 and 1974-79 are statistically not different from one another at 0.05 significance level. Furthermore, the regression lines for the Indus and the Kabul Rivers are also statistically similar in regard to their regression coefficients at 0.05 significance level.

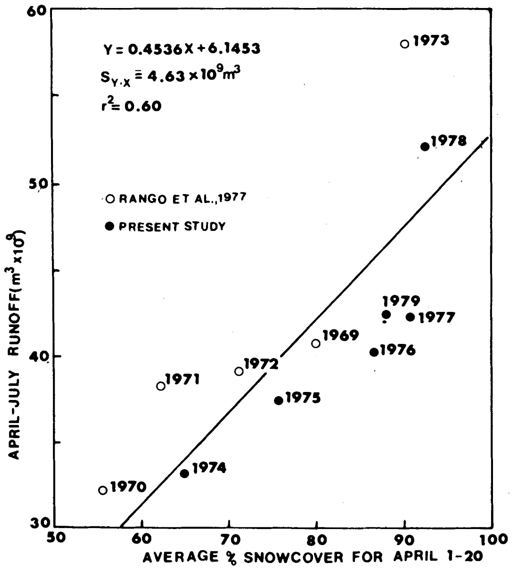

Fig. 4(a) Satellite-derived snow cover estimates versus measured runoff for the Indus River above Besham, Pakistan, 1969-79.

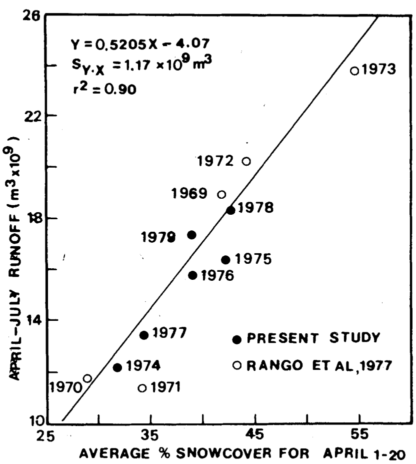

Fig. 4(b) Satellite-derived snow cover estimates versus measured runoff for the Kabul River above Nowshera, Pakistan, 1969-79.

Table 3 – Analysis of Variance for Testing Equality of Regression Coefficients of Snow Cover Area – Runoff Curves for the Indus River at Besham during 1969-79, 1969-73 and 1974-79.

Source of Variation	d.f.	SS	MS	F	
Deviation from hypothesis (Variation among regressions)	2	14.4	7.2	0.32	The critical value of F at $\alpha = 0.05$ is $F_{.05\,(2,16)} \equiv 3.634$.
Separate regressions (variation within regressions)	16	364.44	22.78		Since the computed value of F is less than the critical F-value, the null hypothesis of equality of regression coefficients is not rejected.

In an attempt to improve the Indus relationship, the concurrent runoff in the Kabul river, estimated from the simple regression model relating basin snow-cover area to snowmelt runoff, is used as an additional input parameter along with the original parameter, viz., Indus snow-covered area. The multiple regression model thus obtained is

$$Y = 2.693172 + 0.26348X_1 + 1.1199X_2 \; (R^2=0.79)$$

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

X_1 = Percent snow cover for early April over Indus Basin

X_2 = Kabul runoff, April-July, $10^9 m^3$, estimated from the bivariate regression model in Table 2

The multiple regression equation explains 79% of the variability in flow as against 60% in the earlier bivariate equation. Moreover, the standard error of estimate is reduced by 27%. Two tailed, 95% confidence intervals around the partial slopes, b_1 and b_2, of the multiple regression equation are

$$0.1816 \leq b_1 \leq 0.3454$$

$$0.4006 \leq b_2 \leq 1.8392$$

Since zero is not captured between the confidence limits, the null hypothesis (Ho:β=O) is rejected. Thus, the partial slopes are significantly different from zero.

For each year of the study period, 1969-79, a separate multiple regression equation is developed dropping the data for the year in question from the database and using those for the rest of the years. The snow-cover area and concurrent runoff data are then used to estimate the snowmelt runoff for that particular year. The difference between the estimated and observed dircharge values averaged over the 11 year study period is 10%.

The Indus and the Kabul are adjacent Himalayan basins – Kabul being a tributary to the Indus. Both the basins come under broadly similar climates and environmental settings marked by steep Himalayan slopes and affected by similar cycles of snowmelt and glacier runoff. Concurrent snowmelt runoff in these adjoining Himalayan basins are correlated (r = 0.7). Moreover, the regression equations representing the snow cover-runoff relationship in these two basins are statistically similar (at 0.05 significance level) in terms of regression coefficients. For unknown reasons, the Kabul basin is characterized by a stronger relationship between basin snow cover and runoff than the Indus basin in both the 1974-1979 period and the combined period.

In combining the early (1969-1973) and later (1974-1979) data sets, the difference in the satellite image resolution (4 km vs 0.9 km) may have had an unexplained degrading effect on the Indus River relationship. Inclusion of the concurrent estimated discharge of the Kabul River in the Indus regression provides an additional point of reference that improves the relationship so that it would be feasible for operational application.

Conclusions

The results obtained in this study through simple photo-interpretation techniques and linear regression analysis, are strongly indicative of the potential of satellite derived snow-cover extent data for hydrologic modelling of snowmelt runoff in remote, data-sparse mountain basins like those of the Indus and Kabul Rivers. A regression model relating seasonal flow from April through July, 1974-79, to early April snow cover explains 73% and 82% of the variance, respectively, of the measured flow in the Indus and the Kabul Rivers. When data from two separate periods were combined to increase the data base to 11 years, the relationship was degraded for the Indus (r^2=60%) and improved for the Kabul (r^2 = 90%). In an attempt to improve the Indus relationship, a multiple regression model, with April 1 through July 31, 1969-79, seasonal runoff in the Indus River as a function of early April snow-covered area of the basin and concurrent runoff in the Kabul River, explains 79% of the variability in flow and reduces the standard error of estimate by 27%. For each year of the study period, 1969-79, a separate multiple regression equation is developed for the Indus basin dropping the data for the year in question and using those for the rest of the years. The data for the year dropped can then be used sequentially as input to the multiple regression equation to estimate the seasonal discharge. The difference between the estimated and observed values averaged over the 11 year study period is 10%. High correlation of concurrent flows in adjoining Himalayan, basins like the Indus and Kabul, proves to be an useful input in runoff forecasting models for the region. Use of digital enhancement of the images and incorporation of additional input parameters, proposed for the next phase of the investigation, might allow more sophisticated runoff models to be developed for these basins. But until such time comes, remotely sensed snow-cover area data provide the best available input in empirical snowmelt prediction techniques for these remote basins, which are characterized by rugged physiography, limited physical accessibility and inadequate hydro-meteorological data base. The study has operational value for reservoir management and various other water resources appliations, such as irrigation and hydropower generation.

The results of this study are preliminary. The data set in this study covers 11 years. The results will be tested and improved as additional years satellite derived basin snow-cover data becomes available.

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References

Bowley, C. J., Barnes, J. C., and Rango, A. (1981) Applications Systems Verification and Transfer Project – Satellite Snow-Mapping and Runoff Prediction Handbook, NASA Tech. Paper 1829, Washington, D.C. 87 p.

Dey, B., Moore, H., and Gregory, A. F. (1979a) Snow cover, snowmelt and runoff in the Mackenzie Basin. Proceedings of Canadian Hydrology Symposium on Cold Climate Hydrology, Vancouver, B.C. May 1979 (National Research Council of Canada), pp. 449-60.

Dey, B., Gregory, A. F., and Moore, H. (1979b) Application of satellite images for monitoring snowline in the Yukon and Northwest Territories, *Polar Record 19,* No. 122, pp. 145-154.

Draper, N. R., and Smith, H. (1966) *Applied Regression Analysis,* John Wiley & Sons, Inc., New York, pp. 18-21.

Hawley, M. E., McCuen, R. H., and Rango, A. (1980) Comparison of models for forecasting snowmelt runoff volumes, *Water Resources Bulletin, Am. Water Res. Asso., 6,* No. 5, pp. 914-920.

Leaf, C. F., (1971) Areal snow cover and disposition of snowmelt runoff in Central Colorado, USDA Forest Service, Research Paper RM-66, Fort Collins, Colorado, 19 pp.

Rango, A., Salomonsen, V. V., and Foster, J. L. (1975) Employment of satellite snow cover observations for improving seasonal runoff estimate, in Operational Applications of Satellite Snow Cover Observations, NASA SP-391, Washington, D.C. pp. 157-74.

Rango, A., Salomonson, V. V., and Foster, J. L. (1977) Seasonal streamflow estimation in the Himalayan region employing meteorological satellite snow cover observations, *Water Resources Research, Vol. 13,* pp. 109-12.

Rango, A., and Itten, K. I. (1976) Satellite potentials in snow cover monitoring and runoff prediction, *Nordic Hydrology, Vol. 7,* pp. 209-230.

Rango, A., and Martinec, J. (1979) Application of a snowmelt-runoff model using Landsat data, *Nordic Hydrology, Vol. 10,* pp. 225-38.

Salomonson, V. V., and MacLeod, N. H. (1972) Nimbus hydrological observations over the watersheds of the Niger and Indus Rivers, Fourth Annual Proceedings of Earth Resources Review, NASA Doc. Msc 05937, pp. 5.1-5.11.

Tarar, R. N. (1982) Water resources investigation in Pakistan with the help of Landsat imagery – snow survey, 1975-78, Hydrological Aspects of Alpine and High Mountain Areas (Proceedings of the Exeter Symposium), IAHS Publication No. 138, pp. 177-190.

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Address:
B. Dey and D. C. Goswami,
Department of Geology and Geography,
Howard University,
Washington, DC-20059,
U.S.A.

A. Rango, Hydrology Lab.,
Agricultural Research Service,
USDA,
Beltsville, MD-20705,
U.S.A.