Characterizing Snowmelt Regime of the River Swat - A Case Study

M. A. Malik[1], A. Z. Bhatti[2]

[1,2]Pakistan Council of Research in Water Resources (PCRWR), Islamabad, Pakistan
[1]ma.malik379@hotmail.com

Abstract-Snowmelt generates 70 to 80% of runoff of Indus River and its tributaries. Forecasting snowmelt generated flow is important for water management, reservoir operation and channel diversion. River Swat being not direct contributor to the existing reservoirs remained out of focus for characterizing its snowmelt regime. Thirty years (1971-2000) data of upper Swat catchment above Kalam gauging station was acquired from WAPDA. Normal monthly values over the period and average monthly values of each year were determined for stream flow, precipitation and temperature together with average monthly values of weighted and maximum temperature. Snowmelt regime was ascertained from plot of normal values of flow, precipitation and temperature. Using temperature index approach, average monthly flow over the snowmelt months (April, May and June) in terms of mm depth over the catchment was regressed on all the temperature indices using exponential, power and third degree polynomial functions. T_{max} was found the best index for snowmelt with R^2 as 0.902 for the third degree polynomial function. Runoff coefficient (ROC) for the total precipitation was conceptualized and through iteration was found as $T_{max}/100$. The optimized value of ROC was used to segregate rain induced and snowmelt induced runoff. The segregated snowmelt induced runoff was again regressed on T_{max} using the same function which slightly improved R^2 to 0.916. The model was tested for four years of data and forecasted flow was found reasonable in the context of simplicity of the approach.

Keywords-Snowmelt, Reservoir Operation, Normal Montlhly, Average Monthly

I. Introduction

Water is lifeline of agriculture which is mainstay of the economy of Pakistan. The country has the biggest contiguous irrigation system in the world known as Indus Basin Irrigation System (IBIS), which has it's across border catchments extended to India, and China. Despite having the biggest irrigation system, Pakistan, which once had surplus water, is now rapidly becoming water deficit country. Major portion of the water resources of the country originate from glacial and snow melt in high altitude mountainous catchments. Forecasting flow generated by these catchments is critical to water resources management, water distribution, operational regulation of reservoirs and, planning and management for hydel power generation. For forecasting flow, numerous advanced models are available, but their judicious utility requires comprehensive meteorological data on temporal and spatial scale. Whereas, these catchments, apart from being hard, rugged and high altitude mountainous terrains, are in some cases inaccessible due to security reasons.

Inhospitable mountainous terrain and harsh climatic environment further adds to data collection problems. As such limited data are available that too spatially and/or temporally ill representative of the catchments. Flow forecasting capability from the limited available data and a better understanding of snowmelt-runoff generating physical processes and hydrological regimes of these catchments is, therefore, either missing or limited on temporal and/or spatial scale [i-iii].

The IBIS has several tributaries, which originate from moderate to high altitude mountainous terrains and the river Swat is one of its major tributaries. After originating from Hindukush and having confluence with the river Kabul at Charsada, it drains into the Indus at Attock, from where it will feed the proposed Kalabagh dam. A reservoir, called Munda dam, is being constructed at the River Swat below Chakdarra. Water from the river is also diverted for various hydel power projects in Malakand Agency. Since the river was not an active contributor to the existing reservoirs, study of its flow regime never remained an immediate requirement of the concerned authorities. In the perspective of the under construction and proposed dams, thorough study of the river has become imperative. Moreover, study of Swat sub-basin is critical to the entire IBIS as the flow generated from upper Swat basin involves all the three physical processes, such as glacial melt, seasonal pack melt and runoff from instant precipitation, which are common to the entire IBIS. Characterization of flow regime of the Swat basin will also help towards improving flow forecasting capability of the entire IBIS as it can be considered its representative in terms of physical processes involved.

Objectives of this study are, therefore, to have a better understanding of snowmelt regime and runoff generating processes of mountainous watershed of upper Swat and to investigate linkage of river flow with the available climatic data. The critical objective is to determine whether climatological measurements made at limited weather stations at the base of mountainous watershed provide a suitable representation of basins' meteorological variables for forecasting river flow and to develop a deterministic model for that purpose.

The study area encompasses a watershed of River Swat, which originates from Hindukush range and after passing through Kalam and Mangora it drains near Charsada into the river Kabul, which has its confluence with the river Indus at Attock. Normal annual precipitation as recorded at the Kalam gauging station is 910 mm. The dominant source of precipitation is monsoon and westerlies which contribute 55% and 45% respectively [iv]. Flow is generated from instant precipitation, melting of seasonal snow-pack and glaciers [i]. There are two gauging and weather stations, one at Kalam and the other at Chakdarra. The watershed area above the former gauging station (that pertains to this study) is 2025 sq km, having a mean elevation of 3300 meters with 0.3 percent area above 5000 meters. The sub-basin falls between longitude of 72^{o} 10' to 72^{o} 50' N and latitude of 35^{o} 25' to 35^{o} 55' E. The Kalam sub-basin was chosen because of lying at glacier and snow melt outlet of upper Swat catchment.

II. Techniques and Methods

Different techniques and data processing methods used by the researchers for snowmelt-streamflow relationships of different watersheds have been reviewed in detail containing their pros and cons followed by study site data and processing. Regression analysis of flow on different temperature indices is then carried out. For segregation of snowmelt from direct runoff, a runoff coefficient is conceptualized and applied. At the end before drawing conclusions, forecasted flow is evaluated with the gauged flow to find reasonable correlation.

A. Snowmelt Study Approaches

Snow melt estimation is made either by energy balance approach or by using most representative climatic parameters. In energy balance approach, heat energy input to, or output from, snow through various processes such as net radiation flux, heat gained from air, sensible heat flux through evaporation, condensation or sublimation, rainwater heat flux, ground surface heat flux and change in internal energy is involved. In the index method approach, one or more climatic variables are used in empirical expression to determine snow cover energy exchange and resulting snow melt. Most commonly used climatic parameters for this purpose include air temperature, solar radiation, wind speed, and vapor pressure.

The heat energy balance analysis is the most reliable approach for calculating snowmelt. However comprehensive data for heat balance analysis are rarely available. The heat balance approach thus has inherent limitations. The most commonly data recorded on traditional weather stations are precipitation, daily maximum and minimum temperature, humidity and wind speed. Even on the traditional weather stations the routine data are some times missing [i].

That situation demands most readily available indices that best represent basin values from point measurements in time and space and that best serve to describe the snowmelt process. Temperature index is widely used for that purpose. Incorporation of all energy balance variables obviously improves model output; however average temperature alone has also been reported to be the best predictor, if other parameters are not available [v]. Moreover temperature best represents energy fluxes, and is easily measurable and normally available record [vi] and, therefore, is commonly used as snowmelt index [vi]. Rather it is considered the best snowmelt index as it well reflects various other snowmelt operators such as radiation, humidity, air circulation and snow covered area, because the temperature is either directly, or inversely, related to all those operators. The output of temperature index approach is also comparable to that of energy balance approach, which requires detailed evaluation of multiple variables [vii], [ii].

For temperature index approach, snowmelt rate is considered proportional to air temperature with proportionality factor called the snowmelt factor. Normally daily mean temperature is used for that purpose which is considered average of T_{max} and T_{min}. Daily mean temperature may be misleading where T_{min} drops much below 0 °C, giving mean temperature value less than zero. Under these circumstances, no positive temperature would be available while snowmelt might be going on over some part of the day with above zero temperature, thus giving undue weightage to T_{min}. Due to these reasons, only T_{max} is sometimes used for the purpose and has been reported to be accurate as compared to daily mean temperature [viii], but that procedure entirely excludes effect of T_{min}. A compromising way has been proposed wherein higher weightage is given to T_{max} as compared to T_{min} as given by the equation below [ii].

$$T_{wt} = (2T_{max} + T_{min})/3$$

where T_{wt} is weighted index of temperature.

Correlation of the extent of winter snow-pack and winter precipitation with annual stream discharge of the Kunhar sub-basin of the upper Jhelum basin was

Investigated [iii]. It was found that a strong correlation exists between point measurement of annual maximum of snow-pack water equivalent and of the total winter precipitation (at Kunhar sub-basin) with total annual discharge. Significant correlation was also found between total winter snowfall and annual discharge [iii]. The investigation showed altitude not appearing a strong operator in determining usefulness of snow measurements which was made at the valley bottom. On carrying out multiple regression analysis of point measurements of snow accumulation at various stations with discharge at downstream gauging station, and found significant improvement. It was therefore concluded that despite steep vertical and horizontal gradients of snow accumulation, accessible valley sites in Kunhar basin appeared to be as useful as the remote high elevation sites for gaining an index of basin wide snow accumulation, provided the data were available for more than one site. A limited data was dealt in the study not exceeding more than eight years in any case [iii].

The impact of rainfall on runoff characteristics of glacierized catchments in the Himalayan region was studied [ix]. It was concluded that the monsoonal cloud cover reduced snowmelt in July and August owing to decline in radiation energy input and snowmelt production is not offset by runoff production from liquid precipitation during the monsoon. It was inferred that liquid precipitation falling over glacier, analogous to channel precipitation, joins supraglacial melt-water channels and is ultimately routed to the glacier portal through the glacial drainage network without major losses. As such, runoff coefficients of 1.0 and 0.7 were used for glacierized and non glacierized areas respectively for computing total runoff from the basin. The relationship between daily average temperature and daily total discharge from May-October was also studied. The relationship was found poor with R^2 value of 0.54 which improved to 0.62 with rainfall corrected discharge [ix].

In a detailed study, regression analysis between climatic variables (temperature and precipitation) and stream flow data of fifteen sub-basins of the river Indus was carried out [i]. It was concluded that these sub-basins have different hydrological characteristics depending on their mean altitude, relief and exposure to moisture bearing winds. On the basis of the analysis, summer volumes of these basins were categorized into three major categories:

Thermal control in the current summer: These are the high elevation catchments where summer runoff is generated by melting of glacier and permanent snow predominantly by summer energy input such as in river Hunza, Shigar and Shyok.

Winter and spring precipitation controlled regime: It includes catchments where summer runoff is predominantly controlled by preceding winter and spring season precipitation such as River Astore, Kunhar, Swat and upper Indus.

Current precipitation controlled regimes: These include southern foothill catchments where runoff depends directly on current rainfall such as river Brando, Siran and Khan Khawar.

It was further shown that precipitation measurements at standard valley weather stations can be used as a basis for forecasting volume of flow in winter and spring precipitation controlled regimes [i].

B. Data Source and Processing Technique

Flow and precipitation records of IBIS are maintained by the Surface Hydrology Wing of the Water and Power Development Authority (WAPDA). The authority made available flow, precipitation and temperature data pertaining to Kalam sub-basin from 1971 to 2000. The raw data was in the form of daily values of maximum and minimum temperatures, daily precipitation and daily flow records at Kalam gauging station. The daily maximum and minimum temperature data were converted into mean daily temperatures, from which monthly averages were calculated for each month of the data years. Similarly monthly averages of stream flow and precipitation were determined. From the average monthly values of temperature, precipitation and stream flow, normal monthly values from 30 years data record were calculated and plotted to determine overall data trends. For regression analysis, average monthly values of temperature, precipitation and stream flow for snowmelt months of April, May and June over the period of 1971-1995 were used and the data for the remaining years were used for testing the results thereof.

III. Results and Discussion

Normal monthly temperature, precipitation and stream flow (in terms of mm depth over the catchment) as distributed over the year are presented in Fig. 1. As is evident from the figure, that the flow hydrograph starts rising in the beginning of March, concurrent with the peak normal precipitation, and attains its peak somewhere in June, almost concurrent with, but slightly lagged behind peak normal monthly temperature. Although, the start of flow rise coincides with peak precipitation, but then onward both have entirely opposite trends flow persistently continues rising and precipitation persistently continues declining.

On the other hand, temperature rise starts in the mid of January without any influence on flow regime. That means the rise of temperature in January, without any significant influence on flow regime, merely causes ripening of snow i.e. bringing the temperature of snow profile from below zero to zero Celsius conducive to snowmelt [ii]. A little rising trend in flow at the end of February seems due to its coincidence with peak precipitation. Over the month of March, there is a significant rise in flow but that period also coincides with the period of maximum precipitation, which seems contributing to the flow rise. Pertinent to mention is that proportion of liquid precipitation of the total precipitation might have increased by that time due to rise in temperature. Flow as well as temperature exhibit rise in March, while peak precipitation period still prevails. The peak precipitation seems either have contributed to the flow, or have triggered rain induced snowmelt [x] as temperature rise at the start of snowmelt season is likely to cause only snow ripening instead of snowmelt [ii].

That means snowmelt is unlikely in the early season. Thus the flow rise in the beginning of March may not necessarily be due to commencement of snowmelt but may have substantially been contributed by total precipitation, which by that time might have acquired significant proportion of liquid precipitation at least at low altitude causing its reflection in the stream. All that shows snowmelt does not have necessarily started in March as the initial rise of flow appears to be due to high liquid precipitation in that month or due to rain induced snowmelt.

At the other end of the season, peak of flow coincides with temperature but does not sustain with it, i.e. flow decline starts earlier than the temperature decline. That seems to be due to altitudinal status of the catchment. Mean altitude of the Upper Swat catchment as already stated, is 3400 meter with only 0.14% above 5000 meter [i] which characterize it as the seasonal snowpack dominant catchment. Summer flow is, therefore, contributed mostly by seasonal snowpack-melt with little contribution from glaciers. Seasonal snowpack at medium altitude is likely to exhaust earlier than the catchment dominated by glaciers. Therefore, the flow hydrograph could not maintain its peak with the sustained maximum temperature due to the catchment having exhausted seasonal snowpack.

From March to June, there is almost linear and smooth rise in flow with the corresponding smooth rise in temperature, despite corresponding decline in precipitation, which indicates that snowmelt in upper Swat basin may be relied on from April to June. Further evidence of that will be demonstrated in the further analysis in the coming paragraphs.

Normal annual precipitation and normal annual flow with yearly fluctuations over thirty years period (1970 -2000) are shown in Fig. 2. The Figure indicates that the total annual flow directly responds to the total annual precipitation, but 30 years normal flow and precipitation exhibit significant difference.

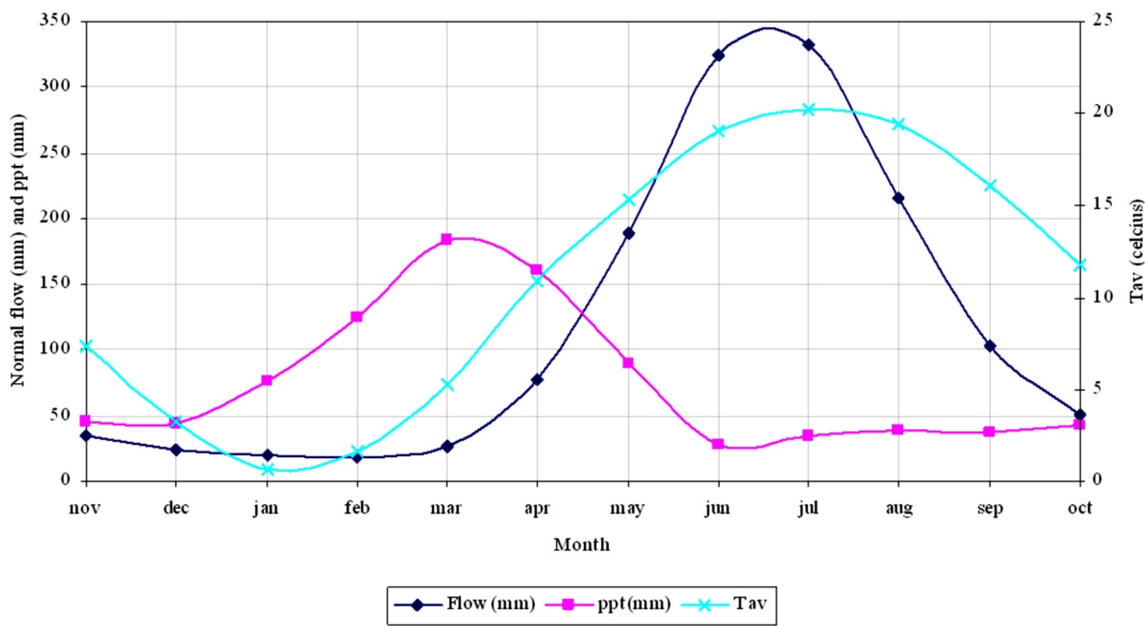


Fig. 1. Normal monthly temperature, precipitation, and flow (in terms of mm depth over the catchment) as measured at Kalam gauging and weather station Swat over 1971-2000.

The upper Swat river flow as recorded at Kalam (in terms of mm depth over the catchment) is 1339 mm against the recorded precipitation which is only 910 mm, meaning thereby that the recorded precipitation grossly underestimate catchment precipitation. The reason is obviously spatial distribution of precipitation over the catchment. In mountainous watersheds, both spatial and altitudinal precipitation distribution are always significant because of high relief, altitudinal variation and air currents turbulence. Snow or rain, therefore, indicates neither same pattern of variation with altitude, nor linear relationship exists for that. For some basins precipitation increases with altitude continuously, while for others, it first increases to certain altitude and then starts declining [ii]. Since the instant flow regime pertains to snowmelt which comes from relatively high altitude, that means precipitation (obviously in snow form) at high altitude would have been more than that recorded at the bottom of the valley.

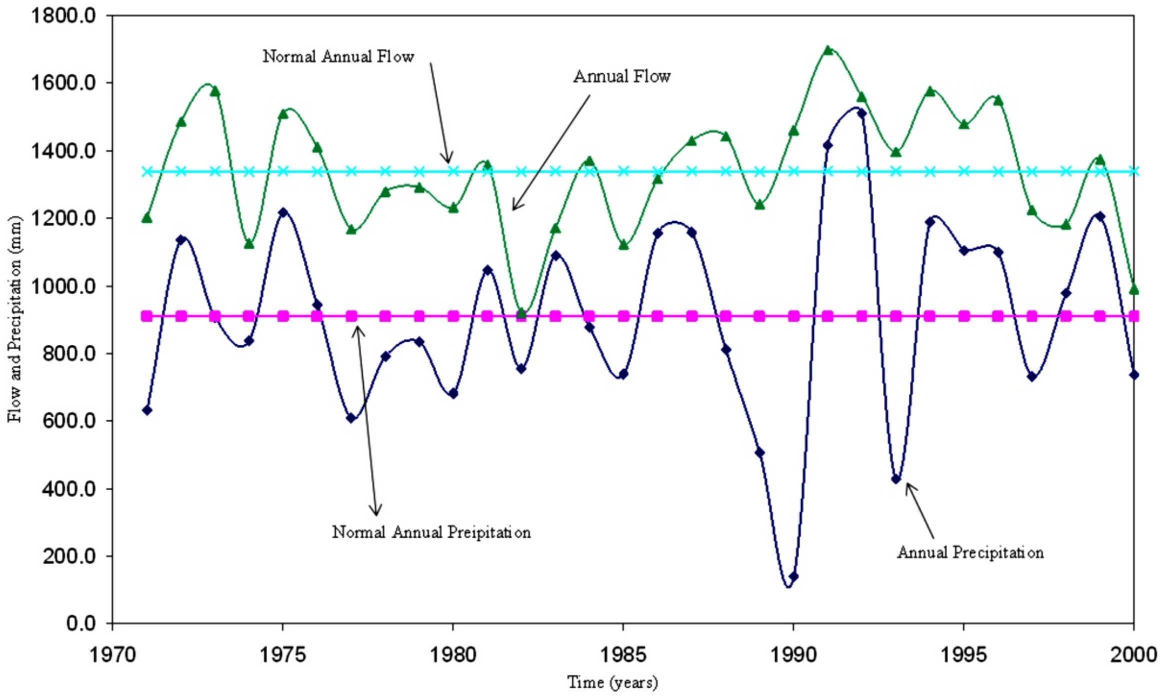


Fig. 2. Annual and normal annual flow and precipitation of 30 years (1971-2000)

An alternate explanation might be that the excess flow might have been coming as ground flow leakage from adjacent basins. Both the factors might be working simultaneously, but spatial distribution and the vertical precipitation gradient seem significant in the instant case, owing to the gauging station located at the bottom of the valley near the outlet of the catchment. Horizontal spatial distribution as well as the vertical precipitation gradient is therefore considered responsible for difference in recorded precipitation data and the river flow. That variation is required to be taken into account in the flow forecasting models.

Regression Analysis

For regression analysis, all the three temperatures based indices *i.e.* average monthly temperature (T_{av}) based on the daily maximum and minimum readings, average monthly maximum temperature (T_{max}) and weighted monthly temperature ($T_{wtd}= (2T_{max}+T_{min})/3$) were used. Keeping in view the snowmelt season as discussed before, monthly average flow (mm depth over the catchment) records for April, May and June of each year over the period 1971 to 1995 were regressed on each of the three temperature indices. It is pertinent to mention that when the data including any of the months before or after April, May and June were included, coefficient of determination was found persistently less than that pertaining to the said three months. As such the data pertaining to the said three months were used for regression. For regression of flow on the temperature index, 2nd degree polynomial, 3rd degree polynomial, power function and exponential functions were fitted to the data. Results of the regression analysis of these functions regressed on temperature indices are presented in Table I.

TABLE I
RESULTS OF 25 YEARS RIVER FLOW REGRESSED ON CATCHMENTS TEMPERATURE BASED SNOWMELT INDICES

variable	Function fitted with flow depth (mm) as dependent variable and corresponding R^2			
	2nd degree polynomial function	3rd degree polynomial function	Exponen -tial function	Power function
T_{av}	0.8697	0.8912	0.8774	0.8786
T_{wtd}	0.8874	0.8955	0.8817	0.8787
T_{max}	0.8993	0.9016	0.8734	0.8659

The results of regression analysis demonstrate that the temperature index in its all the three forms (T_{av}, T_{wtd}, T_{max}) yields comparable results when stream flow is regressed on any one of its forms. Regarding the regression function fitted, the polynomial function was found giving the best and further the third degree polynomial function came out with the highest value of coefficient of determination (R^2 = 0.9016). The function giving the highest value of R^2 was selected as the best representing the river flow verses average maximum monthly temperature and is given below:

$$Y = -0.086X^3 + 6.907X^2 - 149.4X + 1027.4$$

where

Y= monthly river flow as mm depth over the catchment.

X= average maximum monthly temperature (^oC).

The graphic presentation of the best fitted third degree polynomial expression for monthly flow regressed on mean monthly maximum temperature is shown as solid blue line in Fig. 4. The fitted line, of course, includes runoff due to snowmelt as well as precipitation. The figure also shows scatter plot of the corresponding precipitation data for the sake of background input reference.

After regression of flow data on the temperature index (mean monthly maximum temperature in our case), the most critical question was to segregate direct runoff resulting from liquid precipitation to that from melting of solid precipitation (snowmelt). It is evident from the figure that in the beginning of the season precipitation is high which gradually and almost linearly decreases towards end of the season. In the beginning of snowmelt season a substantial proportion, or all of the recorded precipitation, would be in solid form (snow) due to low temperature especially at high altitudinal bands. As the temperature increases with advancement of melt season, the proportion of solid precipitation goes on gradually decreasing, and it is more than likely that at the peak melt season almost the entire precipitation would be in liquid form at almost all the altitudinal bands. especially in the catchment under consideration having moderately high altitude. Now the following factors operate for determining runoff coefficient (ROC) from liquid precipitation.

ROC will increase with increase in temperature due to greater proportion coming up in liquid form.

ROC will decrease with increase in temperature due to decline in snow covered area as liquid precipitation on snow surface is considered equivalent to channel precipitation [ix].

Now the above three variables are simultaneously affecting the ROC in somewhat opposite directions; two of those are causing a decrease in ROC whereas the third one causing an increase. What will be the net affect is uncertain. The ROC will obviously be determined by the fraction of liquid precipitation, but as yet the fraction of total precipitation in liquid form is not known. However, the parameters (overall precipitation and temperature) affecting the runoff coefficient are likely to counteract, but neither in equal nor in known proportion. Which parameter would have more effect on runoff coefficient, remains the most critical question. To decide the runoff coefficient for segregation of snowmelt and direct runoff was thus a bit tedious job. Under these conditions, a trade off might work. As such, for segregation of snowmelt runoff from liquid precipitation induced direct run off, it was assumed that runoff coefficient was directly proportional to temperature index (average T_{max} in the instant case). That is based on the concept that with rise in temperature fraction of liquid precipitation out of total precipitation goes on increasing in a pattern as conceptually elaborated in the Fig. 3.

The Figure is based on average T_{max} and precipitation over the snowmelt months of April, May and June. As depicted in the diagram, at low temperature (start of the melt season) total precipitation is high and liquid precipitation is low or zero. With rise in temperature, total precipitation is decreasing at higher rate and so is its solid precipitation part, but liquid precipitation is increasing at lower rate due to overall decrease in total precipitation. That makes liquid precipitation line almost parallel to temperature line. However, liquid precipitation is unknown yet, but the line almost parallel to it, temperature line, is known. That concept tempted these authors to assume runoff coefficient proportional to temperature for the catchment under consideration. Thus runoff coefficient may be taken as directly proportional to temperature index. Taking that assumption into account, we assumed runoff coefficient as:

$$ROC = K * T_{max} \text{(monthly average)}$$

where

ROC= runoff coefficient

T_{max}= average maximum monthly temperature

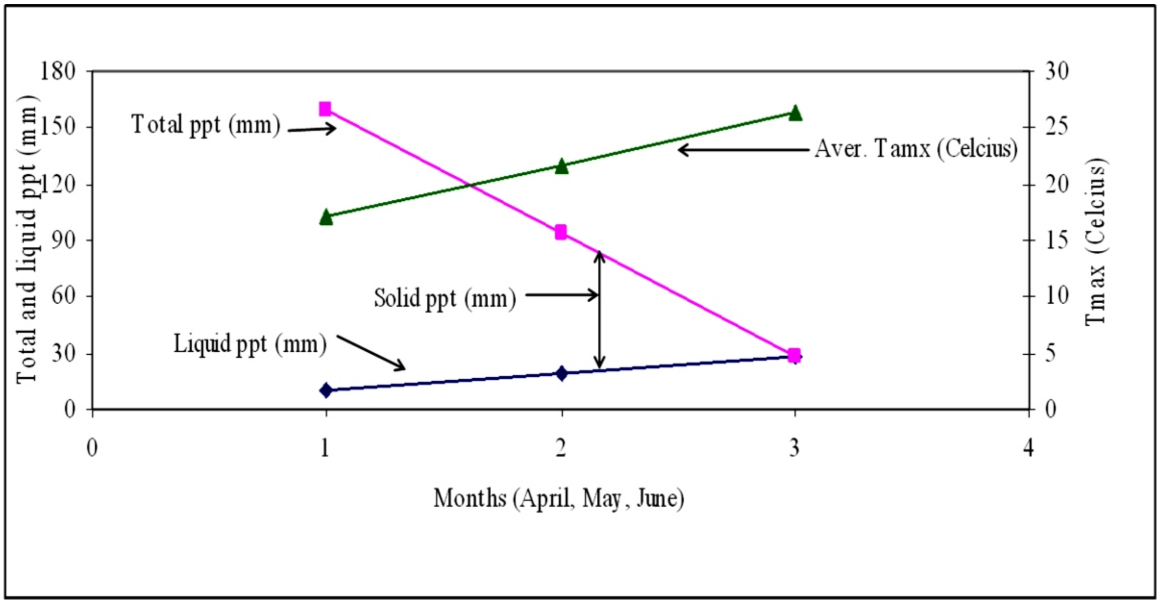


Fig. 3. Conceptual segregation of total precipitation into liquid and solid parts and variation with temperature

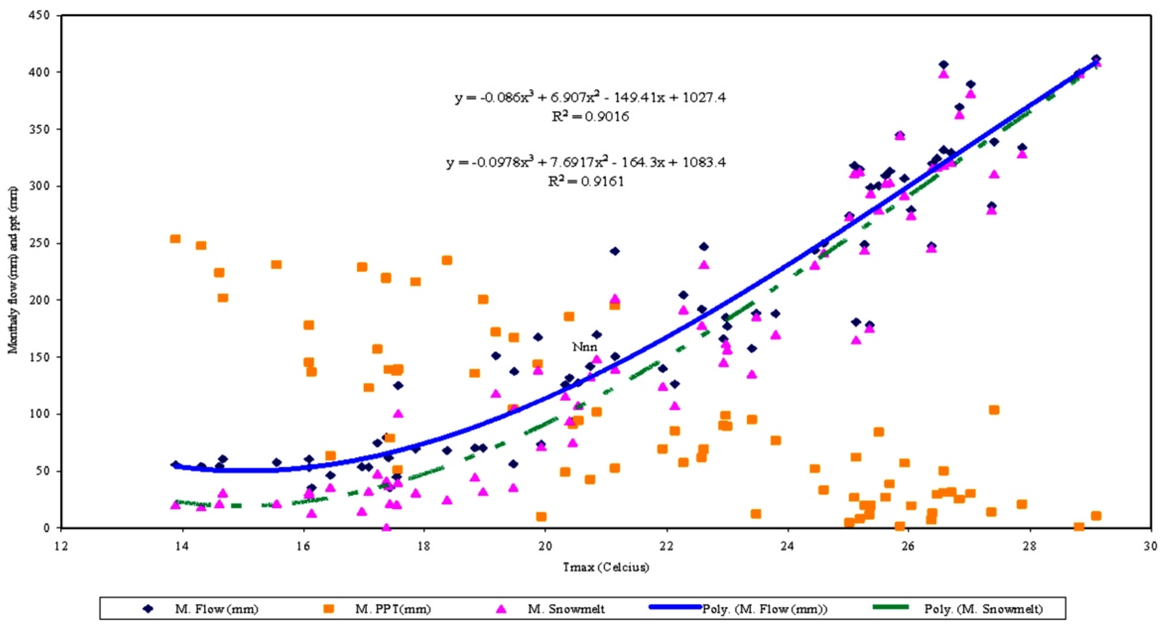


Fig. 4. River monthly flow and snowmelt (in terms of mm depth over catchment) vs. Average maximum monthly temperature (1971 to 95)

Using the so optimized value of K, which came out 1/100 in our case, direct runoff from total precipitation was deducted from stream flow and the resulting snowmelt was determined as per formula below:

Snowmelt = Total flow Precipitation x ROC

where, ROC = $K \times T_{max}$

The snow melt runoff so derived was again regressed on the maximum mean monthly temperature index. It was assumed that by applying the runoff coefficient and subtracting the resulting runoff from stream flow should reduce the river flow scatter around the regression line and should accordingly improve the coefficient of determination (R^2). At the same time the optimized runoff coefficient should not bring the winter minimum flow to zero level, in any of the data years. Accordingly through iteration, the fraction of temperature index ($T_{max}/100$) was considered as runoff coefficient for which the derived snowmelt gave best fit against the temperature index. The best fit line so derived is shown as a dotted green line in Fig. 4. As is also shown in the figure that with the incorporation of the so assumed runoff coefficient, R^2 value of the third degree polynomial function improved from 0.9016 to 0.9161. This improvement in the value of R^2 appears very nominal, but it happens so when R^2 is in the range of 0.90, where an analogy of law of diminishing returns applies. Even if it is considered no improvement in the R^2 value of the fitted function, that does not discredit the method used for segregation of the snowmelt runoff from stream flow.

The trend of the segregation is as expected. In the beginning of the snowmelt season, precipitation is high and although liquid precipitation proportion will be less but overall liquid precipitation amount will be high, as such the corresponding direct runoff is high. As the season advances, precipitation goes on decreasing and difference between snowmelt and direct runoff goes on decreasing and ultimately entire runoff becomes snowmelt runoff.

The model so developed for snowmelt runoff was used, incorporating direct runoff contribution from liquid precipitation accordingly, for flow forecasting and compared it with available flow data for years 1996 to 1999. The actual and forecasted flows are shown in the Figures 5-8.

The forecasted vs. actual flow results for the three summer months of April to June appear promising. These results are required to be seen in the perspective that a single climatic parameter, i.e. temperature index, was used for snowmelt forecasting, whereas snowmelt, in fact depends on multiple climatic parameters such as solar radiation, wind and humidity apart from air temperature. But, the record of all those climatic variables is lacking in the high altitude mountainous basins and one has to rely on the only available climatic variable i.e. temperature index.

The values of the unavailable climatic variable do not vary as smoothly as the temperature index and day to day drastic variation of other parameters and especially of wind speed may cause a lot of day to day variation in snowmelt factor. Thus a lot of scatter in snowmelt may go unaccounted for when only a single climatic variable is taken for snowmelt prediction. Nevertheless, the results indicate that the temperature index can be relied on for snowmelt prediction when other data is lacking for application of comprehensive snowmelt model.

Figure 5. Forecasted flow vs measured flow over April, May and June 1996

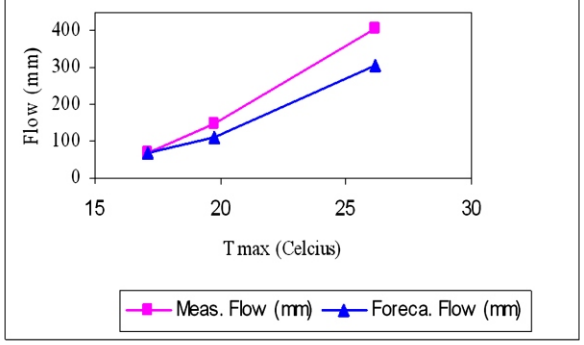


Figure 6. Forecasted flow vs measured flow over April, May and June 1997

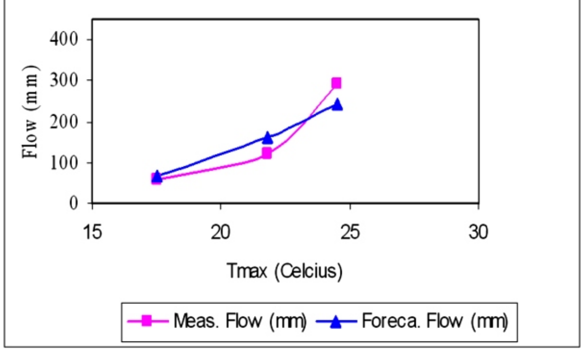


Figure 7. Forecasted flow vs measured flow over April, May and June 1998

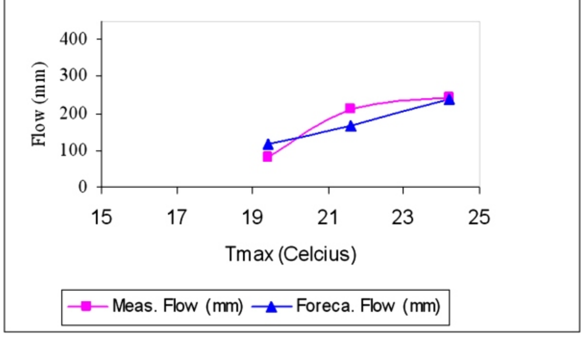
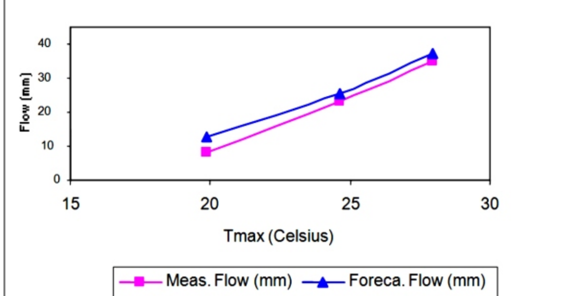


Figure 8. Forecasted flow vs. measured flow over April, May and June 1999



IV. CONCLUSIONS

That the snowmelt season in upper Swat catchment is normally expanded over three summer months of April, May and June.

That the temperature index, if other climatic variables and snow accumulation parameters are not available, can give reasonable estimation of snowmelt.

That the snowmelt have significant correlation with all the three temperature indices, but maximum temperature index comparatively better describe snowmelt at least in the catchment under consideration.

That the precipitation data recorded at the valley bottom, though underestimate overall precipitation (liquid plus solid precipitation), can be useful for segregation of snowmelt and direct runoff.

That the runoff coefficient for mixed precipitation (liquid plus solid precipitation) is directly related to some fraction of temperature index. In the instant case it was found hundredth of average maximum monthly temperature.

That regression analysis of twenty five years snowmelt data on mean monthly maximum temperature yielded a good third degree polynomial fit with R^2=0.916.

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