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The role of environmental parameter (degree day) of snowmelt runoff simulation

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Abstract

The upper Indus basin comprises the high mountains covered with snow and glaciers. So the major portion of flow from Indus basin is due to snow and glacier melt runoff. The terrain is difficult to measure the hydrological and hydraulics data. Most of the data is available at catchments outlets. Due to the data constraints Snowmelt Runoff Model (SRM) was used to estimate the snow melt runoff in Astor basin during, year 2000. The input data included daily temperature, precipitation and division of catchment in to different zones on the basis of elevation difference. The elevation zones were made from the Digital Elevation Model (DEM) of the area. The snow depletion curves were made by Landsat TM satellite data analysis on the monthly basis. The model output was discharge hydrograph. The model performance was tested by calculating the statistical parameters such as coefficient of efficiency (COE) and volume difference in percentage. The COE for simulation was 0.91 which illustrates a good relationship between simulated and measured values of runoff. The volume difference (Dv) for simulation was 9.01. The statistical test showed that model performance was good. The results of SRM model encouraged to use temperature index approach for snowmelt runoff estimation in Indus basin.

Keywords: *Indus basin, landsat, runoff simulation, temperature index, digital elevation model*

Introduction

The models based on temperature index (TI) approach are also known as degree-day models. These models are more simplified as compared to the energy balance in form of data requirement and computation. The temperature index models physically lump all the components of the surface energy balance into a degree-day melt factor. The degree day melt factor is a proportionality coefficient that calculates melt rates on the basis of air temperature (normally in excess of some threshold value) alone. Several operational models used to estimate snowmelt runoff from mountainous area are based on temperature index approach, including the Snowmelt Runoff Model (SRM) (Martinec, 1975; current version described Martinec *et al.*, 2005) and HBV (Bergstrom, 1975). They have also been used extensively as research tools to investigate snowmelt runoff and mass balance on glaciers (Lang, 1986; Arendt and Sharp, 1999; Laumann and Reeh, 1993; Singh *et al.*, 2000; Braithwaite, 1995; Braithwaite and Zhang, 2000).

Most temperature index models operate on a daily time step, which eliminates the need to simulate snowpack process that operates on sub-daily timescales, such as diurnal variations in meltwater flux and surface refreezing. The main advantage of temperature index approach is that the data requirements may be limited to as little as average daily air temperatures, the most easily measured and widely available meteorological variable.

By applying temperature index method, a snow melt runoff estimation model was developed by Martinec (1975) for smaller catchments in European countries. Due to spatial data problems at larger scale catchment the remotely sensed data was used by Rango (1983) for calculating the area coved by snow at different time and watersheds. It is difficult to differentiate between the snow and cloud while analyzing the satellite data, because most of the time snow and cloud give the similar reflectance of the electromagnetic radiations. To overcome this problem Dozier and Frew (1990) studied that band 5 having wave length (1.57-1.78 μm) of Landsat satellite can be used for differentiating clouds and snow. The snowmelt runoff has major contribution to the Indus basin. So, the snowmelt runoff is of great concern for assessment and planning of water resources in Indus basin. It is very much important to know the aerial distribution of snow and ice to access that how much water is stored in form of snow. The measurement of snow extent and depth are difficult, because of its variation from point to point, especially in the mountainous regions (Najafzadeh, 2004).

The emissivity of radiation is used for snow cover estimation Griggs (1968) studied that snow covered and

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non snow covered areas have emissivity values 99% and 95%, respectively. The degree day factor is used for estimation of area melted with different temperature at different days; this is called the degree day factor. The clear snow and dust covered snow have different values of degree day. Singh *et al.* (2000) studied that catchment at high altitude above 4000 m. They calculated degree day factor 5.7 mm/ºC/day for dust covered snow and 6.4 mm/ºC/day for dust free snow. Similarly, for dust free ice and dust covered ice values were 8.45.7 mm/ºC/day and 7.45.7 mm/ºC/day, respectively. There was 9 to 12% increase in snowmelt factor due to the presence of dust layer on the snow and ice. Nabi (2009) studied the phenomena for snowmelt runoff in Indus basin. He applied the SRM model on different sub-catchments where the major flow contribution was due to snow and glacier melt runoff.

The Astor river catchment in Northern areas of Pakistan was selected for this study. The SRM model was used for calculation of discharge of Astor river due to snowmelt. The discharges are measured at Doyian rim station. It is the outlet of Astor river catchment. The input data used in the model include topographic data (spatial data) and meteorological data (temporal data). The topographic data were topographic information such as digital elevation model (DEM), landuse and vegetation cover. The temporal data included precipitation, minimum and maximum temperature and solar radiation.

The study was focused on estimation of snow covered areas by analyzing the satellite data, development of snow depletion curves for different timescale, and calculation of discharge of Astor river using SRM model.

Study area

The Astor River basin is located in northern areas of Pakistan. The geographic location 34º,45' to 35º,38' N latitude and 74º,24' to 75º, 14' E, longitude. The area is covered with high mountains. The elevation varies from 1,200 m to 7,500 m above mean sea level. The high peaks such as Nanga Parbat are located near this catchment. The total area of catchment is 4,214 km^2 with 607 km^2 glaciated area (NARC, 2005).

The digital elevation model is the basic data required for GIS analysis of the catchment. The spatial resolution of the DEM was 90 m. The spatial information, slope, stream network, and elevation zones were derived from the DEM. The other data related to landuse, and vegetation cover were estimated by analyzing the remote sensing data. The digital elevation model, stream network, and snow cover area of Astor basin is shown in Figure 1.

Materials and Methods

Description of model

The mathematical models are used for rainfall runoff modeling. The mathematical modeling comprises empirical, physically based and conceptual models, which are used in different problems. Nabi et al., (2008) used empirical approach for assessment of soil erosion in Soan river catchment. Similarly Jabeen and Ahmed (2009) have used multivariate approach for analysis of environmental parameters for Rawalpindi. The SRM is conceptual, deterministic model commonly used for simulation and forecasting daily rainfall and snow-melt runoff in the mountainous catchment developed by Martinec (1975). Initially the model was developed for small basins. Due to easy availability of satellite data for snow cover estimation for larger catchments, it is possible that SRM model can be applied to large basins.

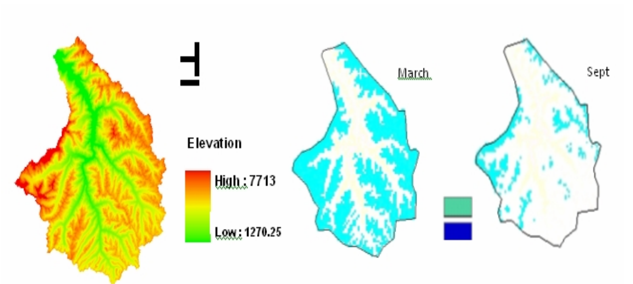

Figure 1: Digital Elevation Model and snow cover area of Astor Catchment

The model was applied to Ganges River basin, which has an area of area of 917,444 km^2 and elevation up to 8,840 m.a.s.l. (meter above sea level). SRM model has been applied at 112 different catchments worldwide (SRM, user manual). In general, SRM model can be applied to spatial and temporal scale. Runoff computations by SRM come out to be relatively easily understood.

In SRM model discharge from rainfall and snow melting is calculated on daily basis. The basic equation of the model is as under:

$$Q_{n+1} = [Csn.a_n(T_n + \Delta T_n)S_n + C_{Rn}P_n]\frac{A*10000}{86400}(1 - K_{n+1}) + Q_n K_{n+1} \quad \textbf{(1)}$$

Q = discharge (m^3/sec), c = discharge coefficient, *a* =degree-day constant (cm /C^o/day), T = number of degree-days (C^o /day), S = snow area, P = daily rainfall (ppt), A = area (km^2), k = recession coefficient, k = m, m+1 are the sequence of days during a true recession flow period, n = sequence of days. The detail values and other characteristics of the parameters used in equation (1) are mentioned in Martinec *et al*. (2005).

Accuracy criteria

Generally the results of the model are verified by comparison between the computed and measured discharge. The computed and measured discharges were plotted. The computed and measured graphs matched well with each other. Apart from the visual observation, the model accuracy can also be checked by statistical parameters. SRM model used two other accuracy criteria based on the statistical coefficients; one is coefficient of determination (R^2) and second is volume difference (D_v). The equations for R^2 and D_v are as under.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_i - Q_i^{'})^2}{\sum_{i=1}^{n} (Q_i - \bar{Q})^2} \qquad (2)$$

Where: Q_i , $Q_i^{'}$ are observed and simulated discharge while $\bar{Q}$ is average observed discharge. The deviation of runoff volumes, D_v is computed as follows:

$$D_v[\%] = \frac{V_R - V_R^{'}}{V_R} * 100 \qquad (3)$$

Where: V_R is simulated volume, V'_R is observed volume

Input data for setting up the model

Temperature data

Temperature forms the basis of energy balance computation. The snowmelt and glacier melting are influenced by energy balance using the temperature as melting parameter. In Astor catchment, temperature and precipitation data are measured by metrological department at Astor town, whereas the discharge and sediment are measured by WAPDA (2000) at Doyian. Since temperature varies with elevation, therefore, temperature elevation relationship helps to estimate the temperature at the unmeasured locations. Temperature used for calibration was from October, 2000 to September, 2001 of Astor and Rama stations situated inside the study area. The relationship was calculated on daily basis. Eight stations were selected to develop temperature laps relations. The elevations of the station varied from 615 m to 2341 m as shown in Figure 2.

The temperature values were not available at different elevation in the basin. The interpolation was done to generate the missing values. The relation between elevation and daily average temperature was developed for different stations as given in Figure 3. Temperature laps rate estimated from the above Figure 3 was 8.5 ^oC km^{-1}. The mean temperature laps rate for Himalaya region is about 6.5 ^oC km^{-1}. Different temperature laps rates are found for minimum maximum and mean temperatures. These values vary with altitude and time as well. Singh (1991) found average laps rate of 9.42, 7.42 and 8.45 ^oC km^{-1} for the station elevation variation from 1066 m to 2336 m in Western Himalayas.

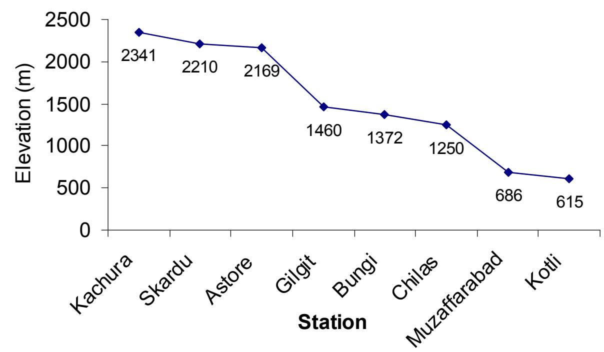

Figure 2: Stations used for Temperature-Altitude relationship

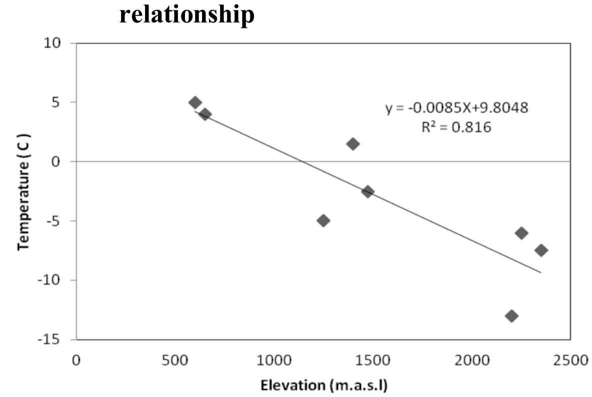

Figure 3: Relationship between average daily minimum temperature and Altitude

The snow and glacier melt mainly depend on the temperature. The temperature and discharge data was collected from Surface Water Hydrology Project (SWHP) from 1992 to 2000. The correlation between temperature and discharge was developed as shown in Table 1**.**

In Table 1, Q is the discharge in cusecs and X is maximum daily temperature in centigrade. It is clear from the above table that temperature and discharge have good correlation for different years. The correlation coefficient R^2 varied from 0.7 to 0.81. The correlation coefficient reveals that temperature is the main parameter for snow melt runoff in Astor basin. It is also supportive that temperature index approach can successfully be used for Snowmelt Runoff Modeling. The same was conformed by application of SRM model to Astor basin, which s based on temperature index approach.

Table 1: Temperature discharge rating equations for Astor catchment for different years

Year	Rating Equation	R^2
1992	$Q = 26.39e^{0.0938x}$	0.81
1993	$Q = 25.98e^{0.0857x}$	0.77
1994	$Q = 30.27e^{0.0839x}$	0.78
1995	$Q = 34.46e^{0.0738x}$	0.70
1996	$Q = 21.09e^{0.1038x}$	0.71
1997	$Q = 20.08e^{0.073x}$	0.75
1998	$Q = 19.30e^{0.089x}$	0.74
1999	$Q = 19.95e^{0.094x}$	0.76
2000	$Q = 22.30e^{0.075x}$	0.74
2001	$Q = 20.59e^{0.095x}$	0.84
2002	$Q = 18.35e^{0.081x}$	0.69
2003	$Q = 22.30e^{0.055x}$	0.73
2004	$Q = 21.30e^{0.075x}$	0.74
2005	$Q = 27.10e^{0.095x}$	0.80

Determination of elevation zones

The Digital Elevation Model (DEM) was used for topographic information. The resolution of DEM was 90 m grid. The elevation varied from 1270 m to 7713 m. The study area was divided in five sub areas with elevation interval of about 1300 m. For this purpose, DEM was reclassified into five different elevation zones starting from 1389 m with 500 m interval up to 7861 m. The area under each division of elevation is presented in Table 2. The zonal mean elevation was calculated for each zone. The area elevation curve for Astor catchment was drawn as shown in Figure 4.

Table 2: Catchment areas under different Elevation Zones

Zone	Area (km^2)	Cumulative Area (km^2)	Elevation (m.a.s.l)	% of Total Area
1	429	429	1389	10.16
2	856	1285	3779	20.28
3	1249	2534	4323	29.59
4	1200	3734	5157	28.43
5	487	4221	7861	11.54

Snow depletion curves

The simulation of Astor catchment was done for year 2000. The input data included the daily rainfall, minimum and maximum temperatures and catchment area under different zones. The elevation varied from 1270.25 m to 7713 m, so, the whole catchment was divided into five elevation zones. In mountainous catchment, aerial extents of snow cover varied at different elevations. At higher elevation, there is permanent snow cover called glacier. The snow depletion curve is made from periodical snow area estimation, from which snow depletion rate can be calculated. For this purpose, the monthly Landsat TM data was downloaded for year 2000 and 2001. About ten images were analyzed .The cost of fresh image is 550 US$ per image, that is why the old data was used which was relatively cheaper. The supervise classification technique was used for snow cover mapping for each month. The snow cover maps for each month were prepared for each elevation zone. The snow depletion curves were made for each elevation zone from March to September as shown in Figure 5.

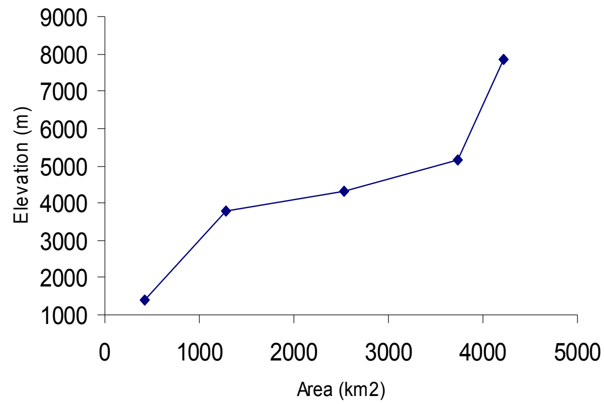

Figure 4: Area Elevation Curve of Astor Catchment

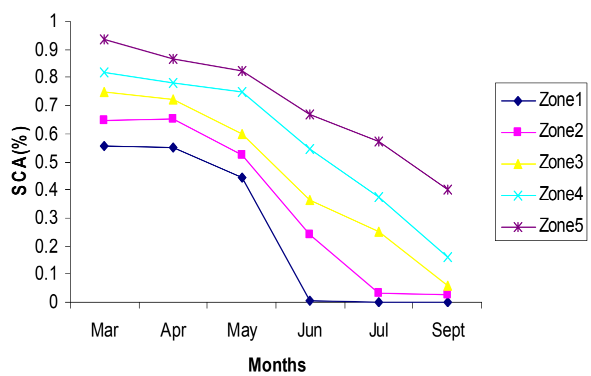

Figure 5: Snow Depletion Curve for different Area of the Astor Basin, SCA is snow covered area in (%)

The Figure 5 shows the percentage of snow cover area in different months and different zones. It is clear from the above figure that almost all the snow melts up to September in zone 1 to zone 4, whereas in zone five some of the snow remains un-melted that is called permanent snow or glacier.

Precipitation data

The precipitation was measured at metrological station usually located at lower elevation of the catchment. The precipitation in mountainous areas is not uniform with intensity and extents. Precipitation data for 2000 was used in model calibration. The daily average temperature, observed discharges and rainfall data are presented in Figure 6.

Along with the topographic, metrological and hydrologic parameters, a number of input parameters are required for SRM model for snow melt simulation. The default values of these parameters are given in the model. The values of the parameters were changed according to the local conditions. The detail descriptions of these parameters are given in SRM User manual. The parameters values used for the Astor catchment are given in Table 3.

Table 3: Parameter values used for Astor Catchments for year 2000 simulation

Parameter	Range
Recession coefficient	x = 1.118, y = 0.015
Time lag	18 h
Critical temperature	0.75 - 3°C
Runoff coefficient for snow	0.6 – 0.85
Runoff coefficient for rain	0.6 – 0.95
Degree-day factor	0.3 – 0.75
Rainfall contributing area	0 (May – Sept.)
Reference elevation	1270 m
Temperature laps rate	0.6°C/100 m
Precipitation laps rate	3.5 mm
Initial discharge	30 m^3/sec

Results and Discussion

Simulation by SRM model

The model output was compared with the snowmelt discharge for the year 2000. The comparison between the observed and calculated discharge is shown in Figure 7.

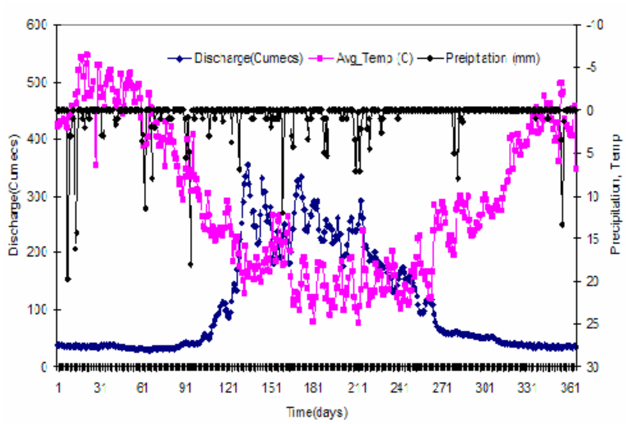

Figure 6: Daily rainfall, temperature and discharge for Astor Catchment

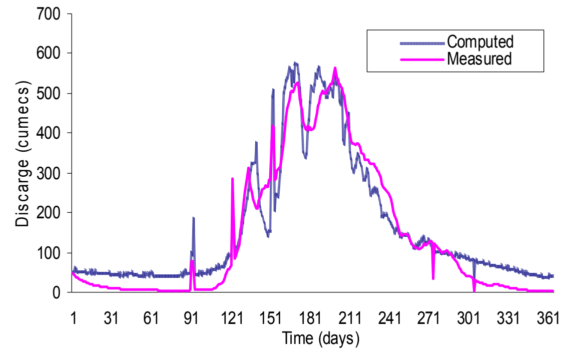

Figure 7: Comparisons between measured and computed discharges

The statistical criterion for evaluation of goodness of fit between observed and calculated values was applied. Coefficient of model efficiency (COE) was calculated (Nash and Suteliff, 1970) as described in Equation (1). The COE for simulation was 0.91 which shows a good correlation between the observed and calculated values. Another indicator, volume difference ratio, D_v was calculated as given in equation (2). The D_v value becomes zero when the observed and model values are very much close to each other. The D_v value for simulation run was 9.01. The statistical test showed that model performance is satisfactory. The results of the study confirmed the use of temperature approach for estimation of snowmelt runoff in Astor catchment covered with snow and glacier.

Conclusion

The snow cover mapping using the remote sensing data is very efficient technique for catchment having difficult terrain and large areas. The snow cover area for different elevation zones was used for derivation of snow depletion curve for upper Indus catchments. For estimation of the snowmelt runoff the temperature index approach along with the remote sensing data can be successfully applied to the upper Indus basin for glacier and snowmelt simulation. The Snowmelt Runoff Model (SRM) was applied to the Astor basin and the model efficiency was 0.96. The satellite data is expensive at present; more data should be purchased to develop the snow depletion cover for other years. In this way, it may be possible to have a generalized snow depletion curve for better estimation of runoff.

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