# DEGREE DAY FACTOR MODELS FOR FORECASTING THE SNOWMELT RUNOFF FOR NARAN WATERSHED

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***ABSTRACT**: Hydrological flow forecasting used precipitation-runoff modeling in order to predict flow from anticipated precipitation events which included rainfall, snowmelt and groundwater runoff. Modeling of snowmelt process becomes important for catchments where the major portion of the flow originated from snow or glaciers. Several snowmelt runoff models were available which either used temperature index or energy based approaches. Snowmelt Runoff Model (SRM) used the temperature as a key index for Degree Day Factor (DDF). Present study was focused on the development of DDFs for Naran watershed along River Kunhar. DDF had been a calibrating parameter for snowmelt runoff Models which was a factor of temperature. Instant information was needed prior to the calibration about the DDFs values for a particular climatic and physiographic condition of the watershed. Hence, there was a need to develop DDF values as a function of aforesaid parameter. This study intended to develop such relationships. Degree day factors were developed using the Time step and Z-curve approaches. A new equation with the combination of temperature and elevation had also been developed to compute the degree day factors. Developed equation was tested with the observed data and the results showed promising match between the observed and simulated flows. The developed equation of DDF recommended for the watershed having similar hydro-meteorological characteristics.*

**Keywords:** Degree day factor, Snowmelt runoff modelling; Naran watershed; Time Step; Z-curve

## INTRODUCTION

Snowmelt runoff modelling is an important tool nowadays especially for the countries like Pakistan where the reservoirs mostly receive water from snowmelt, glacier melt and rainfall runoff. Two commonly used strategies in modeling snowmelt are the energy balance and temperature-index methods. Both methods have been used extensively. The main advantages of temperature-index method are its simplicity, wide-availability of air temperature data and the computational efficiency in calibration and simulation. Energy balance models are often not practicable due to large data requirements and uncertainties about spatial variability of data. Hence, due to good performance, low data requirements and simplicity, temperature-index methods are usually used for snowmelt modelling.

The degree day factor (DDF) is not constant, and changes in response to changing snow properties and atmospheric conditions. Researches & Modelers like [2,5,12,14,15,16 respectively] have used the temperature index approach but there is no general relationship that can describe a criterion, how to select the degree day factors for snow fed catchments. The general recommended range of degree day factor is from 0.01 to 0.99 cm $^{o}C^{-1}day^{-1}$, which is very large. There is a need to develop correlations from available observed data to get the reliable degree day factors in order to guide the modelers for the better snowmelt runoff forecasting.

The degree day is a unit expressing the amount of heat in terms of persistence of temperature for 24-hours period of one degree centigrade departure from a reference temperature [16].

The degree day factor indicates the decreases of water content in the snow cover caused by increase of 1-Degree Centigrade above freezing in 24-Hours. It is a ratio of water content difference and of degree days. The unit for DDF is cm.$^{o}C^{-1}$.$day^{-1}$ [11].

The empirical formula to determine the DDF is given as under:

$$DDF = \frac{Density\ of\ Snow}{Density\ of\ Water} \quad (1)$$

[11] pointed out that the values of DDF are growing in the course of winter, probably in accordance with the raising density of snow.

[1] Suggest some techniques and values for the DDF for the Beas Catchment.

The proposed melt equation is as under

$$M = a(T_{max}) \quad (2)$$

Where, "a" is degree day factor and "$T_{max}$" is the maximum daily temperature. The main assumption in the proposed equation is that snow line follows elevation contours. [10] also gave an equation about the restricted degree day radiation balance approach.

$$M = r(T_d) + (m_Q)R \quad (3)$$

Where, M is snowmelt (cm $day^{-1}$), r is constant restricted DDF (cm $day^{-1}$ $^{o}C^{-1}$) its range is 0.20 and 0.25 cm $day^{-1}$ $^{o}C^{-1}$, $T_d$ is degree days ($^{o}$C), $m_Q$ is physical constant converting the Radiation to Snow water equivalent [0.026 cm day-1(W $m^{-2})^{-1}$] and R is net radiation in (W $m^{-2}$).

[8] suggest that the DDF changes as the physical properties of snow changes over time. The albedo or reflectivity of a snow pack decreases as the snow settles and becomes denser. With more radiation absorbed by a ripe pack, melting takes place at higher rate.

[7] suggested that by applying a separate calculation of snowmelt and ice melt as appropriate Degree Day Factor (DDF) for snow cover and for exposed ice, the accuracy of Runoff Modeling in Glacierized Catchments can be improved.

[13] observed that days near the end of the melt season also give very low Degree Day Factors probably due to incomplete snow cover on the snow pillow.

[14] express that effect of the melt rate was more prominent on the snow than that of ice. The pressure of debris on the ice

increased the melt rate by about 8.5%, whereas for snow it increased by about 11.6%.

[16] elaborated that snowmelt is not measured quantitatively but can be estimated by periodical monitoring of the snow cover area (SCA) during the snowmelt season is an essential requirement for short term and seasonal forecast.

[18] concluded that Maritime Glaciers are likely to have higher Degree Day Factors than Sub-continental and extremely congenital Glaciers.

[5] emphasized on the need to measure the snow depth at multiple points in the study area in order to understand the behavior of Degree Day Factor (DDF).

[2] express that Temperature and Snow Cover Area (SCA) are inversely correlated. Due to the rise in temperature from April to August, the runoff is dominated by snow and glacier melt and thus a number of peaks are observed in the simulation.

[12] is of the view that degree day melt factor is the proportionality coefficient that calculates the melt rate on the basis of air temperature alone.

[15] explained that Snowmelt Runoff model (SRM) counts the precipitation input twice during the simulation once in the form of snow cover and then in the form of precipitation data input. The main objectives of this Study is to develop the Degree day factor model and also investigate the effect of physiographic and climatological parameters on DDF.

## DESCRIPTION OF THE STUDY AREA

Naran catchment was selected as study area. The basic reason for selection of Naran catchment for this study was the severe winter season of this catchment in which almost total area was covered with the snow. In the early Kharif (April-June) the maximum flows in the Naran catchment are generated from the snowmelt. This will help to develop the degree day factors for a catchment which was fully covered with snow. The coordinates of Naran stream gauging station were 34°54′28″N, 73°38′57″E. climatological measurements were also observed on this station. It was a medium sized town in upper Kaghan valley in Mansehra District of Khyber Pakhtunkhwa province of the Pakistan. It was located 119 kilometers from Mansehra city at the altitude of 2500m. Kunhar River passes through the Naran catchment. The total catchment area of Naran was approximately 1095 $km^2$. Lake Saif-ul-maluk & Lulusar are main attractions in the Naran valley. Location of Naran stream gauging station was shifted slightly downstream to Kaghan in 2011. Figure-1 shows the Naran catchment, Kunhar River and location of climate and stream gauging station.

## DATA SOURCES

In present study data had been acquired from different data sources which include satellite data as well as the ground observations. The relevant data and their data sources is given as follows:

- Digital Elevation Model (DEM) was acquired from Shuttle Radar Topography Mission (SRTM) http://www.srtm.csi.cgiar.org

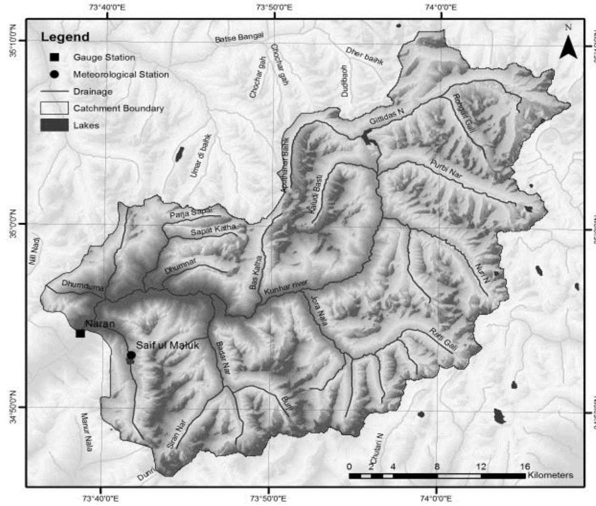


**Figure-1: Naran Catchment and Kunhar River Map**

Figure-2 shows the hypsometric mean elevation curve for the Naran catchment.

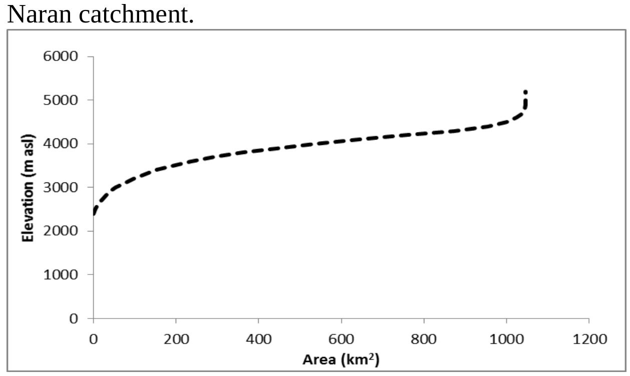


**Figure-2: Hypsometric curve for Naran Catchment**

- Snow Cover Area (SCA) was obtained from Moderate resolution Imaging Spectroradiometer (MODIS) ftp://n5eil01u.ecs.nsidc.org/SAN/MOST/MOD10A1.005/
- Precipitation data taken from National Oceanic and Atmospheric Administration (NOAA) http://iridl.ideo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.FEWS/.SASIA..REFv2/.DAILY
- Temperature (2000-2012) was obtained from Pakistan snow and Ice Hydrology Project (PSIHP) of Water And Power Development Authority (WAPDA)
- Discharge (2000-2012) data had been acquired from Surface Water Hydrology Project (SWHP) of WAPDA.

## MATERIALS AND METHODS

The main approach adopted for this study was to extract the snow cover area in Naran catchment by analyzing the MODIS snow cover imageries for the years 2000 to 2012. An automatic process for downloading the daily snow cover tiles was devised. These downloaded tiles were then converted into the Tagged Image File Format (.tiff). After that cloud cover had been eliminated from the tiles then snow cover analysis was run to get the daily snow cover area in terms of percentage (%) covered area by snow. The results of snow covered area were then used in the model as basic input.

Daily NOAA tiles in .tiff format had been downloaded. Then these Tiff tiles were analyzed by calculating the precipitation through each cell of the grided precipitation. The resolution for NOAA tile was 0.1°. Accuracy of NOAA spatial precipitation was judged by plotting areal averaged NOAA precipitation with the observed precipitation at Saif-ul-maluk.

Temperature lapse rate was assessed using the observed data for Naran (2400m) and Saif-ul-maluk (3235m). A very simplistic approach was adopted for calculating the temperature lapse rate. There are two temperature stations in the catchment the difference of temperature between the higher (saif-ul-muluk) and lower (Naran) stations was divided by the difference of their elevations.

First of all the model was calibrated in a way that at the end only the calibration of degree day factor was remained. Then degree day factors were calibrated. After that for these calibrated degree day factors analysis was being carried out by using the Time step and Z-curve approaches which has been explained in results and discussion.

Effect of climatic and physiographic parameters on DDFs were analyzed by using the different climatic parameters which included the precipitation, temperature, solar radiation, relative humidity and snow cover area. Then an equation was developed with the arrangement of temperature and altitude for the DDFs which could be applied to any other snow driven catchment.

A methodology had been devised to calculate the runoff contribution separately from rainfall and snowmelt. In this method, model was run for snowfall only by providing the input of precipitation, only for those days when temperature was less than critical temperature and no input data of rainfall. Then these flows due to snowmelt were subtracted from the total simulated flows which were given to rainfall runoff and base flows. In this way all the intended research objectives were being carried out.

## DESCRIPTION OF SNOWMELT RUNOFF MODEL

SRM was a temperature index snowmelt runoff model. We used percentage areal snow cover, daily temperature, and daily precipitation as critical input Variables. SRM divided the watershed into elevation zones and accounted for degree-days in each elevation zone to drive the amount of snowmelt. Specific basin characteristics include runoff coefficients, degree-day factors, and historical recession coefficients and the zonal mean hypsometric elevation was determined for each zone from this curve.

The strength of SRM was its primary reliance on snow cover areal extent which was arrayed as a depletion curve over the snowmelt period. This allowed for limited data input needs, as the snow covered area data could be derived today from readily available Remote Sensing Snow data by various agencies.

Each day, the water produced from snowmelt and from rainfall was computed, superimposed on the calculated recession flow and transformed into daily discharge from the catchment according to the equation given below:

$$Q_{n+1} = [c_{Sn}.a_n(T_n + \Delta T_n)S_n + c_{Rn}P_n]\frac{A.10000}{86400}(1 - k_{n+1}) + Q_n k_{n+1} \quad (4)$$

Where, Q was average daily discharge [m3/s], c was runoff coefficient expressing the losses as a ratio (runoff/precipitation), Cs referred to snowmelt and Cr to rain, a was degree-day factor [cm/°C/d] indicating the snowmelt depth resulting from 1 degree-day, T was number of degree-days [°C d] ΔT was the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the catchment or zone [°C d], S was ratio of the snow covered area to the total area, P was precipitation contributing to runoff [cm]. A preselected threshold temperature $T_{Crit}$ determined whether this contribution was rainfall and immediate. If precipitation was determined by $T_{crit}$ to be new snow, it was kept on storage over the hitherto snow free area until melting conditions occurred, "A" was the area of the catchment or zone [$km^2$], k was recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall, n was sequence of days during the discharge computation period. Above equation was written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. In this case, the number of degree-days measured on the nth day corresponded to the discharge on the n + 1 day. Various lag times could be introduced by a subroutine, 10000/86400 was conversion from [$cm \cdot km^2/d$] to [$m^3/s$], T, S and P were variables to be measured or determined each day, Cs, Cr, lapse rate to determine ΔT.

Table-1 showing the calibrated parameters for the Naran catchment.

**Table-1. Calibrated Parameters for Naran Catchment**

| Parameter | Symbol | Value | Units | Remarks |
|---|---|---|---|---|
| Degree Day Factor | $a_n$ | 0.15 – 0.90 | ($cm^oC^{-1}d^{-1}$) | |
| Lag Time | L | 18 | h | = 1 day |
| Critical Precipitation | Pcrit | 0.1 | cm | |
| Runoff Coefficient Snow | $c_S$ | 0.15 – 0.80 | – | |
| Runoff Coefficient Rain | $c_R$ | 0.20 – 0.80 | – | |
| Recession Coefficient | k | 0.96 | – | kx =1.005 & ky = 0.012 |
| Temperature Lapse Rate | λ | 3.5 | °C/km | Calculated from observed data |

## RESULTS AND DISCUSSION

There were two main approaches adopted to develop the degree day factors for the study area.

1. Time Step DDF Approach
2. Z-Curve DDF Approach

## TIME STEP DDF APPROACH

The most important parameter for the snow-melt component in SRM was the degree-day factor. During model calibration, for the sake of transparency the degree-day factors were applied basin-wide. The degree-day factor generally increased during melt season, as the snowpack becomes "ripe" with increasing temperature [9]. It was obvious, that this process happens later at higher elevation zones as temperatures were lower up there. In order to find a common increase pattern of the degree-day factors as well as a rule when this pattern started in each elevation zone, zone-wise degree-day factors were introduced trying to keep the simulation results as good as during the model calibration phase.

In order to determine a common function for each zone, all graphs commenced at the same point, although the actual start may differ from year to year. Then linear regression of resulting degree-day factor patterns for elevation zones 3 (3001 – 3500 m a.s.l) and 5 (4001 – 4500 m a.s.l) which fit the observed hydrograph best are given in Figure-4 and Figure-3. It was applied to obtain the number of periods needed to arrive at a degree-day factor of 0.9 [cm/°C/d] which was set as the maximum value. Finally, the values of period's in-between were determined by linear interpolation. As a trend apparent from, the time the snowpack needed to become ripe was shorter in higher elevations, which might be related to the setting in of monsoon.

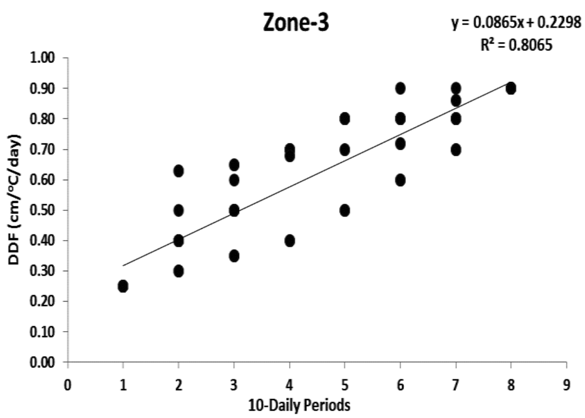


**Figure-3: DDF regressions for zone 3**

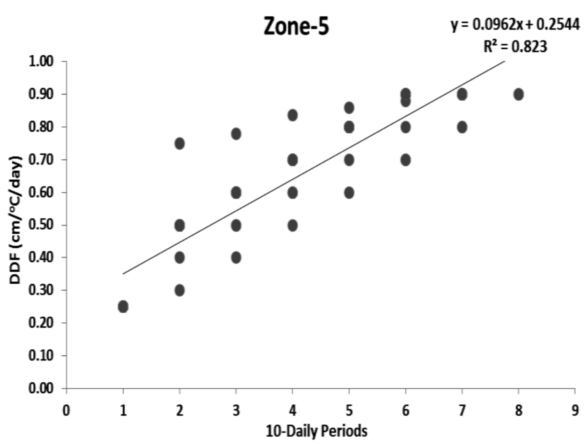


**Figure-4: DDF regression for zone 5**

**Table-2. Zone-wise Degree-Day Factor Functions**

| Period | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Zone 6 |
|---|---|---|---|---|---|---|
| 1 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2 | 0.46 | 0.55 | 0.63 | 0.71 | 0.75 | 0.76 |
| 3 | 0.47 | 0.57 | 0.65 | 0.73 | 0.78 | 0.78 |
| 4 | 0.49 | 0.60 | 0.68 | 0.75 | 0.84 | 0.83 |
| 5 | 0.51 | 0.62 | 0.70 | 0.78 | 0.86 | 0.86 |
| 6 | 0.55 | 0.65 | 0.72 | 0.80 | 0.88 | 0.90 |
| 7 | 0.60 | 0.68 | 0.86 | 0.86 | 0.90 | |
| 8 | 0.90 | 0.90 | 0.90 | 0.90 | | |

Zone wise DDFs are shown in Table-2. When the degree-day factors reached their maximum value of 0.9 [cm/°C/d], this value was kept constant until end of July as all the snow cover faded away up to the month of July which was also evident from the snow cover mapping. Starting from October onward, when the new snow-pack was build up during the winter, degree-day factors in all zones were set to the minimum value of 0.15 [cm/°C/d] until again the degree-day factor functions are applied in the following year. In August and September the degree-day factors in all zones were set to 0.4 [cm/°C/d] as the snow falling in the first snow events after summer, which often melted immediately, it was expected to be "wetter" than under temperatures well under the freezing point.

It was noted, that the degree-day factor functions, i.e. the increase of the degree-day factors, did not start at the same date for all zones. Obviously, the start was related to the rise of temperature, especially when the mean daily temperature advances above 0°C. On the basis of the above functions, a general rule was developed when to start with the increase of the degree-day factors at each zone. For this purpose, the average daily mean temperature of each 10-days period for each elevation zone was calculated. If that value was higher than the specific temperature threshold given in Table-3, the degree day factor function for the respective zone was applied. The general DDF equations for calculating the zone wise DDF on 10-daily time interval was also given in equation 5 through 10.

**Table-3. Start Temperature Threshold [°C] for Degree-Day Factor Functions**

| | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Zone 6 |
|---|---|---|---|---|---|---|
| T10d ** | 4.0 | 3.0 | 2.0 | 1.0 | 1.0 | 1.0 |

** $T_{10d}$ = average daily mean temperature of the preceding 10-days period

$$DDF_{Z-1} = 0.083(10 - daily\ period) + 0.191 \quad (5)$$

$$DDF_{Z-2} = 0.084(10 - daily\ period) + 0.203 \quad (6)$$

$$DDF_{Z-3} = 0.086(10 - daily\ period) + 0.229 \quad (7)$$

$$DDF_{Z-4} = 0.094(10 - daily\ period) + 0.262 \quad (8)$$

$$DDF_{Z-5} = 0.096(10 - daily\ period) + 0.254 \quad (9)$$

$$DDF_{Z-6} = 0.108(10 - daily\ period) + 0.203 \quad (10)$$

Where, Subscript Z-1 indicated elevation zone from 1 to 6. An example for the start period rule and the application of the degree-day factor functions was given for the year 2003. Table-4 showed the average 10-daily temperature for each zone with an indication of the temperature threshold and Table-5 showed the resulting zone-wise degree day factors.

**Table-4. Average 10-daily Temperature [°C] in the Year 2003**

| 10-daily Period | Elevation Zones | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| **JAN-1** | -3.55 | -4.68 | -6.40 | -8.15 | -9.65 | -11.08 |
| **JAN-2** | -2.56 | -3.69 | -5.41 | -7.16 | -8.66 | -10.09 |
| **JAN-3** | -0.38 | -1.50 | -3.23 | -4.97 | -6.47 | -7.91 |
| **FEB-1** | -3.42 | -4.55 | -6.27 | -8.02 | -9.52 | -10.95 |
| **FEB-2** | 1.49 | 0.37 | -1.36 | -3.10 | -4.60 | -6.03 |
| **FEB-3** | 1.68 | 2.94 | 1.21 | -0.53 | -2.03 | -3.46 |
| **MAR-1** | 2.21 | 3.23 | 1.69 | 0.59 | -0.91 | -2.34 |
| **MAR-2** | **4.07** | 3.85 | 1.90 | 0.80 | -0.70 | -2.13 |
| **MAR-3** | 5.18 | **4.06** | **2.33** | 1.51 | 2.06 | 0.63 |
| **APR-1** | 5.39 | 4.27 | 2.54 | **3.56** | -1.46 | -2.89 |
| **APR-2** | 8.15 | 7.03 | 5.30 | 0.04 | 0.21 | -1.22 |
| **APR-3** | 4.64 | 3.51 | 1.79 | 1.71 | **1.86** | 0.43 |
| **MAY-1** | 6.31 | 5.18 | 3.46 | 3.37 | 5.22 | **3.79** |
| **MAY-2** | 7.96 | 6.83 | 5.11 | 6.72 | 5.71 | 4.28 |
| **MAY-3** | 11.31 | 10.19 | 8.46 | 7.21 | 7.43 | 6.00 |
| **JUN-1** | 11.80 | 10.68 | 8.95 | 8.93 | 9.01 | 7.58 |
| **JUN-2** | 13.52 | 12.40 | 10.67 | 10.51 | 9.42 | 7.99 |
| **JUN-3** | 16.51 | 13.98 | 12.25 | 10.92 | 10.41 | 8.98 |
| **JUL-1** | 16.49 | 15.37 | 12.67 | 11.91 | 11.40 | 9.97 |
| **JUL-2** | 15.43 | 16.31 | 13.58 | 12.90 | 12.34 | 10.91 |
| **JUL-3** | 16.93 | 15.81 | 14.08 | 13.34 | 12.84 | 11.41 |

**Table-5. Degree-Day Factors [cm/°C/d] in the Year 2003**

| 10-daily Period | Elevation Zones | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| **JAN-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **JAN-2** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **JAN-3** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **FEB-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **FEB-2** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **FEB-3** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **MAR-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **MAR-2** | **0.25** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **MAR-3** | 0.46 | **0.25** | **0.25** | 0.15 | 0.15 | 0.15 |
| **APR-1** | 0.47 | 0.55 | 0.63 | **0.25** | 0.15 | 0.15 |
| **APR-2** | 0.49 | 0.57 | 0.65 | 0.71 | 0.15 | 0.15 |
| **APR-3** | 0.51 | 0.60 | 0.68 | 0.73 | **0.25** | 0.15 |
| **MAY-1** | 0.55 | 0.62 | 0.70 | 0.75 | 0.75 | **0.25** |
| **MAY-2** | 0.60 | 0.65 | 0.72 | 0.78 | 0.78 | 0.76 |
| **MAY-3** | 0.90 | 0.68 | 0.86 | 0.80 | 0.84 | 0.78 |
| **JUN-1** | 0.90 | 0.90 | 0.90 | 0.86 | 0.86 | 0.83 |
| **JUN-2** | 0.90 | 0.90 | 0.90 | 0.90 | 0.88 | 0.86 |
| **JUN-3** | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| **JUL-1** | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| **JUL-2** | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| **JUL-3** | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| **AUG-1** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **AUG-2** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **AUG-3** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **SEP-1** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **SEP-2** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **SEP-3** | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| **OCT-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **OCT-2** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **OCT-3** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **NOV-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **NOV-2** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **NOV-3** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **DEC-1** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **DEC-2** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| **DEC-3** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |

## Z-CURVE DDF APPROACH

In this approach the basic theme was like the time step approach but the basic difference was that in this approach the accumulated temperature (Positive Degree Days) above zero are taken into consideration which are most important in terms of producing the snowmelt runoff. The main idea was that by calibration a set of DDFs was obtained then a relationship was made in between number of positive degree days and degree day factors which were obtained from the calibration. A restriction was applied to the degree day factors that up to a certain number to positive degree days there would be a constant value of degree day factors [4]. When these degree day numbers were achieved by a certain elevation zone then the degree day factors start to change in this zone as defined by the regression results between the degree day factors and the number of positive degree days. The end point was defined for each zone that after gaining the maximum number of degree days for a certain elevation zone no further increase in the value of the degree day factor and the degree day factor would remain constant. Because after a certain period the snow in each elevation zone was finished and there was no melt contribution from that elevation zone hence a constant value of the degree day factor was used after that period. The start and end points of degree day application was defined on the basis of analysis done for different years. The graphical representation was also shown below in Figure-5 and Figure-6.

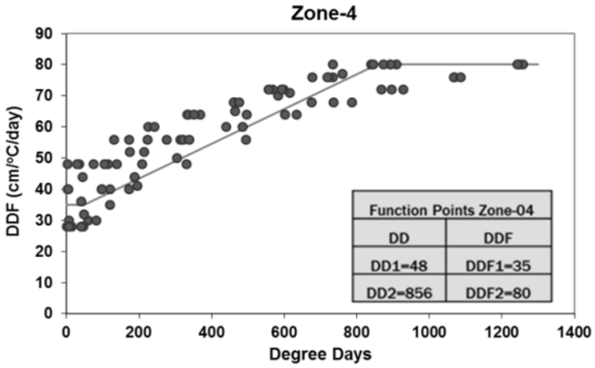


**Figure-5: Relationship between DD and DDF (zone-4)**

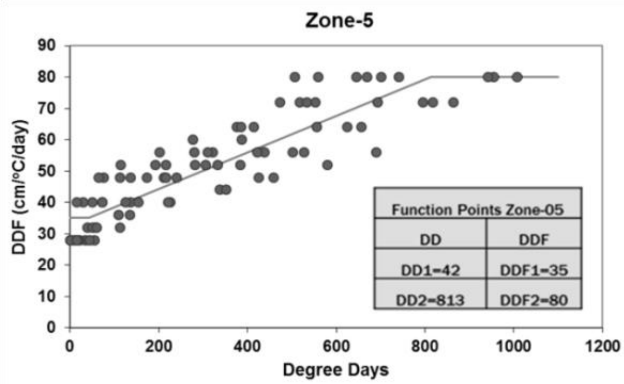


**Figure-6: Relationship between DD and DDF (zone-5)**

**Table-6. Average 10-daily Degree Days in the Year 2005**

| 10-daily Period | Elevation Zones | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| **JAN-1** | 0 | 0 | 0 | 0 | 0 | 0 |
| **JAN-2** | 0 | 0 | 0 | 0 | 0 | 0 |
| **JAN-3** | 2 | 0 | 0 | 0 | 0 | 0 |
| **FEB-1** | 2 | 0 | 0 | 0 | 0 | 0 |
| **FEB-2** | 2 | 0 | 0 | 0 | 0 | 0 |
| **FEB-3** | 2 | 0 | 0 | 0 | 0 | 0 |
| **MAR-1** | 10 | 3 | 1 | 0 | 0 | 0 |
| **MAR-2** | 11 | 3 | 1 | 0 | 0 | 0 |
| **MAR-3** | **28** | 11 | 3 | 0 | 0 | 0 |
| **APR-1** | 72 | **44** | 20 | 4 | 0 | 0 |
| **APR-2** | 124 | 85 | 47 | 20 | 8 | 3 |
| **APR-3** | 178 | 127 | **73** | 33 | 15 | 6 |
| **MAY-1** | 260 | 198 | 126 | **69** | 37 | 18 |
| **MAY-2** | 306 | 233 | 146 | 76 | **38** | 18 |
| **MAY-3** | 369 | 285 | 181 | 95 | 46 | 19 |
| **JUN-1** | 457 | 360 | 237 | 132 | 66 | **26** |
| **JUN-2** | 570 | 462 | 322 | 199 | 118 | 64 |
| **JUN-3** | 688 | 568 | 411 | 271 | 176 | 107 |
| **JUL-1** | 823 | 692 | 518 | 360 | 250 | 167 |
| **JUL-2** | 974 | 832 | 640 | 465 | 340 | 243 |
| **JUL-3** | 1129 | 976 | 767 | 575 | 434 | 323 |

**Table-7. Degree-Day Factors [cm/°C/d] in the Year 2005**

| 10-daily Period | Elevation Zones | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| **JAN-1** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **JAN-2** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **JAN-3** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **FEB-1** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **FEB-2** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **FEB-3** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **MAR-1** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **MAR-2** | 0.18 | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **MAR-3** | **0.26** | 0.20 | 0.23 | 0.25 | 0.25 | 0.26 |
| **APR-1** | 0.35 | **0.24** | 0.23 | 0.25 | 0.25 | 0.26 |
| **APR-2** | 0.46 | 0.39 | 0.23 | 0.25 | 0.25 | 0.26 |
| **APR-3** | 0.54 | 0.45 | **0.35** | 0.25 | 0.25 | 0.26 |
| **MAY-1** | 0.59 | 0.51 | 0.39 | **0.36** | 0.25 | 0.26 |
| **MAY-2** | 0.68 | 0.59 | 0.43 | 0.42 | **0.35** | 0.26 |
| **MAY-3** | 0.72 | 0.67 | 0.51 | 0.53 | 0.41 | 0.26 |
| **JUN-1** | 0.79 | 0.75 | 0.58 | 0.61 | 0.48 | **0.35** |
| **JUN-2** | 0.80 | 0.80 | 0.64 | 0.72 | 0.56 | 0.49 |
| **JUN-3** | 0.80 | 0.80 | 0.71 | 0.80 | 0.63 | 0.56 |
| **JUL-1** | 0.80 | 0.80 | 0.79 | 0.80 | 0.70 | 0.67 |
| **JUL-2** | 0.80 | 0.80 | 0.80 | 0.80 | 0.76 | 0.71 |
| **JUL-3** | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |

The proposed formula for the calculation of degree day factors for each elevation zone was also given in equation 11 and 12.

For DD<DD1

$$DDF = DDF1 \tag{11}$$

And for DD>DD1

$$DDF = DDF1^{\frac{(DDF2-DDF1)}{(DD2-DD1)}} + (DD - DD1) \tag{12}$$

Where "DD" was the Number of Degree Days and "DDF" was the degree day factor. The range was obtained with least square method. DD1/35 and DD2/80 (DDF are taken as multiple of 100 for calculation purpose) were the two points according to which DDF functions were defined. Average 10 daily DD are given in Table-6 while using the Z-curve approach DDFs on 10 daily bases were given in Table -7.

## EFFECTS OF CLIMATIC PARAMETERS ON DEGREE DAY FACTOR

The Degree day factor was a temperature dependent parameter and the temperature was also dependent on different climatic variables. In this section the effect of climatic and physiographic parameters were analyzed to see which of the parameters was the most critical for the degree day factors. In this analysis temperature, relative humidity, snow cover area, solar radiation and precipitation were considered to check the most critical climatic parameter. In order to investigate the effect of physiographic parameters on Degree day factors the considered parameter was zonal elevation. Figure-7 to Figure-11 showing the relationships for all the climatic parameters used in this study.

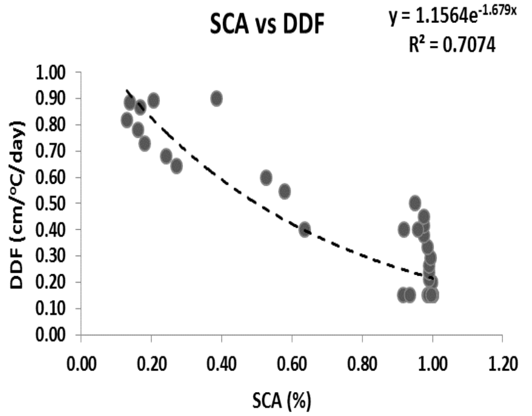


**Figure-7: DDF and Snow Cover Area relationship**

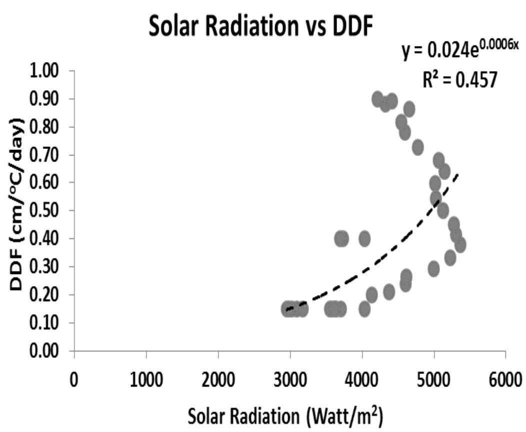


**Figure-8: DDF and Solar Radiation relationship**

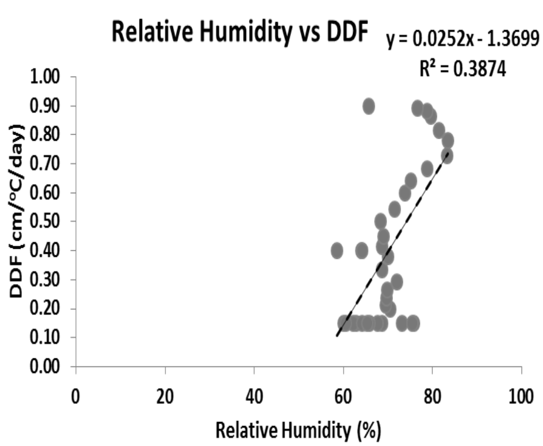


**Figure-9: DDF and Relative Humidity relationship**

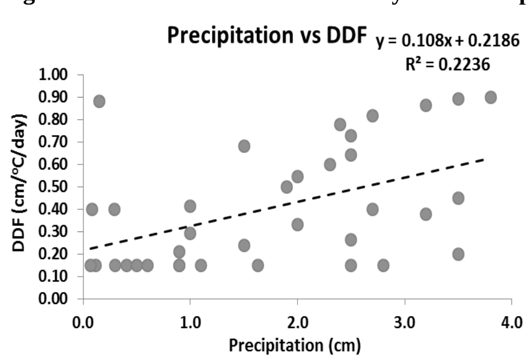


**Figure-10:** DDF and Precipitation relationship

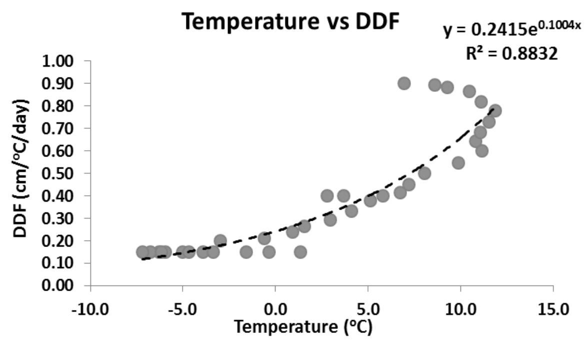


**Figure-11: DDF and Temperature relationship**

It was evident from the above correlations that the best correlation was in between the temperature and the degree day factors. The 2nd best correlation was between the solar radiation and the degree day factors. The solar radiation had an impact on the variation of the degree day factors for higher elevation zones which was mentioned by [8] but in this study the authors were not able to find a good correlation between the solar radiation and degree day factors. It may be because of the inconsistency of the available solar radiation data.

After these analysis effects of temperature on DDFs were investigated zone wise. These relationships were shown in Figure-12.

After having perform this analysis a secondary regression analysis was also carried out. The reason for this analysis was to incorporate the physiographic parameters in the final equation. For this purpose the general equation from T1 vs DDF1 was taken as a base line equation and temperature for different zones were selected and again a relationship was made between the calibrated degree day factors and the degree day factors which were obtained from the equation. The altitude was considered as a ratio of the elevation zone at which the degree day factor needed to be calculated to the hypsometric mean elevation of 1st elevation zone. In case of present study the hypsometric mean elevation of 1st elevation zone for Naran catchment was 2468m asl. In this way an equation was proposed to calculate the degree day factors at any elevation with respect to the temperature. Figure-13 showing the relationship between the calibrated degree day factors and the degree day factors obtained from the proposed equation.

A generalized equation for DDF was developed which was given in equation 13. It was evident from the equation that there was an exponential relationship between the temperature and DDF while temperature was also dependent on elevation.

$$DDF = 1.1466\frac{(Elevation\ Zone)}{(1st\ Elevation\ Zone)}(0.1733e^{0.0936T}) \quad (13)$$

Figure-14 and 15 showing the calibration and validation results of SRM for year 2003 and 2009 respectively for Naran catchment. The coefficient of determination ($R^2$) for the calibration year was 0.94 while for validation year it was also 0.94.

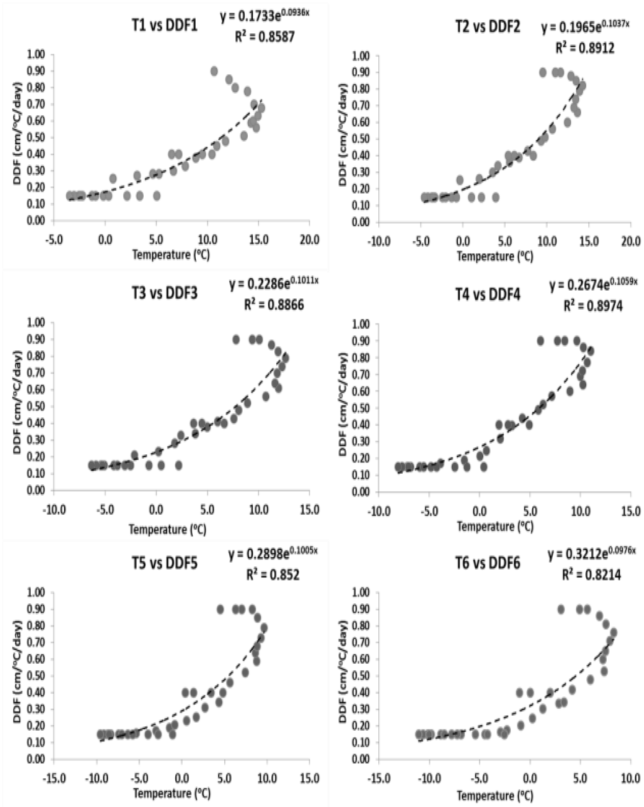


**Figure-12:** DDF vs Temperature for each elevation zone

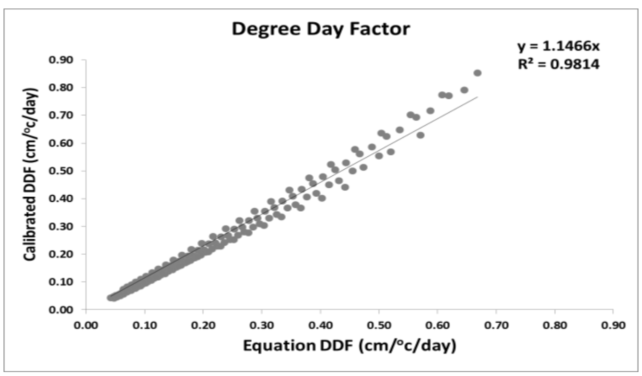


**Figure-13:** Relationship between the calibrated and proposed DDF

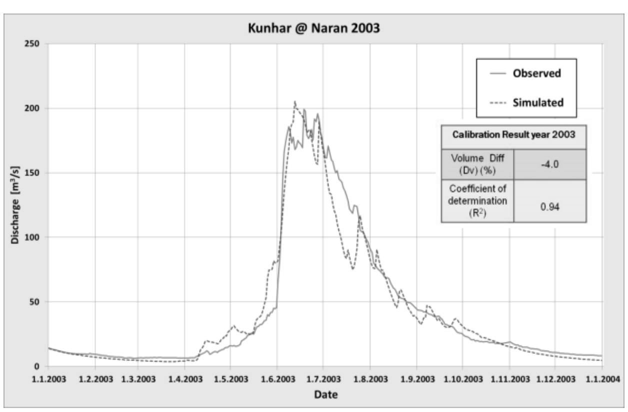


**Figure-14:** Calibration of the model for year 2003 for Kunhar River at Naran

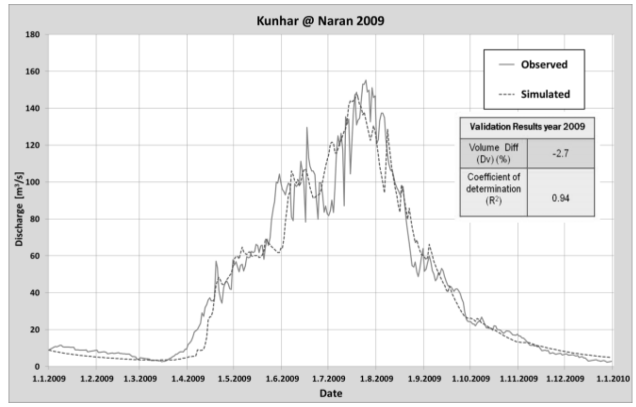


**Figure-15:** Validation of the model for year 2009 for Kunhar River at Naran

An overall comparison from the developed DDFs approaches for the period 2000 to 2012 show that time step approach for DDF was having good coefficient of determination as compared to the Z-curve approach. The results were shown in Table-13.

**Table-13.** Comparison of DDFs Approaches

| Year | Time Step Approach | | Z-Curve Approach | |
|---|---|---|---|---|
| | $D_v$ (%) | $R^2$ | $D_v$ (%) | $R^2$ |
| 2000 | -9.1 | 94% | -2.1 | 81% |
| 2001 | -11.9 | 91% | -9.3 | 85% |
| 2002 | -7.4 | 97% | -5.3 | 89% |
| 2003 | -4.0 | 94% | -10.6 | 82% |
| 2004 | -4.4 | 95% | -0.6 | 82% |
| 2005 | -12.7 | 93% | -10.5 | 81% |
| 2006 | -8.7 | 88% | -8.5 | 86% |
| 2007 | -7.3 | 89% | 6.2 | 83% |
| 2008 | -8.8 | 96% | -11.0 | 88% |
| 2009 | -2.7 | 94% | -3.0 | 86% |
| 2010 | -12.6 | 87% | -10.4 | 84% |
| 2011 | -12.9 | 90% | -12.9 | 87% |
| 2012 | -13.6 | 86% | -12.8 | 82% |
| **Average** | **-8.93** | **92%** | **-6.98** | **84%** |

## CONCLUSIONS AND RECOMMENDATIONS

SRM was well calibrated and validated for Naran catchment. DDF in time step approach gave better results as compared to z-curve approach. A generalized equation for the assessment of DDF was developed. DDF approach was good for the flow forecasting and it will also help the water managers to do the water resources planning and management.

DDF method was also good for the snow driven catchments in Pakistan as if good forecast of snowmelt runoff process would enhance the crop production preferably in Kharif season when most of the water contribution was snowmelt. Developed generalized equation for DDF was recommended for Naran watershed, however, the use of this equation was also recommended for other catchments having similar hydro-meteorological characteristics. It was also recommended that the effect of solar radiation on DDF may also be incorporated.

Indus River System Authority (IRSA) and other such organizations might use this method for appropriate distribution of forecasted water share between the provinces.

It was concluded from the above discussion that snowmelt runoff model was a temperature index model which uses the degree day factor for the determination of snowmelt runoff contribution [9].

The other factors which also had an impact on the snow melting process was the solar radiation and snow albedo. In a very general and precise way it could be said that all in all snowmelt runoff modelling was directly related to the degree day approach [8].

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