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Response of different snowmelt algorithms to synthesized climatic data for runoff simulation

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Abstract

Snowmelt-runoff simulation is an important concern in different aspects of snowy watershed management. But data scarcity is often an obstacle in such a simulation. Inadequate data has restricted the modelers to employ simpler methods. The present paper is aimed at modeling ungauged snowy catchments with more complicated methods, wherein the required data has been generated. For this objective the SWAT (Soil and Water Assessment tool), Degree-Day, SRM, and SNOW17 are identified for detailed evaluations, which are combinations of temperature, temperature-radiation and energy budget based methods. These methods have been programmed and linked with the SWAT model so as to take advantage of SWAT weather data generation capability, and also to ensure uniformity in evaluation of the snowmelt algorithms. Off line performance evaluation of these selected modules has been carried out for the Ammameh watershed in Iran. The results show better performance of the energy budget method using synthesized data, compared with solely simple temperature-based method.

Key words: Snowmelt simulation, Ungauged catchments, Synthetic climate data, SWAT model

1 INTRODUCTION

Snowmelt-runoff simulation is an important phenomenon in snowy terrain and plays a significant role in water budget of the watershed and its subsequent management. In spite of the importance of snowmelt-runoff simulation, data have been one of the main obstacles for such simulation. Majority of snow bound catchments are ungauged and because of high altitude and inaccessibility, less observatory stations are available, the problem that is more pronounced in developing countries.

Snowmelt simulation usually is a module in the hydrological models. The extent of sophistication deployed in the representation of the snowmelt process through these modules depends largely on the availability of data. Excellent reviews on different mathematical formulations for operational snowmelt runoff models are available in WMO (1986), Singh (1995), USACE (U. S. Army Corps of Engineers, 1998) and Melloh (1999). They focused on structure and approach, strength, and limitations of snowmelt models, but less attention has been given to the ungauged catchments. Since the required data is always scarce for these kinds of catchments, there is a need to have comprehensive evaluation of various snowmelt models for simulating with the synthesized data.

This paper emphasizes the snowmelt-runoff simulation for ungauged catchments. The main objective is to assess performance of different algorithms for this simulation using synthesized data. The temperature based, temperature-radiation based and energy budget methods are selected. Of course, there are few other algorithms like statistical one (Aizen, et al., 1996), but all of them need some field and observed data and thus are not appropriate for consideration in this study. Subsequently some operational models are also studied.

Degree-day (Linsley, 1943), SWAT (Arnold et al., 1996), SRM (Snow Runoff Model) and SNOW17 (Anderson, 1973) are the models that have been evaluated for the considered objective.

However ARNO (Todini, 1996), SHE (Bathurst and Cooley, 1996), HEC1 (USACE, 1990) and Kuzmin (Alekhin, 1964) were also assessed to investigate their performance, which all energy budgets approach. But, since we are more concerned about algorithms rather than models and because of the limitation of space in the paper, we restrict ourselves to the discussing results of the first four models, which are known representative of the selected algorithms.

The enhanced developed module for snowmelt through this study has been embedded into the SWAT model. The SWAT is a complex conceptual, distributed model to predict water yield at a daily time scale, in ungauged catchments (Arnold et al., 1996). This makes it possible to compare the response of different algorithms to synthesized data at the same level.

2 DESCRIPTION OF THE STUDY AREA

The Ammameh catchment was selected to demonstrate the methodology and algorithms investigated in this paper. The Ammameh catchment (16.1 km^2) is one of the alpine subcatchments of Jadjroud River, in Iran, rocky and with steep slopes. The Ammameh station at the downstream end of the catchment records daily meteorological information. Average annual precipitation is 567 mm. Snowfall constitutes about 60% of this amount. The catchment is an open area with dominant land use of pastures. Since the catchment is a mountainous area the majority of which consists of hard rocks and not much ground water contribution, especially during the first five months (Jan. to May) we have attributed all stream flows to snowmelt during this period. The stream flow in this period consists of all major components of snowmelt (e.g. snowmelt due to heat, radiation and precipitation).

3 DESCRIPTION OF THE SELECTED SNOWMELT METHOD

In this section, a brief explanation of the selected methods has been given and for more details readers can refer to the cited references.

3.1 The SWAT module in version 97.1

Snowmelt depth in SWAT is calculated by using a simple equation (Arnold et. al., 1996) that we call temperature based equation (TBE):

$$S_{melt} = 4.57\ T_{max} \qquad (1)$$

where T_{max} is maximum daily temperature (°C) and S_{melt} is snowmelt depth (mm). To have more accurate snowmelt computation, the model incorporated a band elevation option in which a subcatchment can be divided up to 10 elevation bands and melt process gets separately calculated in each band with respect to temperature lapse rate. It is worth noting that version 98.2 of the SWAT (Arnold et al., 1998) has used statistical algorithm. And since this version needs some additional observed data (e. g. highest and lowest rate of snowmelt during a year), we did not select it for this study.

3.2 Degree-day method

The degree-day method calculates the daily snowmelt depth, Smet, by multiplying the number of degree days (T_d) by the degree-day ratio (α_d) (Linsley, 1943):

$$S_{melt} = 10\ \alpha_d\ T_d \qquad (2)$$

The most important part of using this method is the estimation of α_d parameter. Linsley (1943) determined the degree-day ratio from temperature and the basin runoff. He showed monthly variation of α_d. Research works in CRREL (Cold Regions Research and Engineering Laboratory) show both spatial and temporal variation of degree-day ratio (Davice, Personal communication, 1999). More discussion about this method is available in Rango and Martinec (1995).

3.3 Snowmelt Runoff Model (SRM)

The SRM, originally is a simple degree-day model (Martinec, 1975), which is designed for simulation and forecasting daily stream flow in mountainous catchments where snowmelt is major part of annual runoff. In the recent attempt, Brubker et al. (1996) incorporated radiation in the model and instead of applying degree-day factor (a_d), they suggested restricted degree-day factor (a_r). The snowmelt equation is expressed as

$$S_{melt} = m_Q\ R_{ad} + a_r\ T \qquad (3)$$

where m_Q is physical constant converting energy to water mass or depth (0.026cmW^{-1} m^{2}day^{-1}), R_{ad} is incident radiation (cal), and T is mean daily temperature (°C). The only parameter in the above equation is a_r. The observations showed that (a_r) is less variable in time than (a_d) (Martinec, 1989). The term including the restricted degree-day factor represents melt attributed to turbulent energy exchange, while the second term converts net surface radiation (R_{ad}) to depth of melt in snow water equation. The mathematical expression of a_r. is available in Brubker et al. (1996).

Martinec (1989) assessed daily values of the restricted degree-day coefficient in the Swiss Alps; values of a_r vary between 0.20 to 0.25 cm°C^{-1}day^{-1}. For the study area of this paper, using mathematical expression of a_r and weather information of the Ammameh station, this value has been calculated to be about 0.20 cm°C^{-1}day^{-1} (Morid, 2000).

It needs to be clarified that only snowmelt component has been extracted from SRM and other components are accounted for through the SWAT model.

3.4 SNOW17

Anderson (1973) described the snow

accumulation and ablation model with respect to the physics of snow cover energy exchange. of primary importance is the energy exchange at the snow-air interface. This work was published in the report No. 17 (Anderson, 1973) and so it is called SNOW17. Under most conditions, and especially during melt periods, most of the energy exchange occurs at the snow surface. Anderson (1973) presented the snow cover energy balance as given below which became the basis for many of the models that used energy budget approach.

$$\Delta Q = Q_n + Q_e + Q_h + Q_m + Q_g \qquad (4)$$

where Q_n is net radiation, Q_e is latent heat transfer, Q_h is sensible heat transfer, Q_m is heat transfer by mass changes and Q_g heat transfer across the snow-soil interface. For all the components in the equation 4, Anderson (1973) expressed individual equations. The combination of these equations yields equation 5. The original units of the equation 4 are cal/cm^2 and they have been converted to mm per unit area where it is defined as energy required to melt 1 mm of ice (approximately 8 cal/cm^2).

Anderson defined change in the heat storage of a snow cover as follow:

$$\begin{aligned}\Delta Q &= Q_i(1-A) + Q_a - 14.68\times 10^{-9} \\ &(T_0+273)^4 + 8.5 f(u_a)[(e_a - e_0) + \gamma \times \qquad (5) \\ &f(u_a)(_a - T_0)] + (C/80) P_x T_w + Q_g\end{aligned}$$

Where Q_i is incident solar radiation (mm$_e$), A is albedo, Q_a is incoming longwave radiation, $f(u_a)$ is wind function, T_a ,T_o, e_a and e_o are air temperature and vapor pressure of the air and snow surface respectively. γ is the psychrometric constant, C is specific heat of water and ice, depending on precipitation status (rain or snow), P_x is precipitation (mm) and T_w is wet-bulb temperature.

4 METHODOLOGY

4.1 Data organization and generation

To overcome data problems, the SWAT model has resorted to the use of equations and formula, to represent some of these entities in terms of the usually observed data. It has been found that with some modifications, part of the data requirements can be taken care of by weather generation subroutines of SWAT. For example, to calculate n/N (actual sunshine hours to potential), we have used Penman equation (Singh, 1992):

$$R_s = (0.18 + 0.55\ n/N)\ I_0 \qquad (6)$$

Where Rs is received radiation which is generated in the SWAT, I0 is extraterrestrial solar radiation that is a function of latitude and day of the year. Calculation procedures by Duffie and Beckman (1980) are included in the SWAT to calculate I0. By having Rs from the SWAT and I0 from the mentioned sources, n/N can be estimated.

SWAT calculates radiation by the model proposed by Richardson (1985). This variable is estimated with respect to latitude of subbasins and Julian date. In this module, monthly average values of received radiation are needed (Arnold et al., 1996). In other attempts authors substituted these methods with a temperature-based algorithm to eliminate need to monthly radiation (Morid et al., 2002)

Long wave radiation is a part of equation 5, which should be estimated. For this study because of the capability of Satterlund equation (1979) in subzero temperature, it was selected. His equation has the following form:

$$T_a = (\sigma a^4) \times 1.08 \left[1 - \exp(-e^{T_a/2016})\right] \qquad (7)$$

Table 1. Data requirement for various modules.

	Air Temp. Max, Min,	Prec.	RH	Dew Point Temp.	Wind Speed	Radiation Sh-Lng wave	Sun Hours (n/N)	Air Pres	Wet-bulb Temp	Satu. Vapor Presu.
	*	*	*	**	**	**	**	**	**	**
TBE§	x	x								
Deg-Day	x	x								
SRM	x	x				x	x			
SNOW-17	x	x	x		x	x	x	x	x	x

§ Temperature based equation

* Observed daily data.

** Synthesized data, estimated by SWAT climate data generator and complimentary equations that have been added to the model in this work.

Where σ is the Stefan-Boltzmann constant and T_a is the temperature of the air near the surface.

Similarly, other required data such as wet–bulb temperature, snow surface temperature, atmospheric pressure, specific humidity, and reflected radiation are also estimated using additional appropriate formula and equations which have been incorporated in the model (Lutgens and Tarbuck, 1979). The list of required data for different methods has been shown in Table 1.

4.2 The SWAT Simulation

Simulation steps with the SWAT, starts with data pre-processing including land use soil type and climatic data. The next step is to identify the sub-watersheds and their configuration. And subsequently simulation run is made. In SWAT, the sub-watersheds are further subdivided with respect to soil and land use without regard to their spatial positioning. These units are aggregated to be called the HRUs (Hydrologic Response Units). There is no routing and subcatchment outputs are obtained by taking the weighted average of the HRUs within the subcatchment (Arnold et al., 1996). This assumption is acceptable for monthly and yearly time scale. But for daily simulation, it can be accepted only for small catchments, where we can assume that surface and lateral flow reach to outlet on the day they occur. This assumption is valid for the study area, because of its size.

4.3 The model performance

To check the model performance, water yields have been compared with predicted water yield, as was done in most studies (Brubaker et al., 1996; Micovic and Quick, 1999). But it needs to be emphasized that during run tests and assessment of the different snow methods, all other parameters and data set have been kept same and all the changes can be attributed to the snow module only. To analyze the methods and their performance, regression coefficient (R^2) and Nash-Sutcliffe coefficients (Nash) were used as criteria for model performance. The best performance of the model yields R^2 and Nash equal to 1.

$$R^2 = \frac{\sum_{k=1}^{K} X_k Y_k}{\sqrt{\sum_{k=1}^{K} X_k^2 \sum Y_k^2}} \tag{8}$$

$$Nash = 1 - \frac{\sum (X_k - Y_k)^2}{\sum (Y_k - A_X)^2} \tag{9}$$

Where X_k and Y_k are observed and estimated values, A_x is average observed values and K is the number of data elements in the period for which the computations are to be made.

To assess the performance of the implemented algorithm estimated discharges have been compared with ten years of recorded data at Ammameh station. It should be mentioned that the first four years of records are used for calibration of parameters and the next six years period is used for validation.

5 RESULTS AND DISCUSSION

Two cases have been considered to present the simulation results. In the first case, it is assumed that there will be no melt during subzero daily temperature (falling season) and only during over zero temperature (melting season). The second case allows snowmelt from some areas even when the temperature is subzero. This treatment is based on the observed data. If the data of

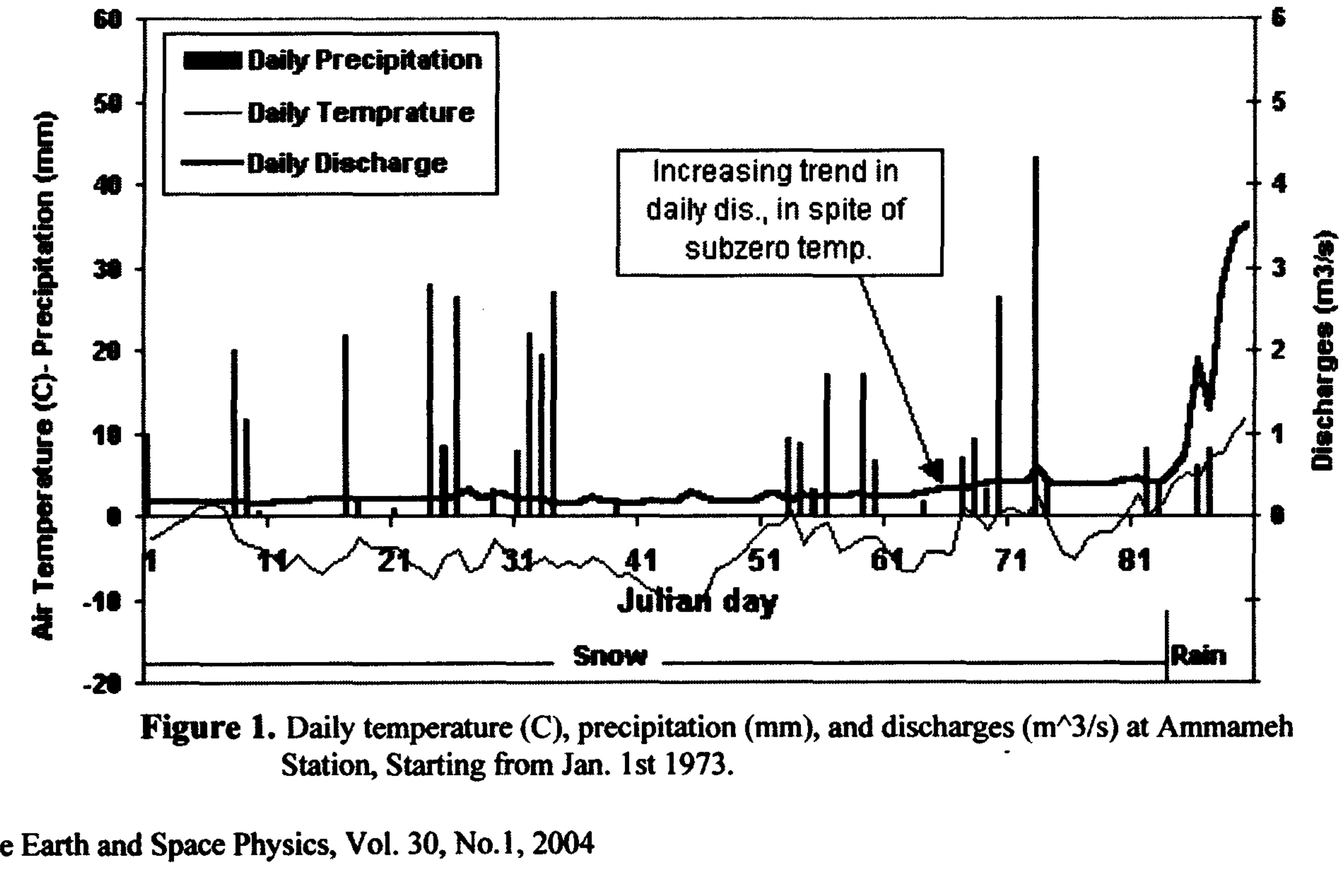

Figure 1. Daily temperature (C), precipitation (mm), and discharges (m^3/s) at Ammameh Station, Starting from Jan. 1st 1973.

Table 2. Comparison of different criteria for the 4 years (calibration period) and the ten years (total period) with no melt during subzero daily temperature.

	R^2-monthly		Nash-monthly		R^2-yearly		Nash-yearly		No.of par.
Method	**4 yr**	**10 yr**	**4 yr**	**10 yr**	**4 yr**	**10 yr**	**4 yr**	**10 yr**	
TBE	.675	.605	.626	.517	.698	.562	.381	.513	0
Degree-Day	.861	.847	.831	.833	.924	.689	.705	.595	8
SRM	.791	.797	.712	.755	.943	.635	.658	.496	1
SNOW-17	.879	.868	.840	.849	.904	.678	.668	.571	1

discharge and temperature be studied, it will be observed that during the first two months (January and February) the daily discharges have a increasing trend, although the daily temperature is usually subzero. Figure 1 shows this increasing trend. The performance of developed algorithm is given at monthly and yearly time scale, and it is further evaluated at daily time scale as well.

5.1 Monthly and yearly simulation with no melt during falling season

Table 2 shows the result of the first run with the new snow module. The table also depicts the number of parameters that are used by each method. For the Degree-Day we have defined monthly melting factor (Rango and Martinec, 1995) (there are only eight values since there is no snow for four months of the year in the study area), whereas in the SNOW17 and SRM only one albedo factors have been applied. The results adapted in the table under TBE model represent the results obtained from the original SWAT (Version 1997). It is evident from this table that among the implemented methods, SNOW17 and Degree-Day give good and almost comparable results. For SNOW17 and SRM, for four years of calibration period, R^2 and Nash coefficient criteria are 0.87, 0.87 and 0.79, 0.78; respectively, where as in TBE they are 0.67 and 0.64, respectively and in Degree-Day they are 0.86 and 0.85. TBE shows poor results. The same trend can be observed from Table 2 for the 10-year period.

5.2 Monthly and yearly simulation with melt during falling season

To bring this part in to snowmelt simulation, we used results of experimental study conducted by Anderson (1976). He suggested that when the air temperature is subzero, the snow surface temperature is 2.5°C less than the air temperature, and when it is zero or more than zero, the snow surface temperature is zero. It is also assumed that the snow pack is isothermal.

With the available energy, which mostly comes from solar radiation, the temperature of maximum snowpack depth increases to zero and then melt takes place. Of course some other factors are also involved like water holding capacity, ice content. But, one option has been added to the purposed model that does not let this process take place for the whole area of a subbasin and occurs only at lower elevations (the idea was obtained from a field visit). In this regard, we activated and used elevation band option of the SWAT and user should define value of this threshold elevation band.

Table 3 shows the next results of the new snow module with the above capabilities, for calibration and validation period. The results show a significant improvement in simulation, especially for SNOW17 and SRM methods. It is clear that we do not expect any changes in the temperature-

Table 3. Comparison of different criteria for the 4 years (calibration period) and the ten years (total period) with melt during subzero daily temperature.

	R^2-monthly		Nash-monthly		R^2-yearly		Nash-yearly		No.of par.
Methods	**4 yr**	**10 yr**	**4 yr**	**10 yr**	**4 yr**	**10 yr**	**4 yr**	**10 yr**	
TBE	.675	.605	.626	.571	.698	.562	.571	.513	0
Degree-Day	.861	.847	.831	.833	.924	.689	.833	.595	8
SRM	.912	.904	.774	.823	.975	.669	.823	.506	2
SNOW-17	.924	.908	.829	.850	.951	.725	.850	.710	2

based methods. This table also shows an increase in the number of parameters to two for SNOW17 and SRM of the methods, yet it belongs to albedo only. This is because of the requirement to one more value of albedo for falling season (subzero temperature period).

The 4-year simulations for SNOW17 and SRM result R^2 and Nash coefficient criteria equal 0.92, 0.89 and 0.91, 0.87; respectively. For 10-year period they are 0.90, 0.89, 0.90 and 0.87.

5.3 Evaluation of the model performance at daily time scale

To show the applied algorithm, daily model performances are also assessed through the concerned periods of this study, when snowmelt is the dominant flow (Jan. to May). For more discussion about the results, observed and estimated flow of the TBE, Degree-Day, SRM, and SNOW17 have been shown in Figures 2 to 5.

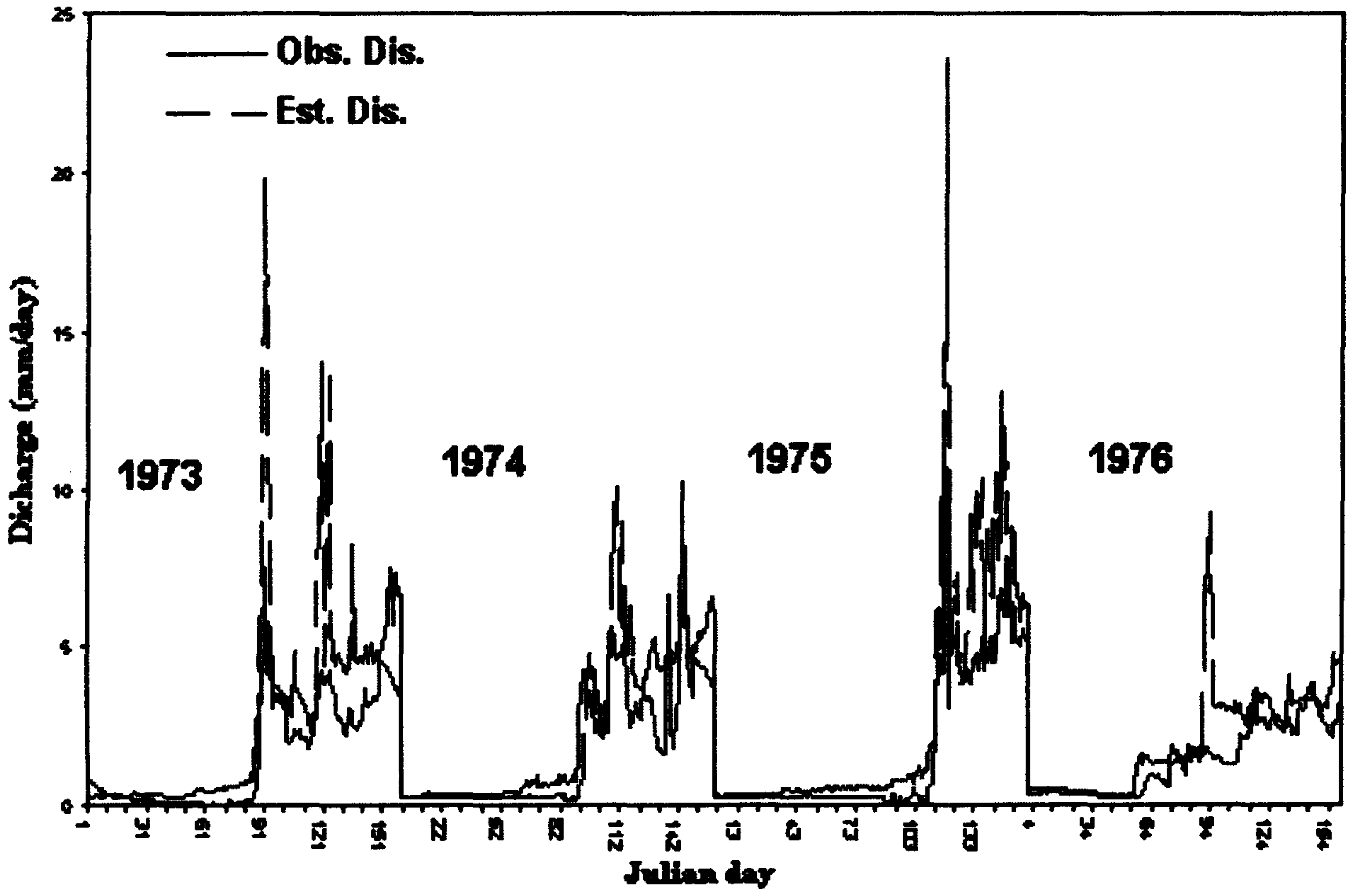

Figure 2. Comparison of observed and estimated discharges with Temperature based algorithm (TBE) for the calibration period.

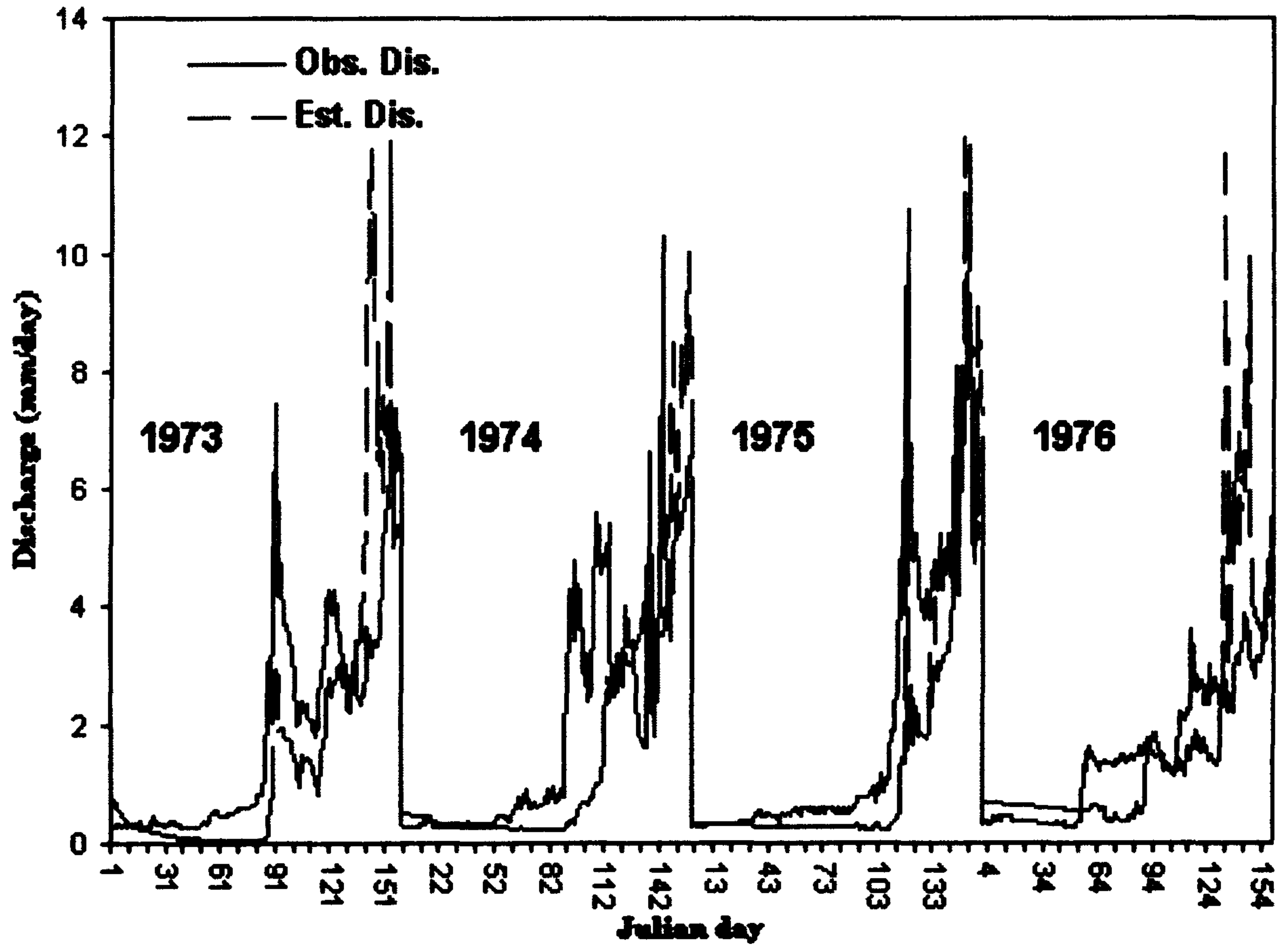

Figure 3. Comparison of observed and estimated discharges with Degree-Day algorithm for the calibration period.

Figures 2 to 3 reveal one definite common point. There is a significant and consistent underestimation of predicated discharge during the first three months, when air temperatures are usually subzero and no snowmelt is predicted. Contrary to this period, in the next two months there is a consistent overestimation. This overestimation can be attributed to the surplus snow accumulation during the previous falling season and its subsequent melting during the melting season. In TBE, a very high response of snowmelt to air temperature is seen. For some days, the differences between the observed and estimated discharges are more than 15 mm/day. In Degree-Day, it is less, because it is controlled by putting different monthly degree-day ratios (Figure. 3).

The performance of SNOW17 and SRM models is quite good, especially during low flows. Comparison of SRM (Figure 4) and Degree-Day (Figure 3) simulations confirms the view of model developers about less time variability in restricted Degree-Day factor (Martinec, 1989). Although the constant value of a_r. has been used for the simulation, there is no flash in predicted

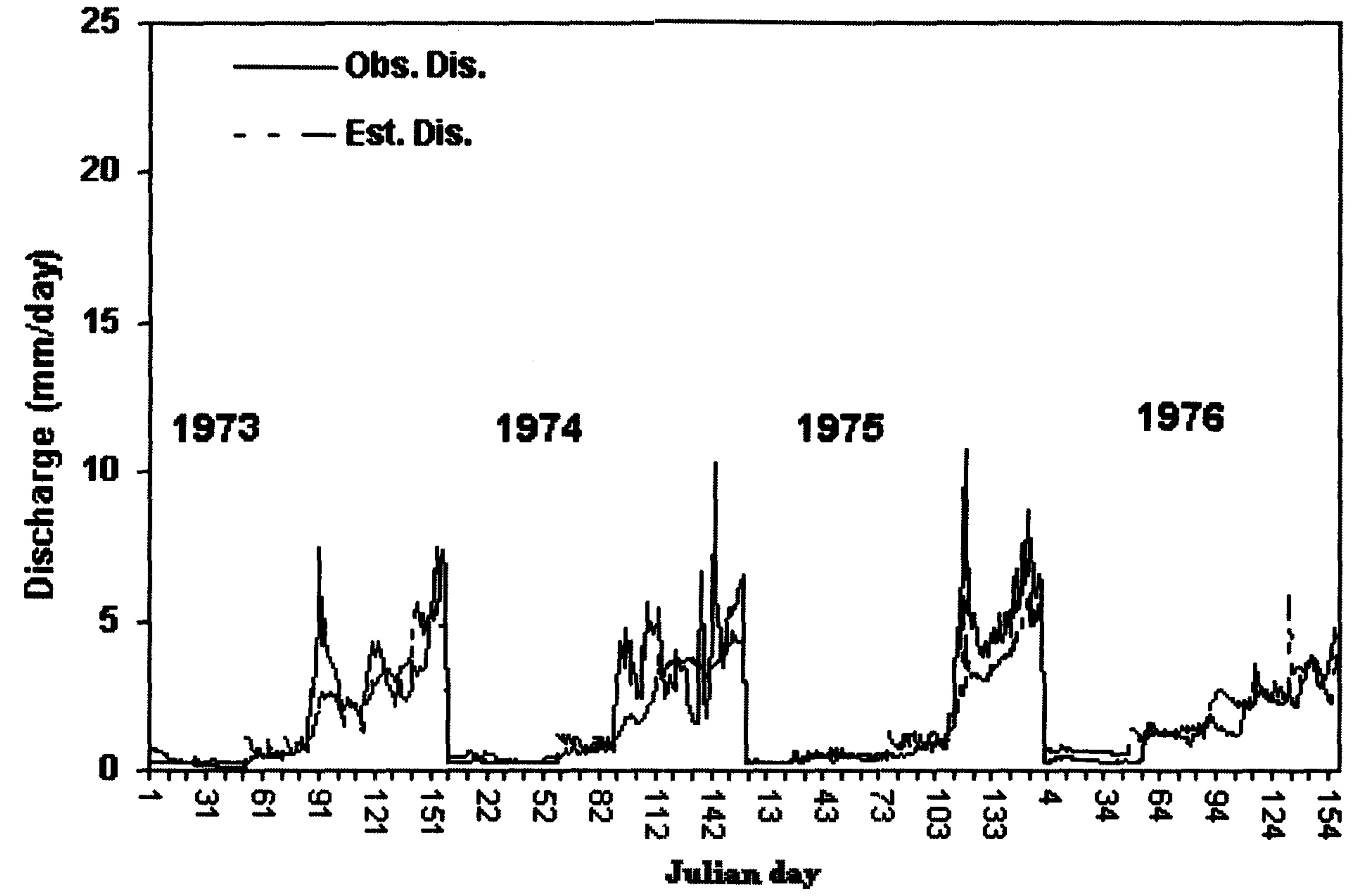

Figure 4. Comparison of observed and estimated discharges with SRM algorithm for calibration period.

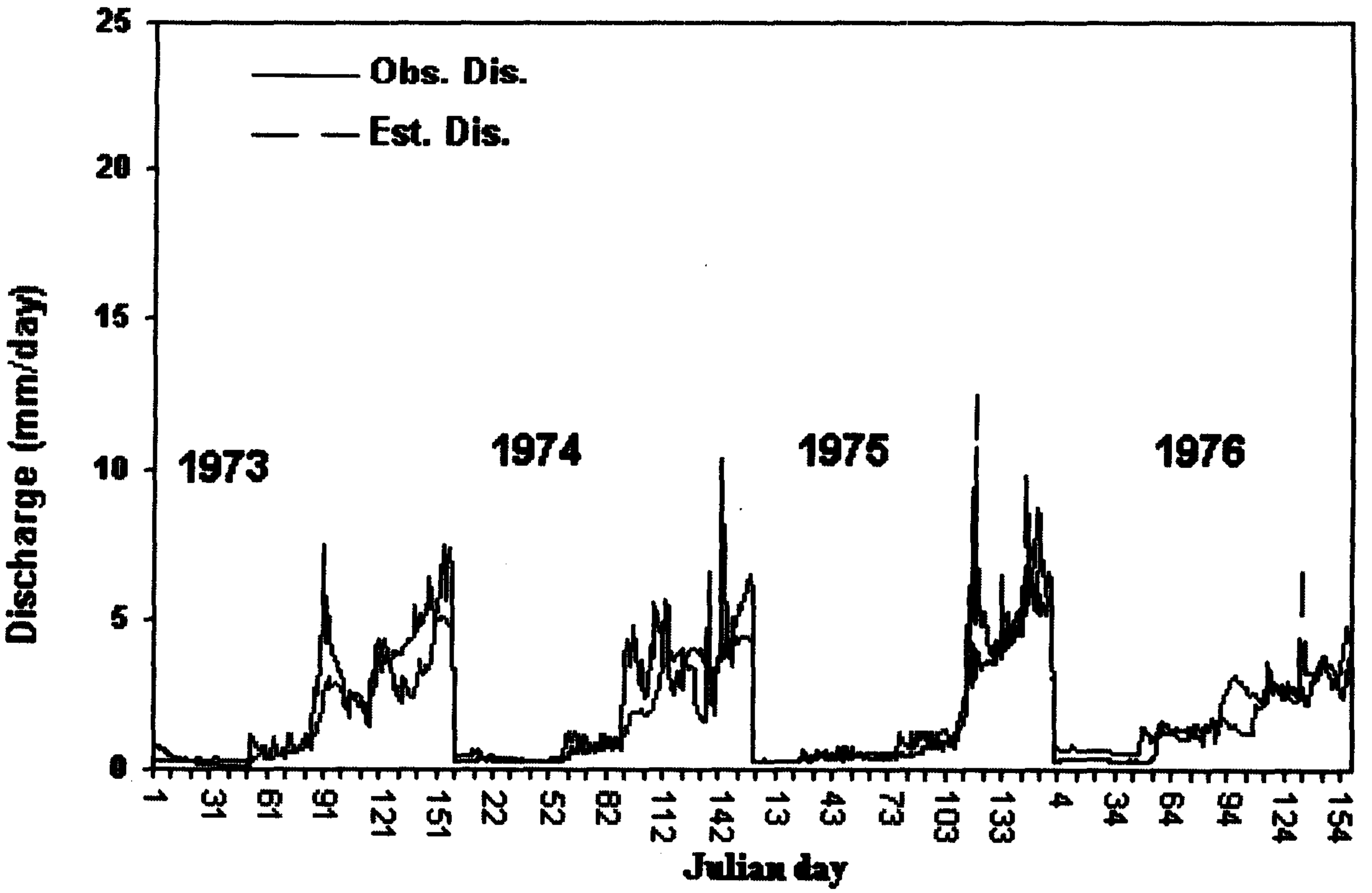

Figure 5. Comparison of observed and estimated discharges with SNOW17 algorithm for calibration period.

flows, the same as what is shown in Figure. 2. The results that have been shown in Tables 2 and 3 are according to a_r equals 0.2. For daily simulation, the SRM method was also run for a_r = 0.25, and the results did not show significant differences (for daily simulation, R^2 is 0.62 for a_r = 0.2 and is 0.60 for a_r= 0.25).

6 CONCLUSION

Four different algorithms including temperature-based equation, degree-day, temperature-radiation based method (SRM) model and energy budget (SNOW17) for the estimation of snowmelt process with synthesized data are used in this study and linked with SWAT model The performances of them are evaluated in yearly, monthly, and daily time scales. The following conclusions are drawn from this study:

1- The results show that the temperature-radiation and energy budget methods (SNOW-17 and SRM) with synthesized data as against simple temperature based method, improve snowmelt-runoff simulation performance. But at daily simulation SNOW-17 performs better. It is noticeable while using different snowmelt algorithms and keeping all other parameters and data set constant, parameters like monthly R2 varies from 0.6 to 0.9 that shows importance of snow module in hydrological models.

2- Using lesser amount of synthesized data, SRM model with fixed value of 'restricted degree-day factor' has given promising results and it is an advantage for this model.

3- The weather data generation module of SWAT and complimentary equations that have been added to the model, have been found to be capable of generating the required data for the simulation of snowmelt runoff with energy budget method.

4- The close simulation results from the temperature-radiation and energy budget methods emphasize the significant role of radiation in snowmelt simulation. From another point of view using the methods that require radiation for snowmelt simulation, make it possible to study spatial variation of snowmelt and monitoring snow water equivalent as well (Morid et al., 2000).

5- Performance of the elevation band of the SWAT model reiterates the effectiveness of the snowbound treatment given to the snowy terrains and thereby brings in the distributed approach.

6- Contributing snowmelt during the falling season has a significant effect on performance of daily flows prediction especially in low flows.

7- Albedo is the only parameter in the proposed algorithm. The given values of this parameter in the literature are used for this study that up to some extent keep model robustness.

This new snow module could be a new facility of the SWAT model, which enhances the simulation capability of the model with practically the same data availability for alpine areas.

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