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An algorithm for monitoring snow water equivalent in un-gauged catchments using GIS

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Abstarct

Monitoring of Spatial variation of snow water equivalent (SWE) and its temporal variation are important analysis in snowy terrain and have a significant role in watershed management. In spite of importance of this analysis, data has been one of the main obstacles for such simulation. Majorities of snow bond catchments are ungauged and because of high altitude and inaccessibility less observatory stations are available, the problem that is pronounced in developing countries. In this research work, an algorithm has been studied to generate required data for spatial analysis of SWE. For this proposed the SWAT (Soil and Water assessment Tool) model after modification and adding new subroutines to it, and a GIS package have been clubbed together for the simulations. It has been postulated that rainfall, temperature and relative humidity are the available data and other data get generated by using them. The validation of the algorithm has been done through the observed and predicted discharges and also local information that confirm relevant performance of the algorithm.

INTRODUCTION

Snow accumulation and depletion processes are highly spatial and temporally varied phenomena. Many factors and parameters like radiation, temperature, precipitation, elevation, slope, aspect, wind, drifting, hill shading, etc. affect these processes, considerably.

Geographical Information System (GIS) has been identified as a powerful tool for data acquisition and pre-processing. It is being used to explore spatial and temporal aspects of snow accumulation and ablation processes, which are related to topography. Use of this technology has been subject of many recent research works. The National Weather Service Office of Hydrology, USA has developed a methodology using GIS to generate real-time, gridded snow water equivalent (SWE) estimates using ground-based and airborne snow data collected over the Western United States (Hills et al., 1994). Hartman et al. (1995, 1996) has used this tool for assessment of spatial variation of snow cover and SWE in mountainous terrain. Usefulness of GIS and remote sensing based approaches for integrating many different and widely varying data sources has been examined by Baumgartner (1997).

Although foregoing analysis is very useful and essential in watershed management of snowcapped terrains, but data is a major obstacle to extend such an analysis for ungauged

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catchments. In this paper, we have tried to formulate an algorithm for monitoring the spatial and temporal variation of snow covered area and SWE, using easily available meteorological data of daily temperature and precipitation. The proposed algorithm has been merged into the existing SWAT (Soil and Water Assessment Tool) model for testing the developed algorithm.

THE STUDY AREA

The proposed algorithm has been applied to the Ammameh catchment. This catchment with 16.1 km^2 area, is one of the snow bond subcatchments of Jadjroud River in, Iran, which consists of four subcatchments (Figure 1). The terrain is mountainous, rocky and with steep slopes. The elevation difference between outlet and highest elevation is more than 2000 meters. There is one precipitation and one discharge station at the downstream end of the catchment, and the meteorological data and river discharges at daily interval are available at these stations. The climate of the Ammameh area is temperate with a mean annual temperature of 8.6°C. Winters are cold, and in the month of March, average monthly temperature reaches to –5.8°C. Daily incident solar radiation is also recorded in the weather station. Average annual precipitation is 567 mm. Snow precipitation constitutes about 50% of this amount. Snowmelt feeds most of the annual stream flow of the Ammameh River. Annual total runoff is 9.5 MCM, with average discharge of 0.30 m^3/s. The dominant land use of the area is pastures.

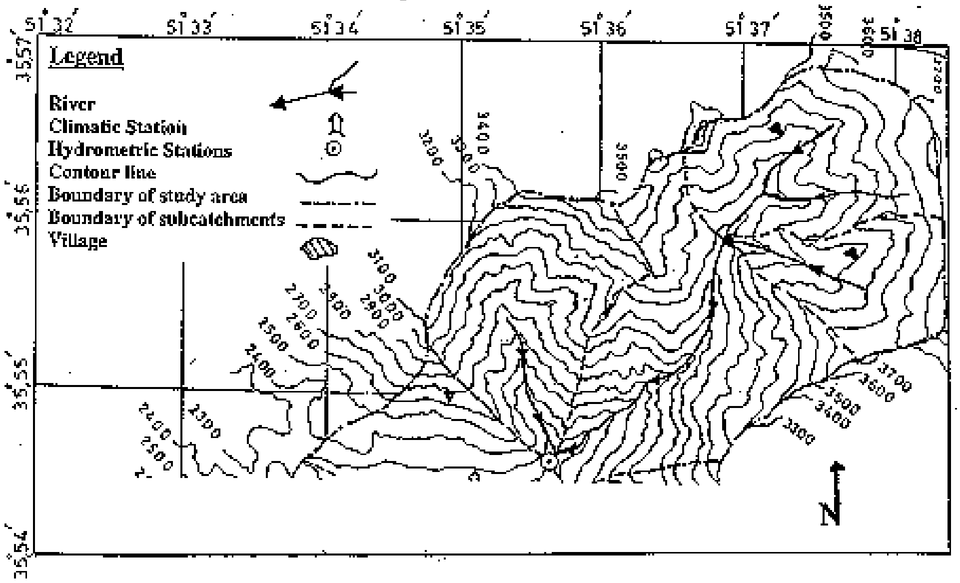

Figure 1. Map of study area (Ammameh catchment, 16.1 km^2) – Iran.

CONVENTIONAL APPROACHES IN SNOWMELT-RUNOFF SIMULATION

To fulfill the objective of this paper, a wide spectrum of the hydrological models and methods that have been implemented to simulate snowmelt, were studied. For ungauged catchment temperature based, temperature-radiation and energy budget approaches are more suitable approaches. But since we are concerning on spatial analysis of SWE, the temperature based equations are not sensitive enough to explore spatial variation of available energy for snowmelt. Energy budget approach and temperature-radiation based approaches need observed data that are more readily available or is possible to synthesize them from other meteorological data. The authors, in another work compared some of snowmelt model using synthesized data and concluded SNOW-17 (Anderson, 1973) and SRM (Brubaker, 1995) models performance with such a data is quite good. For this study SNOW-17 has been selected.

THE PROPOSED ALGORITHM

It was already mentioned the main aim of this study is to present an algorithm for monitoring snow accumulation and ablation processes along with GIS. It is possible to express the required computations in three major steps:

Data preparation and generation
Computation of available enrage
Calculation and exploration of SWE

For the purpose algorithm three different components have been involved. These components are the SWAT Model, GIS, and computer programs that were developed for some parts of computation. These components have been later linked and integrated. We give a brief explanation about these components here and discussion about the above steps will come in next sections.

The SWAT model is distributed hydrological model suitable for ungauged catchments. The model uses daily data and some of the required data also get generated. The SWAT model has been applied in many watersheds in the world with different characteristics and it has shown promising results (Williams and Arnold, 197; Srinvasan, et al., 1998).

ArcVeiw is the GIS package with high capability for spatial analysis. There is one spatial extension for this task. Through spatial analysis physiographical features like slope, aspect and elevation can be extracted from the digitized maps. Also, computed depth of SWE has been shown spatially using this GIS package.

The SWAT originally does not have spatial and temporal analysis of snow cover. To enable the SWAT to perform these tasks, some subroutines have been added to the SWAT and some of the subroutines have been modified. Figure (2) shows the above components of the developed methodology and interaction that have been designed between them.

Computing of Available Energy for Melt

As mentioned earlier, for this study, SNOW17 model (Anderson, 1973) was selected for snowmelt calculation. But it is necessary to see how the SWAT simulates snowmelt, too.

Snowmelt in the SWAT model: *Snowmelt depth in SWAT is calculated by using a simple equation (Arnold et. al., 1996) that we call it fully temperature based equation (For more convenience, through this paper it is called TBE):*

$$S_{melt} = 4.57 * T_{max} \tag{1}$$

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 nothing that version 98.2 of the SWAT (Arnold et al., 1998) has used statistical algorithm. And since there should be some observed data (e.g. highest and lowest rate of snowmelt during a year), we did not take it in to consideration.

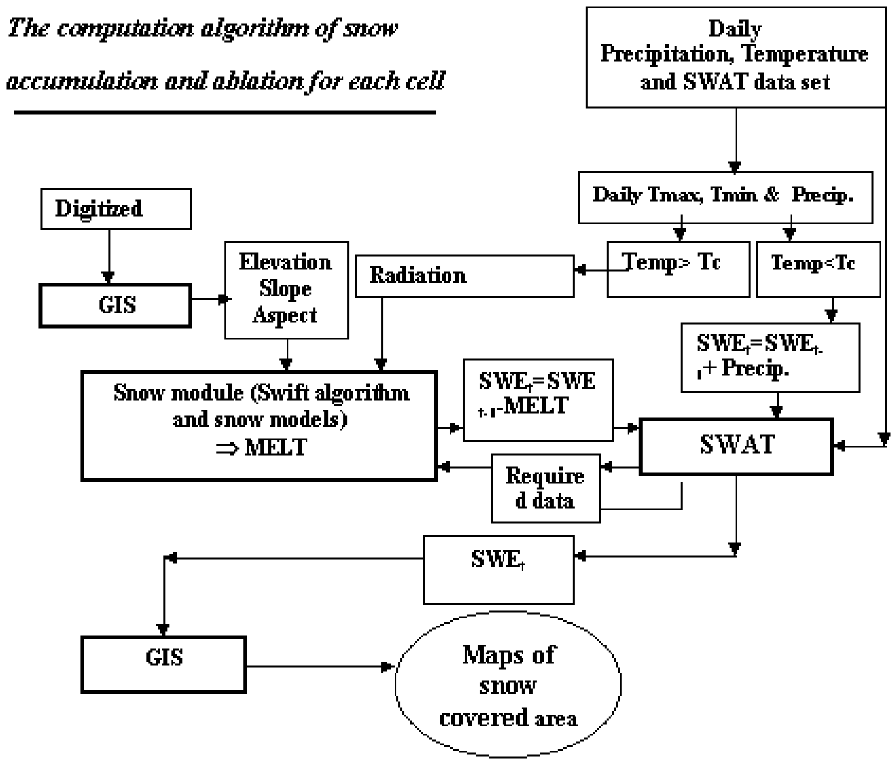

Figure 2. Flow chart of the proposed algorithm for creating of snow covered area.

The Snow17 model: 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. Under most conditions, and especially during melt periods, most of the energy exchange occurs at the snow surface.

Anderson (!973) presented the snow cover energy balance as given below which became the basis for many of the models that used energy budget approach.

$$\Delta Q = Q_n + Q_e + Q_h + Q_m + Q_g \tag{2}$$

by mass changes and Q_g is heat transfer across the snow-soil interface. For all the components in the Eq.(2), Anderson (1973) expressed specified equations. Combination of these equations concludes Eq. (3). The original units of the Eq. (2) are cal/cm^2 and they have been converted to mm$_e$ 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:

$$\Delta Q = Q_i * (1\text{-}A) + Q_a - 14.68 * 10^{-9} * (T_o + 273)^4 + 8.5 * f(u_a) * [(e_a - e_o) + \gamma * f(u_a) * (T_a - T_o)] + (C / 80) * P_x * T_w + Q_g \quad (3)$$

where Q_i is incident solar radiation (mm$_e$), 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 at height z above the snow surface and at the snow surface, respectively; γ is the psychrometric constant; C is the 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.

Programming for Spatial Analysis

In order to take into account spatial variation of land use, soil type and vegetation cover SWAT uses HRU's (hydrological response units) (Anderson, 1976). Similarly for incorporating spatial analysis for calculation of different hydrological components, the model applies elevation bands. Elevation bands are too coarse to account for the spatial variation; therefore in the present study, grid-based spatial scheme was incorporated along with the proposed snow module. To do this, some changes have been made in the SWAT source code. Cell wise computation and flow chart of the SWE calculations is shown in Figure 2.

Data Generation and Preparation

To solve Eq. (3), temperature, precipitation, solar radiation, longwave radiation, wind speed, wet-bulb temperature and vapor pressure are the main meteorological data. Except radiation and wet-bulb temperature, other data are generated by SWAT. Radiation is the most significant data for snowmelt-runoff simulation, especially when spatial analysis is to be considered. From other point of view, this is a rare available data in most of the ungauged catchments. Therefore for the proposed algorithm, it has been postulated that radiation is not available and should be generated from other readily available meteorological data. In the proposed algorithm radiation is generated with maximum and minimum temperature and extraterrestrial radiation. Because of importance of this meteorological variable, brief explanation comes next.

Estimation of solar radiation and its spatial variation

The SWAT model generates radiation data, by having long term mean monthly radiation data. Review from a workshop held on SWAT model at Indian Institute of Technology (1998), revealed that preparing long-term mean radiation data in rural areas is cumbersome. This problem can be anticipated in catchments of many developing countries and even for some areas of developed countries. So we decided to change radiation algorithm in the SWAT and use from temperature based algorithm approaches.

The study carried out by Hargreaves and Samani (1982), and Richardson (1985), which correlated solar radiation (R_s) to temperature and extraterrestrial, have been used more frequently by other studies and climatic data synthesizing software to estimate radiation. Hargreaves and Samani (1982) has the following form of equation to calculate R_s:

$$R_s = K_r(T_{max}-T_{min})^{0.5}R_a \tag{4}$$

where R_s is solar radiation, T_{max} and T_{min} are mean daily maximum and minimum air temperature (°C), R_a is extraterrestrial radiation; and K_r is empirical coefficient.

As it can be eventually understood, in Eq. (4), K_r has a significant role and in fact, it is the unique variable to adjust the equation. Initially K_r was set to 0.17 for arid and semi-arid climates. Hargereaves (Allen (1997) later recommended using K_r = 0.16 for interior regions and K_r = 0.19 for coastal regions. Allen (1995) suggested an equation to calculate K_r according to air pressure. Allen (1997) later suggested a self-calibration method to estimate K_r. Allen (1997) discussed that Eq. (4) produces relationships between R_s/R_a and (T_{max}-T_{min}), which is generally consistent throughout the year. It is conservative in the prediction of R_s/R_a, i.e. it rarely overestimates R_s when skies are clear. These attributes make self-calibration possible by comparing estimates from Eq. (4) with an envelope of R_s expected under completely clear-sky conditions.

Self-calibration involves calibration of R_s by applying Eq. (4) on a daily (24-h) basis using daily measurements of T_{max} and T_{min} and an initial value for K_r. The estimates are plotted over time for at least one year and are then overlain by calculated clear sky solar radiation, R_{so} (the R_{so} envelope represents expected R_s when the sky is free of clouds). R_{so} envelopes have been estimated in different ways (Allen 1996). The R_{so} envelope represents expected R_s when the sky is free of clouds. According to this method, value of K_r is varied until the highest estimates of R_s contact the R_{so}. Using this method, K_r was estimated to be 0.20 for the study area. Since self-calibration method needs some observed radiation data, in case of no availability of this data, the values that are recommended in the literatures are quite good.

R_a is another parameter in this approach. It was calculated according to the method described by Duffie and Beckman (1980). All the mentioned steps to generate radiation, was programmed and embedded in the SWAT. Results of SEE (standard error of estimates) criteria show performance of temperature-based method is better than the SWAT for the study area (32 and 37, respectively).

Incoming radiation at a point and its distribution on a terrain is affected by given Julian day, latitude, slope and aspect, and it has been subject of many observational and analytical studies. Swift, (1976); Kondrayev and Federova, and Hay (Barrey, 1992) suggested different approaches for calculation of radiation falling on slopes of given angle and aspect for direct or global radiation at various latitude. For this study Swift algorithm, because of enough documentation and needing easily accessible data was selected. Figure 3 shows potential solar radiation on some of typical slopes and aspects at January first, using the developed model and Figure 4 shows potential incident solar radiation for a typical day (Jan. first, 1974). The method has been programmed and added as a new subroutine to the SWAT source code.

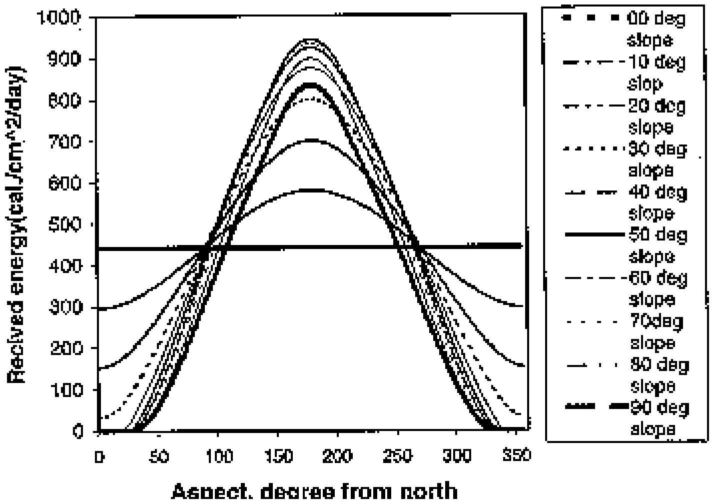

Figure 3. Incident solar radiation at different slopes and aspects – Jan. 1st.

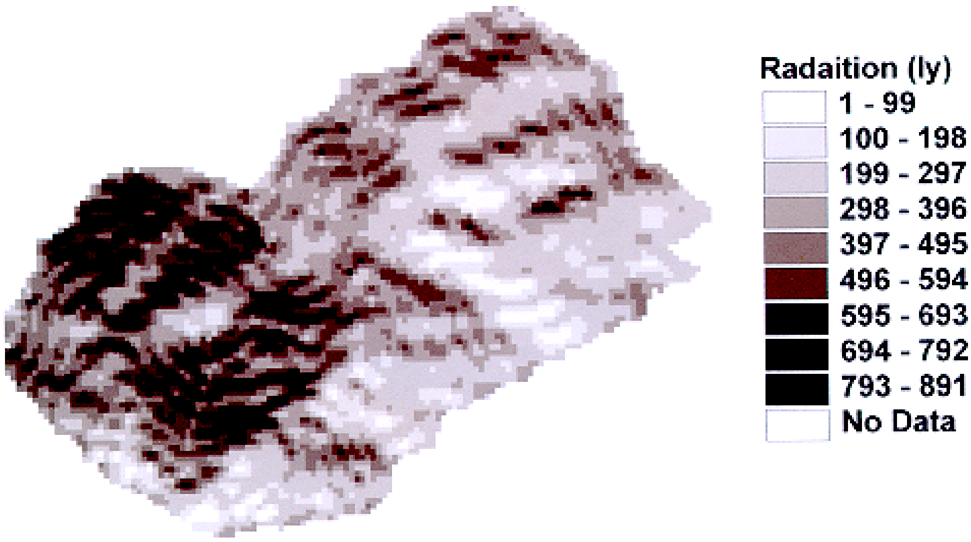

Figure 4. Spatial variation of incident solar radiation on the Ammameh catchment on Jan. 1st, 1974 (iy).

IMPLEMENTATION OF THE ALGORITHM TO THE STUDY AREA

Using Arc/View GIS and digitized map of the study area elevation, DEM (Digital Elevation Model) grid has been created. Subsequently slope and aspect grids are generated using the DEM. These files are further converted to ASCII file, and are used as inputs to the SWAT model after exerted modifications. The created ASCII files are two-dimensional matrices of the above attributes of watershed (e.g. elevation, slope, and aspect)

With the new capability that was added for grid wise simulation in the model, also the methodology that were explained earlier, the SWAT model is now capable to create new output files that contain SWE of the study area for given date. These files have proper format to be readable with GIS software. Fig. 5 and 6 show status of snow covered area and SWE for two typical dates (Jan. first, 1974 and March 20th, 1974).

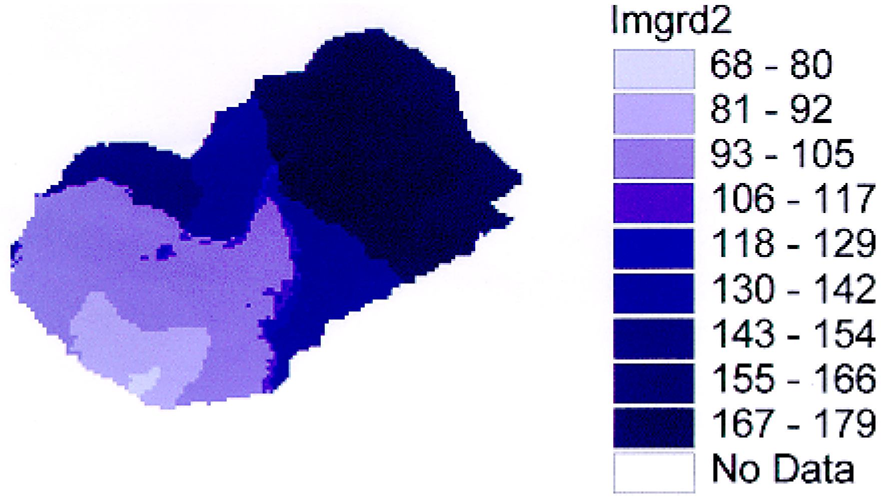

Figure 5. Spatial variation of SWE on the Ammameh catchment on Jan. 1st, 1974.

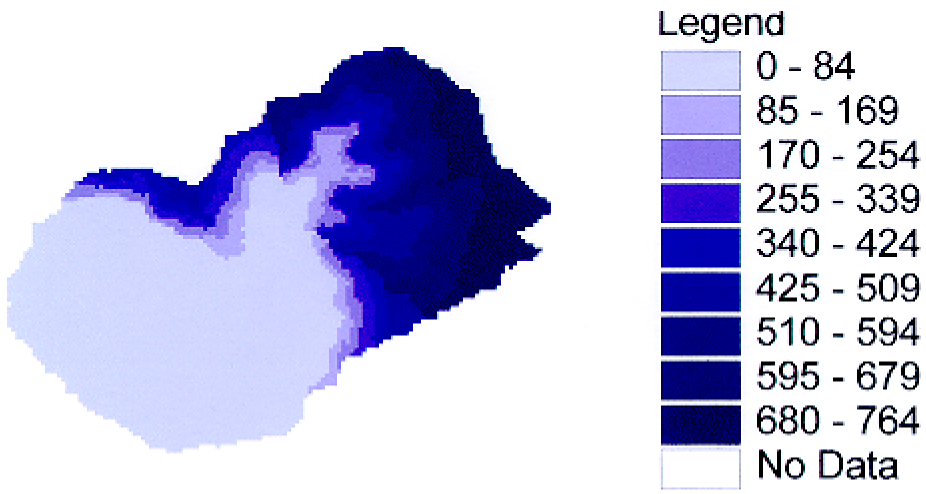

Figure 6. Spatial variation of SWE on the Ammameh catchment on May 30th, 1974.

VALIDATION

Since there has not been any satellite picture or air photo from the study area, the validation of the algorithm, has been checked with observed discharges for 10 years (From 1973 to 1982). Efforts are also going on to prepare satellite picture in this regard.

Spatial algorithm has given satisfactory results. The results have been shown in Tables 1. According to this method, for four years of calibration period, R^2 and Nash-Sutcliffe coefficient criteria are 0.88 and 0.87, whereas in the original SWAT module they are 0.68 and 0.64 percent, respectively. Similarly, for a 10 year of validation period, our algorithm gives 0.87 and 0.84 for the above criteria and the SWAT gives 0.60 and 0.53, respectively.

Table 1. Comparison of criteria for calibration and validation period.

	4 yr R^2-mon.	4 yr Nash-mon.	10 yr R^2-yr.	10 yr. Nash-yr	4 yr R^2-mon.	4 yr Nash-mon.	10 yr R^2-yr.	10 yr Nash-yr.
Method	4 yr	10 yr	4 yr	10 yr	4 yr	10 yr	4 yr	10 yr
SWAT	0.68	0.60	0.64	0.53	0.70	0.56	0.26	0.43
Spatl alg.	0.88	0.87	0.87	0.84	0.90	0.68	0.46	0.66

CONCLUSION

A distributed snowmelt algorithm was developed to monitor SWE for ungauged catchments. Computed energy for each elements of the DEM grid was included in the present SWAT model. The required data is chosen in such a manner that it can be easily prepared for ungauged catchments. Validation of model was done by using observed discharges at the basin outlet, and it was found to be quite satisfactory. Work is currently in progress to obtain a new data set from satellite imaginary of a snow cover area for one of the Indian snow capped catchments for better validation of the algorithm. Using a GIS permits preprocessing a large amount of information, fast extraction of required data and subsequent preparation of the necessary maps. The model requires only 30 minutes run time on a high-level PC. To simulate 10 years daily data set for about 50000 raster elements. Structure of the snow model, its limited data requirement, the low scale dependence of parameters and being in GIS platform, makes the algorithm suitable for use on ungauged catchments and operative purposes even in large catchments.

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