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Modeling of Rainfall-Runoff Response of the Manimuktha Catchment Using TOPMODEL

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Abstract: The semi-distributed topographic based rainfall-runoff model (TOPMODEL) has been applied to the Manimuktha watershed sub-catchment of Vellar River; one of the important catchment which contributes lot of flow in the rainy seasons. Remote Sensing was applied to estimate spatially distributed catchment parameters such as landuse, soil DEM and catchment parameters. SRTM 90m DEM was used to compute the topographic index, the basement and basic input for the TOPMODEL to simulate the stream flow of the sub-catchment. TOPMODEL calculates the actual evapotranspiration from the potential evapotranspiration, the root zone storage deficit and maximum root zone storage deficit for its water balance calculation. The first step in applying TOPMODEL to a watershed involves GIS analysis which results in a raster grid of elevations used for the calculation of the topographic index. Analyses were also performed to determine the sensitivity of TOPMODEL hydrographs to several model parameters. A sensitivity analysis of the model indicated significant changes in the simulation result for the three parameters that are the exponential transmissivity function (m), the soil transmissivity at saturation (To) and the root zone available water capacity (SR_{max}). The hydrographs generated for six storm events and the results are satisfactory with Nash efficiency as much as 78.8% in and Correlation Coefficient 0.69.

***Keywords:** TOPMODEL, rainfall-runoff modeling, topographic index, DEM, Manimuktha watershed*

1. Introduction

The hydrological behavior of a natural watershed is an extremely complex phenomenon due to vast spatial and temporal variability of physiographic and climatic characteristics, and various complex and interdependent processes involved in the transformation of rainfall into runoff (Kumar and Kumar, 2008). Assessments of stream flow in many Indian catchments are limited although emphasis must be given to support water resource management. Planning and execution of a water resource including dams, spillways, detention basins, culverts, and urban storm water systems project require information about stream flow. To accurately predict the peak discharge, runoff volume, and time to peak of design storms, the hydrological processes, which control the rainfall-runoff phenomenon requires a suitable model. Various watershed models have been developed and introduced in the hydrological literature (Singh. 1989; Singh, 1995). Nevertheless, few of these models have become common planning or decision-making tools, largely because of limitations in availability of measured data to satisfy model input. Since the development of the Stanford watershed model (Crawford and Linsley, 1966), numerous operational, lumped or conceptual models have been developed (Singh, 1988).

Lumped models act as a black-box model and estimate runoff only at the catchment outlet. These models cannot provide any information about the distribution of saturated areas within the basin; therefore, they are unable to describe how saturated areas distributed within the basin and what their role in evapotranspiration and runoff production is. In addition, parameters in such models do not have a clear physical interpretation and estimation of the parameters need to have long-term rainfall-runoff time-series of the watersheds. Nevertheless, few of these models have become common planning or decision-making tools, largely because of limitations in availability of measured data to satisfy model input.

Distributed hydrological models account for heterogeneity and spatial variability by considering variations in watershed characteristics across the entire area of watershed. . However, such models include many parameters, which though have clear physical meanings; they are very difficult to be calculated. However, increasing the computer power, Geographic Information System (GIS) packages, and spatially distributed data have made distributed modeling possible.

Distinct from lumped models and distributed models, conceptual models are easier to apply because their model structure is simpler and their data requirements are lower. TOPMODEL (a TOPography based-semi distributed-conceptual MODEL) approach to rainfall-runoff modeling explicitly uses topography to better approximate the overland and subsurface flow generating processes (Beven et al., 1995). Beven and Kirkby (1979) suggested that a conceptual model that can simulate variable source areas could be used for long-term water yield estimation. Based on this approach, several conceptual models have incorporated soil moisture replenishment, depletion and redistribution for the dynamic variation in areas contributing to direct runoff.

In the present study, TOPMODEL is used for rainfall-runoff modeling at the Manimuktha watershed sub-catchment of Vellar River; one of the important catchment which contributes lot of flow in the rainy seasons. Analysis was carried out to investigate possible advantages of continuous models versus event based models. Also sensitivity analysis were carried out for the effect of soil moisture, m and T_o on runoff hydrograph simulation. Also various statistical criteria were used to assess the model efficiency.

2. Methodology

TOPMODEL is a physically based, semi-distributed catchment model of runoff generation that uses topographic information in the form of an index that describes the tendency of water to accumulate and to be moved down slope by the gravitational force (Beven and Kirkby, 1979). TOPMODEL, fully described by Beven et al., (1995) and Quinn et al., (1995) uses the distribution of the topographic index, λ, as an index of hydrologic similarity

$$\lambda_i = \ln\left(\frac{a_i}{\tan\beta_i}\right) \qquad (1)$$

Where, ai(m) is the area draining through a grid square of i per unit length of contour and tan βi is the local surface slope. The basic model assumptions are (Beven et al., 1995): (1) uniform recharge across the catchment with a quasi-steady state condition, (2) local hydraulic gradient can be approximated by the local surface topographic slope, tan βi, (3) using an exponential decline of transmissivity (or hydraulic conductivity) with depth or deficit. Also TOPMODEL represents three layers of the soil column (root, unsaturated and saturated zones) as three interconnected reservoirs. The actual evapotranspiration (AET) is taken from the root zone storage, which can be computed by the following equation:

$$AET_i = RET * SRZ_i / SR_{\max} \qquad (2)$$

Where, SRZi and SRmax are the storage and maximum capacity of the root zone, respectively, RET is reference ET and the subscript of i indicates the location or grid cell.

The unsaturated storage is controlled by the saturation deficit of Si, which is equivalent to the quantity of water required to fill this reservoir. Gravity drainage qvi to the saturated reservoir is delayed as a function of the unsaturated storage SUZi (Franchini et al., 1996):

$$qv_i = SUZ_i / t_d S_i \ \ , with \ \ qv_i \le SUZ_i \qquad (3)$$

Where, td is a constant time delay parameter per unit deficit.

According to the third assumption of the model, the following relation can be considered:

$$K_i(Z_i) = k_o \exp(-fZ_i) \qquad (4)$$

Where, Zi is the depth (Z-axis pointing downwards), k0 is constant hydraulic conductivity at the ground surface and f is a decay factor of hydraulic conductivity with Zi. By applying Darcy's law and the second assumption of the model and using water deficit Si instead of water Table Zi, local lateral subsurface flow qbi from the saturated zone can be calculated by the following equation (Franchini et al., 1996):

$$qb_i = T_o \tan\beta_i \exp(-S_i/m) \qquad (5)$$

Where

$$T_o = k_o / f \qquad (6)$$

Is the transmissivity of the full saturated soil, which, like k_o and f, is assumed constant over the whole sub-basin and

$$m = \frac{\theta_f - \theta_r}{f} \qquad (7)$$

Where, θf and θr are respectively the field capacity and the residual volumetric water contents of the soil and keep constant with depth. By using the first assumption of the model and Eq. (5), the local saturation deficit can be derived (Beven & Kirkby, 1979):

$$S_i = \bar{S} + m(\bar{\lambda} - \lambda_i) \qquad (8)$$

Here, S and λ are the areally averaged values of Si and λ_i, respectively. Then, subsurface flow contribution Q_b can be obtained by contour integration of qb_i (Franchini et al., 1996):

$$Q_b = AT_o \exp(-\bar{\lambda}) \exp\left(\frac{-\bar{S}}{m}\right) = Q_o \exp\left(-\frac{\bar{S}}{m}\right) \qquad (9)$$

where, A is the total drainage area of the sub-basin per unit width; for all points with $S_i \le 0$ the saturation condition has been reached and these points generate a sub-basin fraction that is in a saturated condition where rainfall produces direct overland surface runoff. This excess flow plus subsurface flow Qb at each time step will be the output discharge of sub-basin. According to Eq. (8), all points of the sub-basin with the same topographic index will have the same response in runoff generation. The histogram of topographic index accompanied by meteorological data (precipitation, ET and observed discharge) is used as the model input data. The generated runoff is then routed through the main channel which can be controlled by a routing parameter named CHVEL (Nourani et al, 2011).

For the evaluation of the TOPMODEL performance, the Nash & Sutcliffe (1970) index (NSE) and correlation coefficient between observed data and calculated data (R) have been used. These measures are defined as

$$NSE = 1.0 - \frac{\sum_{i=1}^{No}\left(Q_{i,obs} - Q_{i,sim}\right)^2}{\sum_{i=1}^{n}\left(Q_{i,obs} - \overline{Q}\right)^2} \tag{10}$$

$$R = \frac{\sum_{i=1}^{No}\left(\left(Q_{i,obs} - \overline{Q}_{obs}\right)\left(Q_{i,sim} - \overline{Q}_{i,sim}\right)\right)}{\sqrt{\sum_{i=1}^{No}\left(Q_{i,obs} - \overline{Q}_{obs}\right)^2 \sum_{i=1}^{No}\left(Q_{i,sim} - \overline{Q}_{sim}\right)^2}} \tag{11}$$

ER where, $Q_{i,obs}$ is the observed discharge at $t = i$; $Q_{i,sim}$ is the simulated discharge at $t = i$; No is the number of observed data, respectively and the "bar" sign denotes to the average value.

3. Study Site and Data

The Manimuktha sub catchment of Vellar River basin is located between Latitude of 11°13'N to 12° 00' N and Longitude 78°13'E to 79° 47' E (Fig1). The Manimuktha River in Kalryan hills with drainage area of 749.54 Square Kilometer having two drainages Sankarapuram Taluk at an altitude of about 992m and flows for 72 km. The slopes in the catchment are rather steep, with a mean value of 29.66 percent. The average annual rainfall is 1000 mm in this sub catchmentnamely Mani River and Muktha River originating in the Northern part of the eastern slope of the Kalrayn Hills in. The climate generally becomes pleasant after few showers that usually come in May to June. Again, during the months of September to February the climate becomes cool and pleasant. The average maximum temperature recorded is 36^{o}C and minimum temperature is 27^{o}C. Most of the precipitation (almost 73%) falls during the South West monsoon seasons (October to December).The mean annual precipitation is to be 848.4mm calculated from the five rain gauge stations located in the study area. Daily runoff, evapo-transpiration and hourly runoff (at the time of flood events) are measured at the dam site by the state public Works Department. Fig.1 shows the watershed boundary with Metrological Stations. The sub catchment covers agriculture area in the lower part and upper portion covers forest area. Thick dense forest occurs in the Velli malai and Kalrayan hills. Medium dense forest occurs in the lower Kalrayan hills. Low dense forest and shrub forests are well developed in the slopes and foot of hills. Upper reach of the catchment contains red loamy soil and middle and lower part of the catchment contains clay soil. Isolated pockets calcareous lime contained saline soil are also identified.

Hourly rainfall and runoff data is available for the flood events at the dam site, six storm events were used in this study. Totally five rain gauge stations are available inside the catchment and daily evapo-transpiration is measured at the dam site by the state Public Works Departments.

4. Results and Discussion

Model allows hydrologists to study complex problems in an attempt to simulate and even predict hydrologic behavior. However, model results depend entirely on the model assumptions, inputs, and parameter estimates. The rainfall-runoff model was applied to hourly data from the Manimuktha catchment, using simple event based data. The initial parameter estimates were adjusted by trial-and-error, aiming at minimizing the residuals between observed and simulated values of runoff, surface soil moisture and depth to the groundwater table.

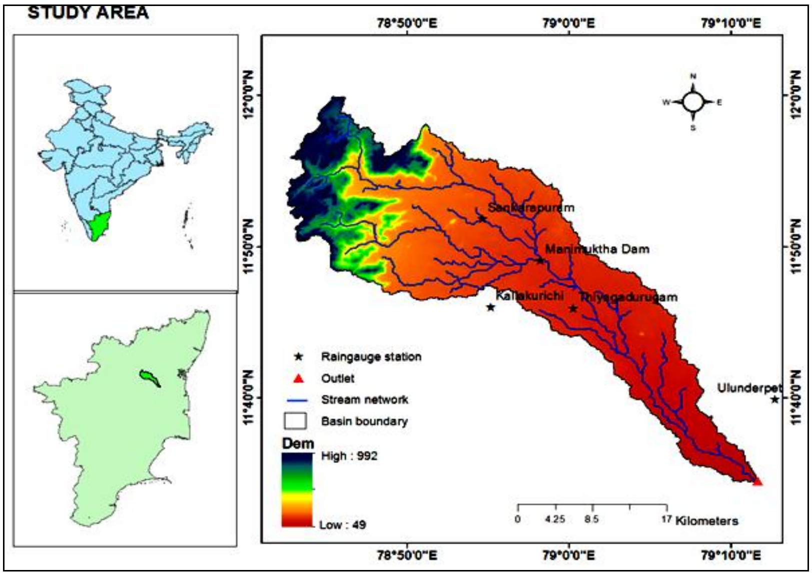

Figure 1*Study area map of Manimuktha sub-catchment*

4.1 Derivation of the topography index

Derivation of Topographic Index (TI) is the basic key parameter in the surface runoff generation and DEM is an input to the model. For the present study, the DEM (Fig 1) is derived from the SRTM 90 m global cover data. It is further analysed to remove sinks in it and the pit free DEM is further used to calculate the spatial distribution of the topography index and catchment slope (Fig 3). The single flow direction and flow accumulation method (Jenson and Domingue, 1988) was used to derive the contributing area and the surface topographic slope grid required to determine the topographic index distribution (λ) using Equation (10). The spatial distribution of the topographic index $\ln\left(a_i/\tan\beta_i\right)$ is shown in Figure 4. The cumulative distribution of the topographic index for the study catchment is shown in Figure 5. This topographic index distribution is a physically measurable catchment attribute and directly influence the value of the lateral transmissivity of soil. Table 1 shows that the lateral transmissivity of soil *To* is 9.8 m^2/hr which is identified at 90m DEM resolution of the Manimuktha catchment.

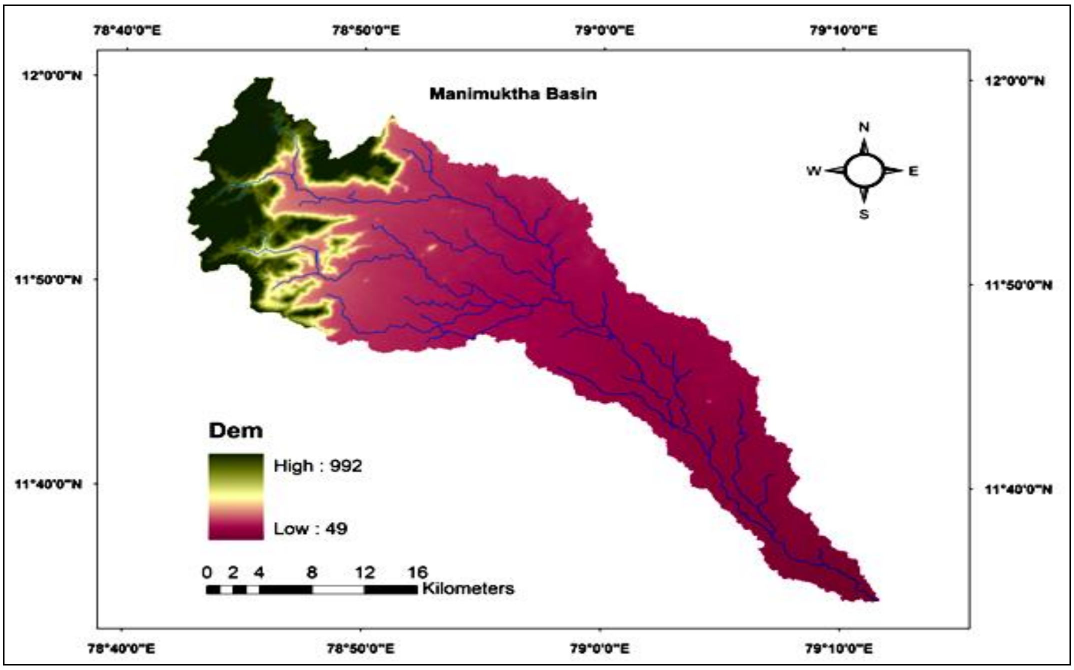

Figure 2 *DEM of the Manimuktha sub-catchment: Vellar River catchmen*

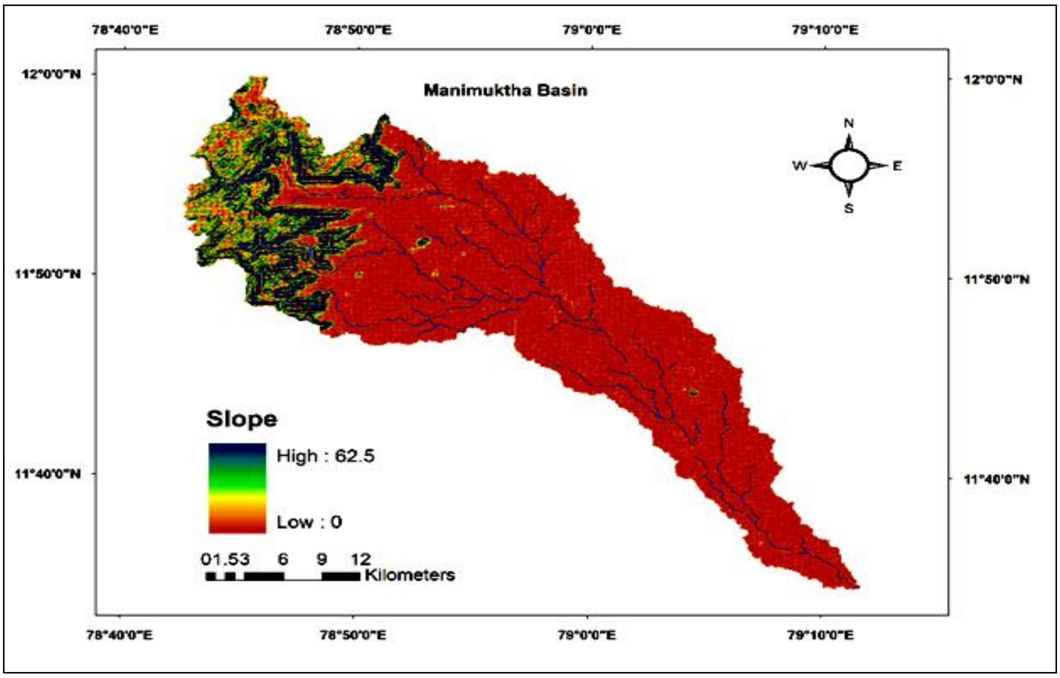

Figure 3 *slope of the Manimuktha sub-catchment: Vellar River catchment*

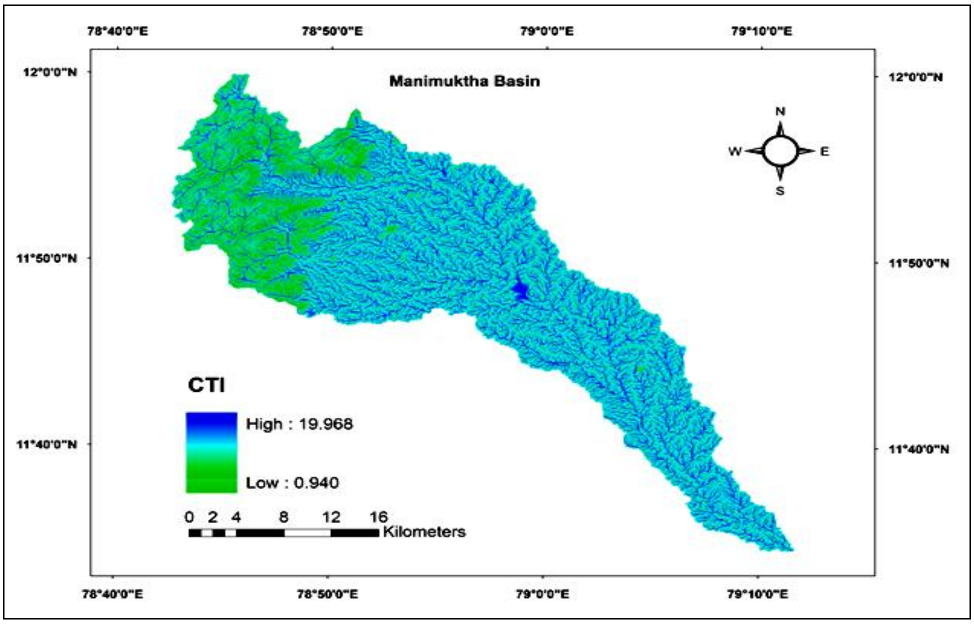

Figure 4. *Compound topographic index of Manimuktha for grid cell size of 90 m*

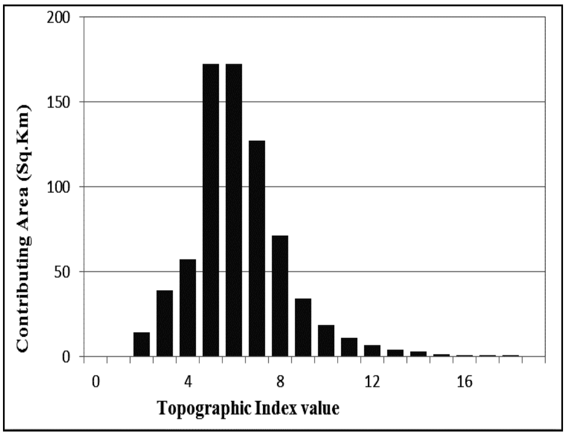

Figure 5. *Cumulative frequency distribution of the topographic index for grid cell size of 90 m*

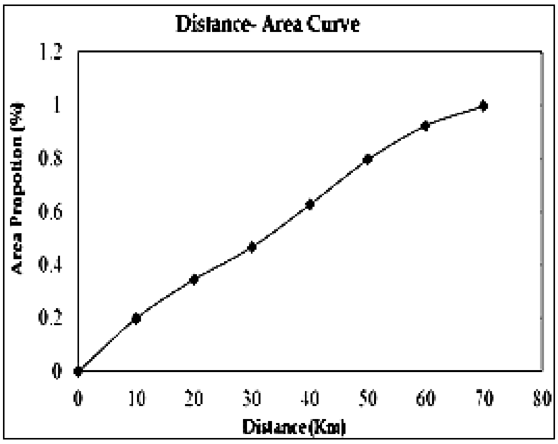

Figure 6. *Distance-area accumulation curve of topographic index the routing method based on the DEM*

In this study flow is routed based on time area routing method,in which the travel time of the watershed is equally divided in to various distance area curve. The distance area curve for the river basin is shown in Figure 6.

4.2 Initial calibration process

Table 1 shows the parameter values used in the initial calibration process and Fig. 7 shows stream flow simulation results. Generally, TOPMODEL was able to successfully reproduce the peaks and for six storm events used in this study. However, the predictions of the model are peaky compared to the observed flow. Fig. 7 also shows that the model did not perform well in the timing of the peaks particularly in complex storm. The Nash Sutcliffe (NSE) model efficiency obtained was 0.716 which is quite satisfactory.

4.3 Effect of TOPMODEL parameter in runoff generation

The calibration of the model was performed at a 1-hour time step using available hydrological data. From the manual calibration, it was found that simulated runoff was highly sensitive to soil parameters [(m), ln(To) and SRmax]. Small value of (m) indicated great variation in saturated hydraulic conductivity with depth. It indicated flashy type of catchment (hydrograph rising and falling very quickly) with runoff governed by quick flow and small contribution of sub-surface runoff. With increasing value of (m) parameter the contribution of sub-surface runoff increased and saturated runoff decreased. For large values of (m), the proportion of rainfall that reaches the outlet via a surface route was decreased. This occurs because large values of (m) indicate a deeper effective soil allowing more rainfall to infiltrate the soil. Small values of (m), thus, indicate a more shallow effective soil allowing less rainfall to infiltrate the soil. The usual range of (m) is from 0.01-0.1m (Beven, 1997; Sigdel et al., 2011; Nourani et al, 2007). Small values of T_o parameter, coupled with high values of the m parameter (Table 2), generated a deep effective soil, but with low water holding and transmitting capacity. This combination produced increased surface saturated runoff and gradual recession curve response in the modeled hydrograph. For smaller value of SRmax the simulation, result shows higher peaks and reduces as its value is increased. However the other parameters, Chv, Grid cell resolution and flow accumulation (single direction or multiple flow direction) and initial moisture level, ground water table are also influencing the simulation accuracy. Also initial discharge (Q_0) and initial root zone deficit (Sd) and they are not calibrated in this study. Fig. 7 shows the computed hydrographs of events in the verification phases, respectively. As it is clear in the Tables 2, there is a reasonable match between the simulated and observed hydrographs, peak points, time to peaks, and total runoff volumes, especially after calibrating the initial parameters.Verification of the model was done by running the model using exactly the same parameters as mentioned above in the calibration process. Figs. 8 show the observed and simulated hydrographs for validation for the storm event dated 15.12.71.

The runoff response of a catchment was found sensitive to the value of ln(T0), represent imperviousness characteristics of the catchment. Small value of ln(To) resulted in large peak and quick recession and recession was gradual for large value of ln(To). With decrease in transmissivity, local ground water table increased which resulted in increased overland runoff due to increased saturation area (Sigdel et al., 2011). The sensitivity analysis of TOPMODEL for the ln(To) parameter has been done for the value range 1 to 25. Figure 8 show the effect of the parameter on the shape and on the peak flow of the hydrograph. The change in the peak flow from lower value (1 to 5) was significant but for the higher value, the observed change is very small. This parameter does not seem to significantly affect the recession tail of the hydrograph. However, the To parameter has significant impacts on the surface runoff so that the peak flow seems to have large impact on the recession tail of the hydrograph or on the baseflow after the rainfall event. For lower value of To the peak flow for most of the years is higher than the observed peak flow. Fig. 8 shows the computed hydrographs of events in the verification phases, and there is a reasonable match between the simulated and observed hydrographs, peak points, time to peaks, and total runoff volumes.

5. Conclusions

A Semi distributed stream flow model was developed for the Manimuktha sub-catchment using TOPMODEL concept. Six hourly storm events used in this study for the simulation of stream flow. Based on the results of this study, Remote sensing and GIS was instrumental in acquiring 90 m resolution SRTM DEM which is critical input for the prediction of low direction, flow accumulation, and slope for this semi-distributed hydrological modeling through the computation of the topographic index. TOPMODEL made an explicit link between catchment topography and the generation of stream flow. The catchment parameters are derived by using ArcGIS 10.2. The sensitivity analysis of TOPMODEL for the ln(To) parameter has been done for the value range 1 to 25. Results show the effect of peak flow from lower value (1 to 5) was significant but for the higher value, the observed change is very small.

Table.1 *shows the initial parameters used for model simulation*

Parameter	**m**	**ln T0**	**TD**	**CHV**	**SRmax**	**Qo**	**SRO**	**INFEX**	**XKO**	**HF**	**DTH**
	[m]	[m^2/hr]	[hrs]	[m/hr]	[m/hr]	[m/dt]	[m]	[-]	[m/hr]	[m]	[-]
Value	0.06	5	22	39.00	1.900	0.09	0	0	3	0.1	0.36

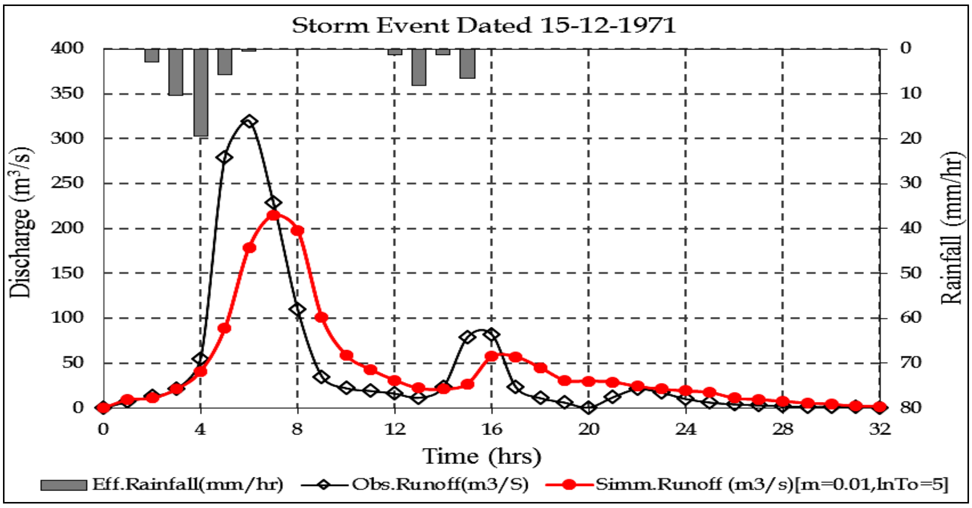

Figure 7. *Observed and simulated hydrographs of initial calibration step*

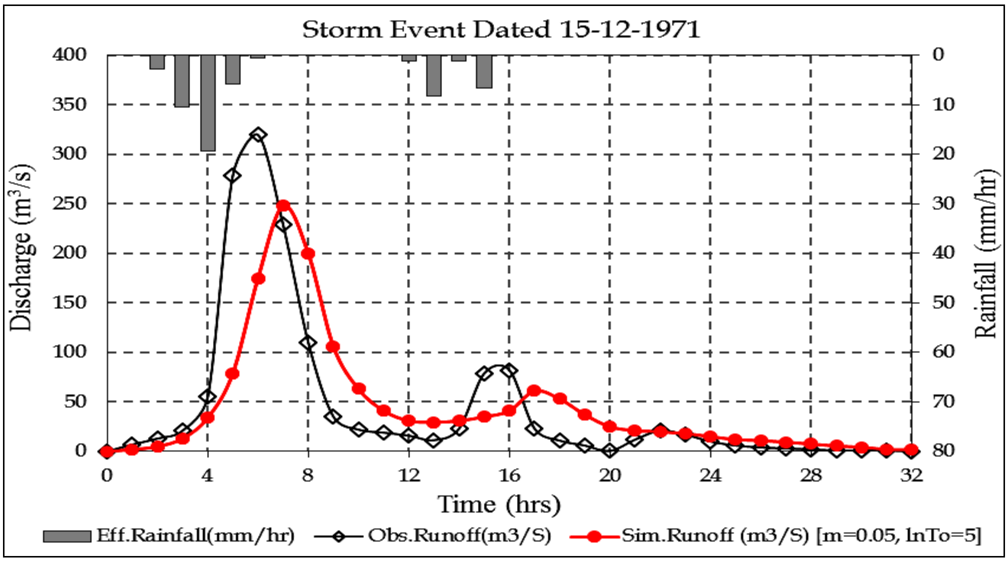

Figure 8. *Observed and simulated hydrographs of initial calibration step*

Table 2. *The flood simulation results of calibration and verification phases of Manimuktha*

Phase	Event	Sim. Peak Flow Qs (m^3/s)	Observed Peak FlowQs (m^3/s)	Sim.Time to Peak Tpo (h)	Observed Time to Peak Tpo (h)	% Err.Qp	% err.Tp	NSE	R
Calibration	15/12/1971	396.7	478	5	5	17.01	0.00	0.79	0.66
	01/10/1977	248	320	7	6	22.50	-16.67	0.778	0.69
	11/12/1980	418.5	469	5	4	10.77	-25.00	0.812	0.891
	21/11/2005	854.5	905	4	4	5.58	0.00	0.67	0.711
Verification	03/10/1995	780	860	4	4	9.30	0.00	0.706	0.78
	11/12/2000	716	870	5	4	17.70	-25.00	0.663	0.774

The sensitivity analysis of TOPMODEL for the "m" parameter has been done for the value range 0.01-0.1m. Small value of (m) indicated great variation in saturated hydraulic conductivity with depth. It indicated flashy type of catchment (hydrograph rising and falling very quickly) with runoff governed by quick flow and small contribution of sub-surface runoff. With increasing value of (m) parameter the contribution of sub-surface runoff increased and saturated runoff decreased. The TOPMODEL concept produced predictions that can be considered much acceptable (final calibration results: Nash-Sutcliffe efficiency was 78.8% as compared to the calibrated efficiency 71.5% and the correlation coefficient 0.625 in calibration and 0.69 in validation.

Thus we conclude that the TOPMODEL can be used to simulate storm event. Based on the variation of NSE, R value and implications on shape of resulting hydrographs, TOPMODEL showed the greatest sensitivity to the m, T0 and SRmax parameters. Similarly a major disadvantage of using event based simulation is, its inability to account the amount of moisture in the soil column.

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