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GIS BASED RAINFALL-RUNOFF MODELLING FOR HEMAVATHY CATCHMENT

NATIONAL INSTITUTE OF HYDROLOGY
JALVIGYAN BHAWAN
ROORKEE - 247 667
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ABSTRACT

The TOPMODEL is a variable contribution area conceptual model in which the predominant factors determining the formation of runoff are represented by the topography of the basin and a negative exponential law linking the transmissivity of the soil with the vertical distance from the ground level. In this model the total flow is calculated as the sum of two terms: surface runoff and flow in the saturated zone. The TOPMODEL is attractive because of its structural simplicity and parsimonious parameterisation. It is one of the few conceptual models that accounts explicitly for the saturation excess overland flow mechanism and integrates the variable contributing area concept, both of which are essential to model the catchment accurately.

Calibration and validation of the TOPMODEL is carried out on Hemavati catchment situated in Western Ghats. Raster DEM input for the model is generated through ILWIS after digitization contour map from Survey of India toposheets. In all 5 years of data was available for simulation study. Available data series was broken in two parts and first part i.e. June 1975-December 1977 was used for model parameter calibration and remaining data series i.e. January 1978 to December 1980 was used for model validation. Simulation results are encouraging. Model efficiency (Nash-Sutcliffe) was more than 0.84 both for model calibration and validation on independent data series.

1.0 INTRODUCTION

Hydrological appraisal of the watersheds is the basic requirement for the planning, design and construction of water resources projects. The analysis of the factors affecting the formation of basin flow is still one of the key area of research in hydrology. The literature contains many works which summarize the current level of understating of the physics of the complex process of rainfall-runoff transformation, and still more focus on the state of the art of the possible ways of schematizing the whole process so as to develop mathematical models (Todini, 1981). In fact, the representation of runoff formation processes has been accomplished, over the decades, with methods which vary according to the purpose and application of the model. These range from the simple (in a manner of speaking) calculation of design discharge to the two-dimensional representation of the various processes, based on suitably conditioned mass balance, energy and momentum equations, and to the three-dimensional representation of all the exchanges. Taken together these latter kinds of model comprise the broad category of distributed differential models (Todini, 1988); they are frequently referred as "physically based models" to highlight the fact that their respective parameters are reflected in the field measurements. Given their nature, they are mainly used in investigations and research as a mathematical support for the interpretation of physical reality. Yet, recently, major criticisms have been levelled against these complex and ambitious models(Beven,1989), calling into question the following :1) the value of using equations which are undoubtedly valid for laboratory construction flow systems which clearly define boundary conditions and properties, but which do not afford equally acceptable guarantees for systems with markedly heterogeneous physical properties in which the boundary conditions remain uncertain, as occurs in a "system" such as the one represented by a basin; 2) the meaning of the word "physical" when assigned to a parameter which by its instead is held to be representative of a loosely defined "mean" value, which in turn is characteristic of the system's space discretisation grid.

Lying between the extreme categories of model indicated there are the distributed integral models (Todini, 1988), which certainly incorporate the large family of models commonly referred to as conceptual models. In these, the many factors listed above are only partly represented and, what is more, this is done by means of simplified schematisation whose basic purpose is to reproduce total flow measurable at the basin outlet.

The TOPMODEL (Beven and Kirkby, 1979) is a variable contribution area conceptual model in which the predominant factors determining the formation of runoff are represented by the topography of the basin and a negative exponential law linking the transmissivity of the soil with the vertical distance from the ground level. In this model the total flow is calculated as the sum of two terms: surface runoff and flow in the saturated zone. The surface runoff, in the most recent versions of the model, is in turn the sum of two components, the first generated by infiltration excess and the second, referring to a variable contributing area, by saturation excess. Though a conceptual model, i.e. one in which the physical reality is represented in a simplified manner, the TOPMODEL is frequently described as being 'physically based', in the sense that its parameters can be measured directly in situ (Beven and Kirkby, 1979). This definition is somewhat optimistic, in view of the doubts and uncertainties encountered even in defining the parameters of the "physically based models", as already mentioned. The TOPMODEL is attractive because of its structural simplicity and parsimonious parameterisation. The TOPMODEL is one of the few conceptual models that accounts explicitly for the saturation excess overland flow mechanism and integrates the variable contributing area concept, both of which are essential to model the catchment accurately.

1.1 Scope of Present Report

Geographic Information Systems (GIS) is a rapidly evolving suit of technologies that consists of computer based programs containing specialized algorithms and associated database-management structures, frequently in an integrated package. These systems are expressly designed to store information about the location, topology and attributes of spatially referenced objects (such as rivers, wetland, political boundaries, and roads). GIS can also provide an analysis of the spatial properties (such as length, area, and perimeter) of these geographic objects. GIS can support many data base queries tied to spatially referenced objects and their related attributes. GIS systems also possess specialized spatial analysis functions, such as overlay of thematic layers and buffer zone generation around the objects. GIS systems provides other more specialized spatial analysis functions: finding shortest path in a network or calculating areal extent of a watershed draining through a specified point given a Digital Elevation Model (DEM).

Topography is recognized as an important factor in determining the streamflow response of watershed to precipitation. Topography defines the effects of gravity on the movement of water in a watershed and therefore influence many aspects of the hydrological system. TOPMODEL is a simple but physical hydrological model that aim to represent the effects of catchment heterogeneity and, particularly, topography on the dynamics of hydrological response. It is a topography based watershed hydrology model that has been used to study a range of topics, including spatial scale effects on hydrological processes, topographic effects on water quality, topographic effects on stream flow, climate change effects on hydrological processes, the geomorphological evolution of basins, the identification of hydrological flow paths etc.

Present report is aimed at application of TOPMODEL in a catchment in Western Ghats. Scope of this report include calibration and validation of TOPMODEL in Hemavati catchment in Western Ghats.

2.0 MODEL DESCRIPTION

Hydrological processes within a catchment are dynamically and heterogeneously distributed. The interactions of vegetation and rainstorm dynamics may lead to very non-uniform inputs to the upper boundary of the soil. Soil and bedrock heterogeneity may further complicate flow paths, causing phenomenon such as linked saturated pockets, macroflow and pipe flow Every model is an attempt to capture the essence of complex hydrological system in meaningful and manageable way, but it is important this conceptualization involves a considerable degree of simplification.

TOPMODEL (TOPography based hydrological MODEL) is now 20 years old and has been subject to numerous applications to a wide variety of catchments.

In TOPMODEL, Stream flow is generated from two processes:

1. Water draining from sub surface saturated zones.
2. Water displaced from saturated and near saturated parts of the catchment. (i.e. rainfall landing on saturated contributing areas and causing movement to the stream via macropore flow, overland flow, or old water displacement. It is distinguished from the subsurface saturated zone discharge because of the much faster speed of response.

In making such a conceptualization TOPMODEL is premised upon two basic assumptions:

A1 that the dynamics of the saturated zone can be approximated by successive steady state representations;

A2 that the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope, $\tan\beta$.

These assumptions lead to simple relationship between catchment storage (or storage deficit) and local level of water table (or storage deficit due to drainage) in which the main factor is the topographic index ($a/\tan\beta$). This topographic index represents the propensity of any point in the catchment to develop saturated conditions. A high index value usually indicate a wet part of the catchment; this can arise either from a large contributing area (valley bottoms or convergent hollows) or from valley flats (bogs on hill tops). Areas with low index value are usually drier, resulting from either steep slopes or small contributing areas. *The saturated contributing areas will both grow and decline during the course of storm event.*

Grid squares with same index value are assumed to behave in a hydrological similar manner. As a result of this assumption, the catchment topography may be summarized by the distribution of the index value. The assumptions are similar to as those used in development of 'wetness' index developed independently by O'Loughlin (1986). TOPMODEL in its original form, however, takes advantage of the mathematical simplifications allowed by a third assumption:

A3 that the distribution of down slope transmissivity with depth is an exponential function of storage deficit or depth to the water table.

$$T = T_0 e^{-\frac{S}{m}} \qquad \textbf{(1)}$$

Where T_0 is local transmissivity when the soil is just saturated (m^2/h). S is local storage deficit (m) and m is a model parameter (m).

In terms of water table depth this can be written as:

$$T = T_0 e^{-fz} \qquad \textbf{(2)}$$

Where z is local water table depth (m) and f is a scaling parameter (m^{-1}). The parameter f and m are approximately related by $f = A0_1/m$ where $A0_1$ is an effective water content change per unit depth in the unsaturated zone due to rapid gravity drainage (down to 'field capacity').

A physical interpretation of the decay parameter m is that it controls the effective depth of the catchment soil profile. This it does interactively with the parameter T_0, which defines the transmissivity of the profile when saturated to the surface. A large value of m effectively increases the active depth of soil profile. A small value, especially if coupled with a relatively high T_0, generates a shallow effective soil, but with a pronounces transmissivity decay. This combination tends to produce a well defined and a relatively shallow recession curve response in the model hydrograph.

Under the assumption A2 of an effective water table gradient and saturated flow parallel to the local surface slope *tanβ*, then at any point i on a hill slope, the downslope saturated subsurface flow rate qs_i per unit contour length may be described by the equation:

$$qs_i = T_0 \exp(-z_i f)\tan\beta_i \qquad (3)$$

Where,

qs_i = local lateral saturated flow per unit length of contour (m^2h^{-1})
z_i = local depth to the water table
β_i = local slope angle
T_0 = lateral transmissivity when the soil is saturated to the surface (m^2h^{-1})
f = exponential decrease in transmissivity with depth (m^{-1}).

Then under the assumption A1 that, at any time step, quasi-steady-state flow exists through the soil, then assuming a spatially homogeneous recharge rate r (m/h) entering the water table, the subsurface downslope flow per unit contour length qs_i may also be given by:

$$qs_i = ra \qquad (4)$$

Where a is the area of the hill slope per unit contour length (m^2) that drains through point i.

By combining Eqs. (3) and (4) it is possible to derive a formula for any point relating local water table depth to the topographic index ln(a/tan*β*) at that point, the parameter f, the local saturated transmissivity and the effective recharge rate, r:

$$z_i = -\frac{1}{f}\ln\frac{ra}{T_0\tan\beta} \qquad (5)$$

An expression for the catchment lumped, or mean, water table depth ($\bar{z}$) may be obtained by integrating Eq. (5) over the entire area of the catchment (A) that contributes to the water table. In what follows we will express this areal averaging in terms of a summation over all points (or pixel) within the catchment:

$$\bar{z} = \frac{1}{A}\sum_i -\frac{1}{f}\ln\frac{ra}{T_0\tan\beta} \qquad (6)$$

In spatially integrating the whole catchment, it is also implicitly required that Eq. (6) holds even at such locations where water is pounded over the surface ($z_i < 0$). Beven (1991)

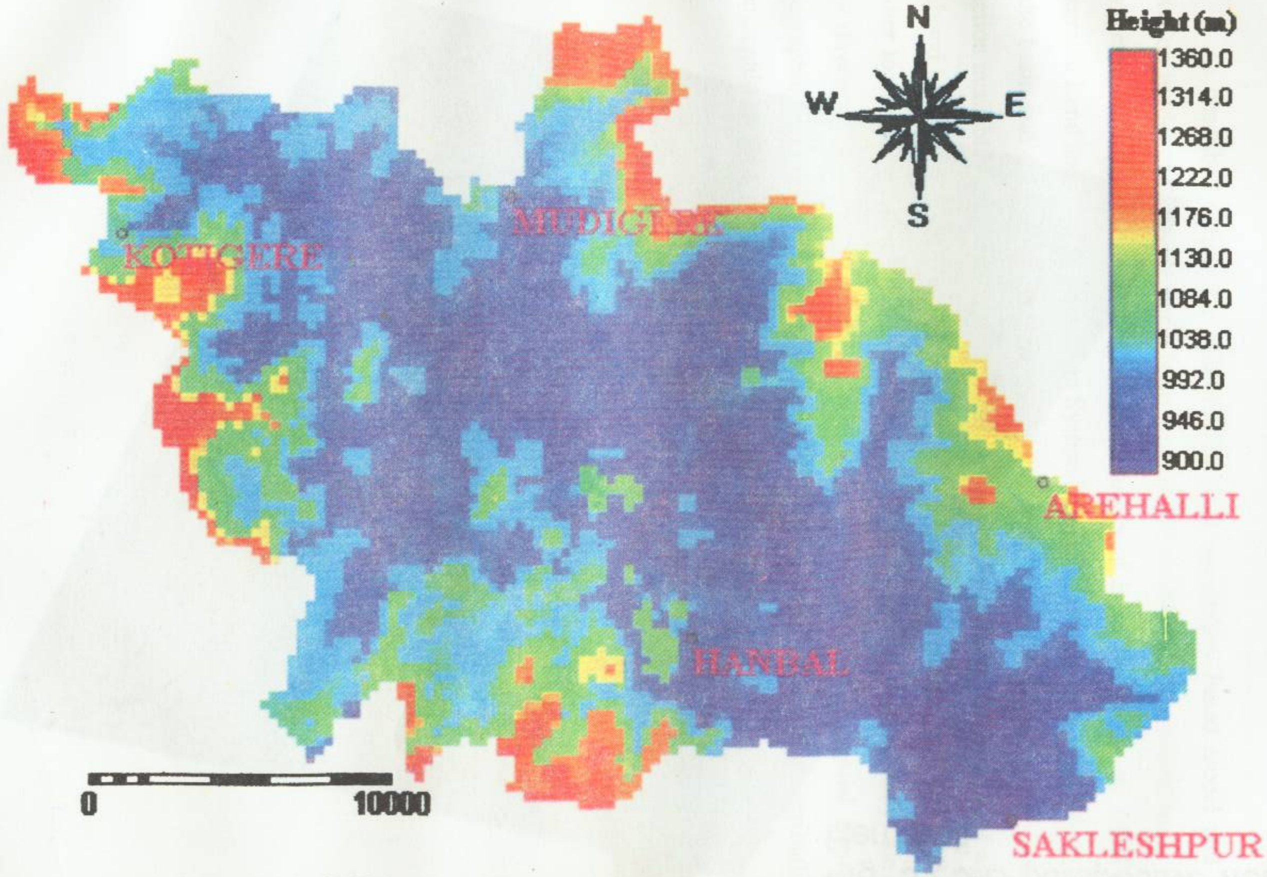


Fig. 2 Digital Elevation Model of Hemavati

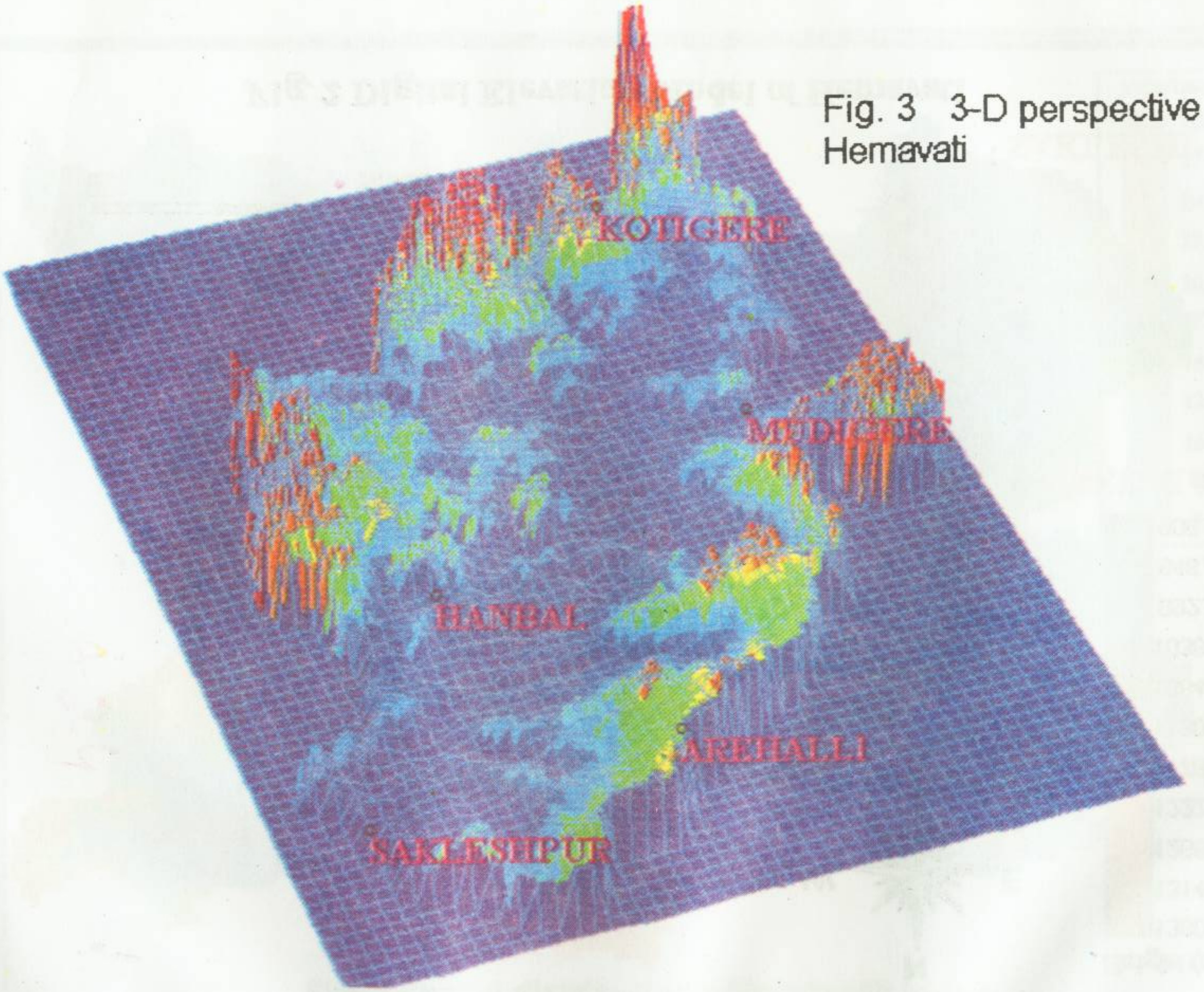


Fig. 3 3-D perspective view of Hemavati

4.0 Computation of ln(a/tanβ) index

As described earlier the TOPMODEL is a topography based model and a digital elevation model of the study basin is an input to the model. For the present study the DEM is generated by digitizing the contours from survey of India toposheets on 1:50,000 scale. Integrated Land and Water Information System (ILWIS) was used to digitize the contour map of the basin and a DEM of the study basin was generated by rasterization and interpolation function available in ILWIS. The pixel size chosen for the DEM was 300m. DEM was further analysed to remove sinks in it by averaging and elevation increment. Sink free DEM is used further to calculate ln(a/tanβ) distribution for the basin. For the present study, the multiple flow direction algorithm reported by Quinn et al. (1995) is followed. Spatial distribution of topographic index ln(a/tanβ) is shown in Fig.4. The cumulative frequency distribution of the topographic index for the study catchment is shown in Fig. 5.

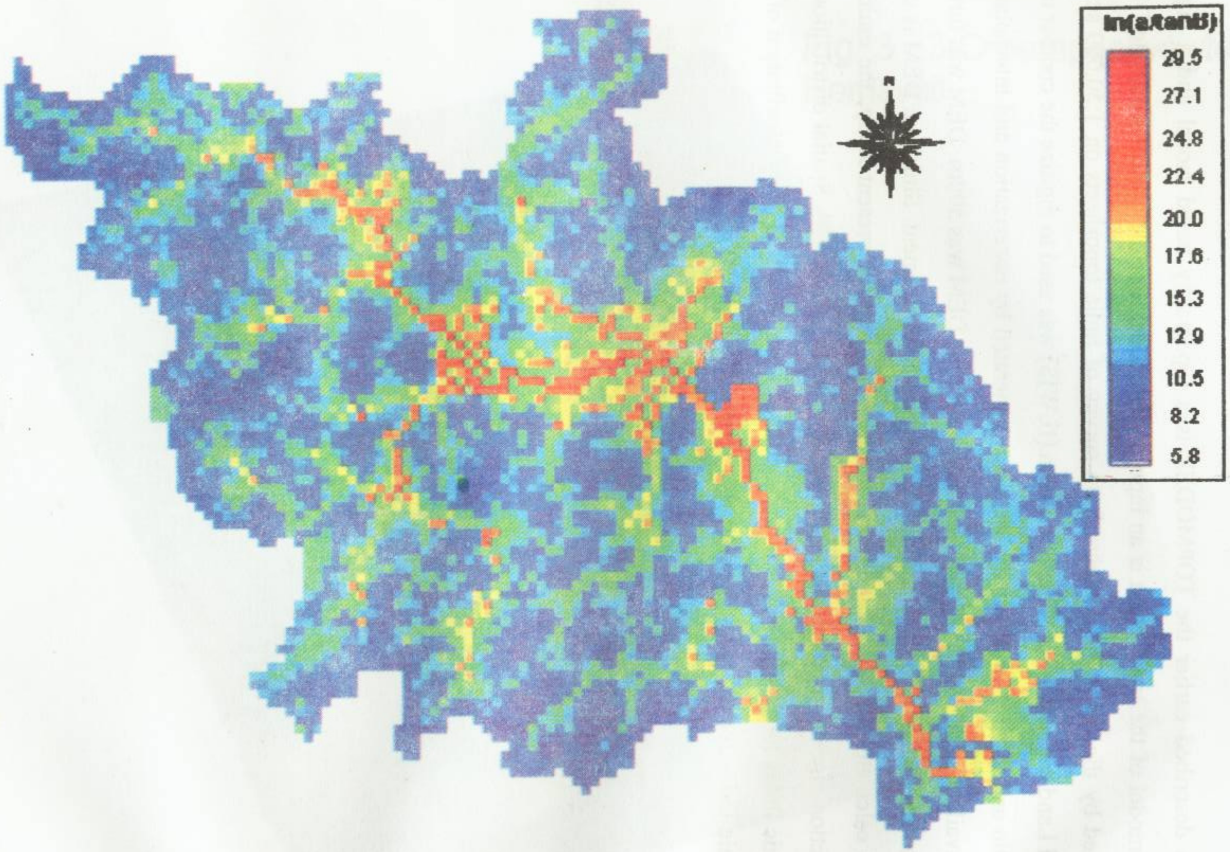


Fig. 4 Spatial distribution of ln(a/tanB) index

justified this assumption on the basis that the relationship expressed by Eq. (3) is exponential and that, for many catchments, surface flow is likely slow due to vegetation cover. By using Eqs. (5) in Eq. (6), if it is assumed that r is spatially constant, ln(r) may be eliminated and a relationship found between mean water table depth, local water table depth, the topographic variables and saturated transmissivity. This has the form:

$$\bar{z} = z_i - \frac{1}{f}\left[\gamma - \ln\frac{a}{T_0 \tan\beta}\right] \tag{7}$$

Where $\ln(a/T_0 \tan\beta)$ is the soil-topographic index, and

$$\gamma = \frac{1}{A}\sum_i \ln\frac{a}{T_0 \tan\beta} \tag{8}$$

A separate areal average value of transmissivity may be defined, thus:

$$\ln T_e = \frac{1}{A}\sum_i \ln T_0 \tag{9}$$

Eq. (7) may now be rearranged to give:

$$f(\bar{z} - z_i) = \left[\ln\frac{a}{\tan\beta} - \lambda\right] - [\ln T_0 - \ln T_e] \tag{10}$$

Where:

$$\lambda = \frac{1}{A}\sum_i \ln\frac{a}{\tan\beta} \tag{11}$$

is a topographic constant for the catchment.

Eq. (10) may also be written in terms of storage deficit as:

$$\frac{(\bar{S} - S_i)}{m} = \left[\ln\frac{a}{\tan\beta} - \lambda\right] - [\ln T_0 - \ln T_e] \tag{12}$$

From Eq. (3) contributing areas are summed over the catchment to give a total flow per unit area from the saturated zones:

$$qs = T_0 \exp(-\bar{z}f - \lambda) \tag{13}$$

Where λ is the areal average of the index given by Eq. (11) and $\bar{z}$ is the mean catchment depth of the water table.

Knowledge of local depth to water table allows determination of areas where water table is at the surface (i.e. the saturated contributing areas, SCA), and this is used to calculate q_{SCA}, the average flow per unit area of the catchment generated by the rainfall on the saturated contributing areas. Hence at a given time t the total flow per unit area is

$$q_t = qs_t + q_{SCA} \tag{14}$$

At each time step the value of $\bar{z}$ is updated ready for use in the next interval:

$$\bar{z}_{t+1} = \bar{z}_t + (qs_t \quad qv_t)/\Delta\Theta \tag{15}$$

Where $\Delta\Theta$ is the storage capacity of the soil as a proportion of total soil volume and qv_t is the total vertical flow through the unsaturated zone down to the saturated zone; qv_t is calculated by summing the local values of vertical drainage. These are derived by assuming that the hydraulic conductivity has an exponential profile with depth (with the same exponential decay parameter as for lateral flow) and that near the water table there is a unit hydraulic gradient. Local vertical flow is then given by:

$$qv_{t_i} = K_0 \exp(-z_i f) \tag{16}$$

Where K_0 is the vertical conductivity at the surface (mh^{-1}). This allows for increasing mean residence time in the unsaturated zone with increasing depth to the water table.

In TOPMODEL evaporation is allowed at the full potential rate for the water draining freely in the unsaturated zone and for predicted areas of surface saturation. When the gravity drainage zone is exhausted, evapotranspiration may continue to deplete root zone store at the rate E_a given by:

$$E_a = E_p\left(1 - \frac{S_{rz}}{S_{rmax}}\right) \tag{17}$$

Where E_p = potential evaporation, S_{rz} = current root zone storage deficit, S_{rmax} = maximum allowable storage deficit.

For many catchments, especially large ones, it may be inappropriate to assume that all runoff reaches the catchment outlet within a single time step. In such cases, some routing of the model output may be required. Overland flow may be routed by the use of a distance-related delay function. The time taken to reach the basin outlet from any point is assumed to be given by:

$$\sum_{i=1}^{N} \frac{x_i}{\upsilon \tan\beta_i} \qquad \textbf{(18)}$$

where, x_i is the length and tan β_i the slope of the i-th segment of a flow path comprising of N segments. The velocity parameter υ (m/h) is assumed constant.

3.0 THE STUDY AREA AND DATA AVAILABILITY

3.1 The Hemavati Basin

The Hemavati, also known as Yennehole, is one of the important tributaries to join the Cauvery on its northern bank. It rises in Ballalara -Yanadurga in the Mudigere taluk of Chickmaglur district in western ghats. The Hemavati, after traversing a length of 193 km in Hassan and Mandya district, joins the river Cauvery in the water spread of Krishnarajasagar reservoir near Akkihebbal. In its upper reaches, the river Hemavati originates from a very heavy rainfall region in the vicinity of Mudigere and Kotigere. Important tributaries of Hemavati are Yagachi and Alur. In addition to these major streams, a number of minor streams join the river all along its course. The river drains an area of 5,200 sq km. The annual rainfall varies from a maximum of 5080 mm to a minimum of 762 mm with an average annual rainfall of 2972 mm. The economy of the basin is primarily dependent on agriculture which is the chief occupation of the people. In the hilly region there are number of check dams constructed across the river during 19th century which are still in use for irrigation. In the undulating plain, tank irrigation is common. Efforts are being made to increase irrigation potential by constructing storage structures.

3.2 The study area

For the present study, the head water catchment of the Hemavati, defined by the Water Resources Development Organisation (WRDO) gauging site at Sakleshpur (area 632.1 km^2) have been considered. The Hemavati basin up to Sakleshpur lies between 12°55′ and 13°11′ north latitude and 75°20′ and 75°51′ east longitude in the south western parts of Chickmaglur and Hassan districts. The area is a typical example of monsoon type of climate. The catchment is hilly with steep to moderate slopes. Fig. 1 shows a map of the study area along with rainfall and discharge stations in the basin. The rain gauge stations are Arehalli, Kotigere, Hanbal, Mudigere and Sakleshpur. Daily rainfall and runoff data from June 1975 to December 1980 were used for the study. Daily pan evaporation data at Gorur were available and used.

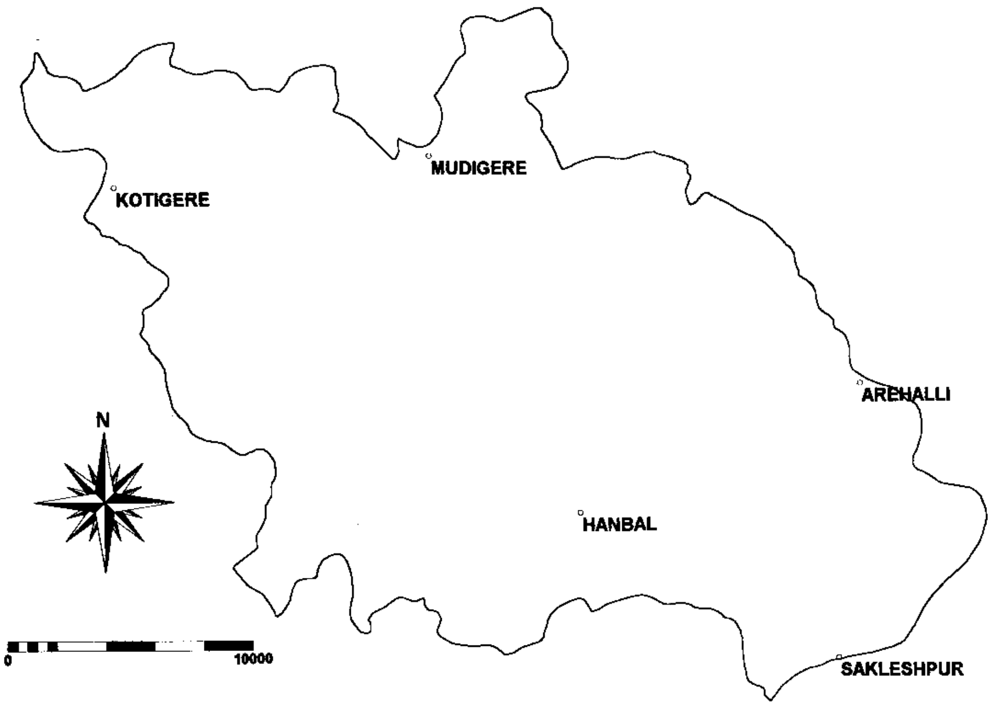


Fig. 1. Map of Hemavati catchment showing raingauge stations

3.2.1 Climate and rainfall

The catchment area is a typical example of monsoon type of climate. The summer season extends from March to May. Rainy season extends from June to October. Heavy to very heavy rainstorms are experienced in the rainy season. November to February are winter months. Severe cold is experienced during these months.

3.2.2 Topography

The area under study is a hilly catchment with steep to moderate slope. The slope is very high in the upper reaches and reduces gradually in the lower reaches. The general elevation of the basin ranges from 890 m to 1240 m above mean sea level. The entire basin may be classified as hilly lands, moderately sloping and low lands (valley lands). Fig. 2 shows the topographic map of the basin. Fig. 3 shows the 3-dimensional view of the catchment.

3.2.3 Geology

The main geological formations are schists, granites and grosses all of Precambrian age. Schists are found in western parts of the basin and some scattered patches are also found in eastern portion.

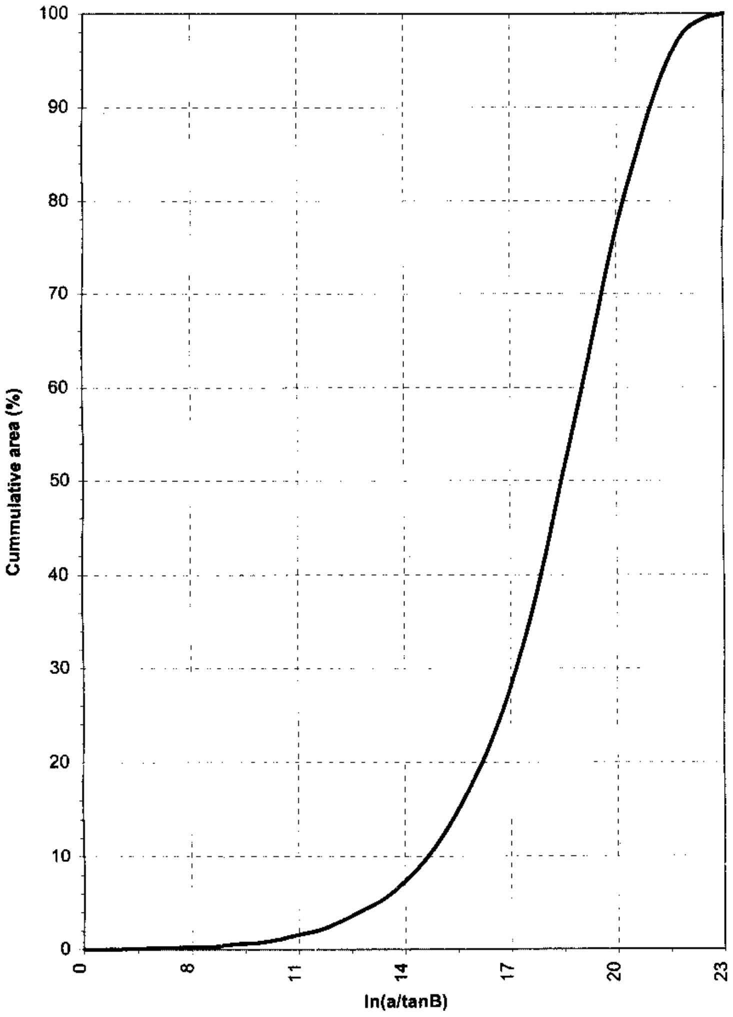
3.2.4 Land use

Agriculture and plantation is the main land use in the basin. The main crops grown are coffee, paddy and Cardamom. Coffee is cultivated on hills slopes, paddy cultivation is practised in valleys and cardamom is grown every where.

3.3.6 Soils

The soil of the basin can be classified into two main categories viz. red loamy soils and red sandy soils. The soils found in forest areas and coffee plantation are greyish in colour due to high humus content. The moisture retention capacity of the soils found in the area is less compared to heavy soils and are unable to sustain a good crop without irrigation. The texture of the soil is fine to very fine. The soils are neutral in nature and the soil pH ranges from 6.5 to 7.5.

Fig. 5 Cummulative frequency distribution of the topographic index for Hemavati catchment.



5.0 MODEL CALIBRATION AND DISCUSSION OF RESULTS

Each formulation of the TOPMODEL may present an individual parameter set to be calibrated; however, there are invariably three or four critical parameters that most directly control model response. These are the saturated zone parameter f (or m in the original storage deficit formulation), the saturated transmissivity value T_0, and root zone parameter S_{max}, and in large catchments a channel routing velocity v. The topographic index was derived from a raster digital elevation model (DEM) with a grid spacing of 300 m using the multiple flow direction algorithm proposed by Quinn et al. (1995).

The model was applied on a continuous basis over periods of approximately 2 year 6 months (June 1975 to Dec. 1977) for calibration of model parameters. Remaining data series i.e. January 1978 to December 1980 was used for model validation. This data length fulfil the criterion suggested by Sorooshian (1983) where he suggested that atleast 1 year data is necessary to calibrate 'conceptual' models and stressed the importance of activating all model components during calibration. A time step Δt of 1 day was selected for simulation.

For model calibration, Q_0 was set to the first observed discharge value and the main channel routing velocity was assigned a value of 0.33 m/sec. Infiltration excess overland flow has been integrated in TOPMODEL's structure using approaches ranging from a simple constant infiltration rate (Beven et al., 1984) to more complex physically based approaches (Sivapalan et al., 1987). To avoid model over-parameterization, it was decided to ignore this mechanism, in the light of existing knowledge of the basin's hydrological behaviour. Remaining parameters i.e. exponential storage parameter (m); the mean catchment value of $\ln(T_0)$ (T_0); the unsaturated time delay per unit storage deficit (T_D); the root zone available water capacity (S_{max}); and initial value of root zone deficit (S_{R0}) were optimized using Marquardt algorithm. The Marquardt algorithm is a non-linear optimization algorithm that allow for convergence with relatively poor starting guesses for the unknown coefficients. A least square objective function is utilized.

After successful execution of the program on calibration data set, one set of parameter values were obtained. These parameters were further refined by giving computed parameters as initial guess in second execution run with narrow band of upper and lower limits and a "best" parameter set for Hemavati catchment was obtained and is given below:

$m=102.129$ mm; $T_0=3.99$ ln(m^2h^{-1}); $T_D=0.001$ h mm^{-1}; $S_{rmax}=160.628$ mm; and $S_{r0}=93.545$mm.

With this parameter set the model efficiency (Nash-Sutcliffe, 1970) for calibration period is 0.846. Table 1 gives year wise efficiency values. A plot between observed and simulated discharge is shown in Fig. 6. Based of plot of Figure 6 and Nash-Sutcliffe efficiency given in Table 1, we can say that a good fit between observed and simulated discharge exist.

Table 1. Nash-Sutcliffe model efficiency

Serial No.	Year	Efficiency
1.	1975	0.759
2.	1976	0.919
3.	1977	0.878
4.	1978	0.834
5.	1979	0.901
6.	1980	0.844

The model is further run with above parameter sets for validation data series (1978-80). A plot between observed and simulated validation data series is shown in Figure 7. The Nash-Sutcliffe efficiency for validation period is 0.856. Table 1 gives year wise efficiency values.

As can be seen from Table 1 the efficiency differ from year to year which could be attributed to data errors and varying catchment conditions. Over all simulation both for calibration and independent data series validation can be rated very good (efficiency more than 0.84) except that some of the peaks were under simulated. From the study it we conclude that the TOPMODEL can very well simulate runoff for Hemavati at Sakleshpur.

Fig. 6 Calibration of TOPMODEL on Hemavati (June 1975-77)

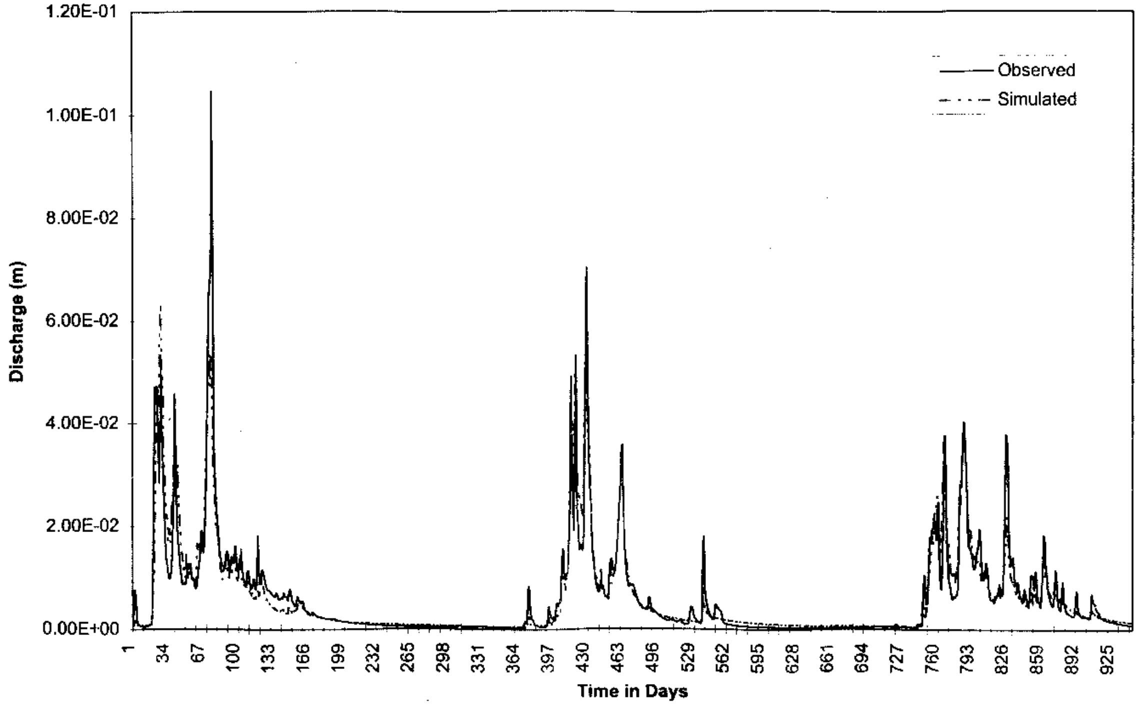
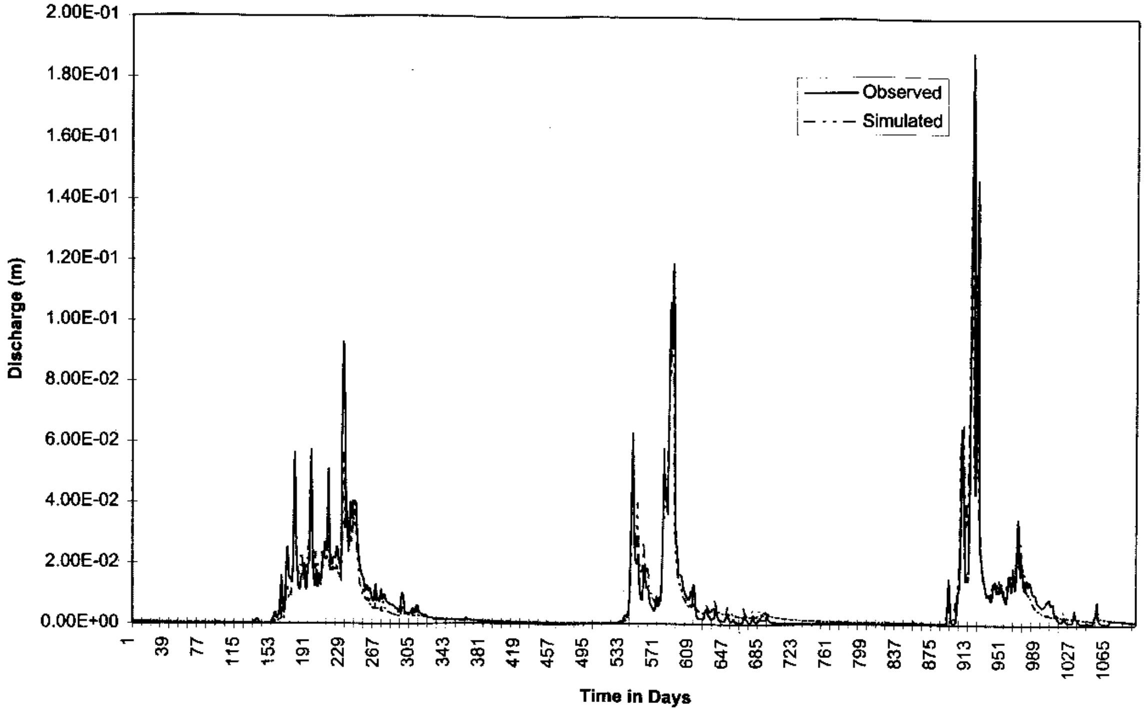


Fig. 7 Validation of TOPMODEL on Hemavati (1978-80)



6.0 CONCLUSIONS

The TOPMODEL is a variable contribution area conceptual model in which the predominant factors determining the formation of runoff are represented by the topography of the basin and a negative exponential law linking the transmissivity of the soil with the vertical distance from the ground level. In this model the total flow is calculated as the sum of two terms: surface runoff and flow in the saturated zone. The TOPMODEL is attractive because of its structural simplicity and parsimonious parameterisation. It is one of the few conceptual models that accounts explicitly for the saturation excess overland flow mechanism and integrates the variable contributing area concept, both of which are essential to model the catchment accurately.

Calibration and validation of the TOPMODEL is carried out on Hemavati catchment situated in Western Ghats. Raster DEM input for the model is generated through ILWIS after digitization contour map from Survey of India toposheets. In all 5 years of data was available for simulation study. Available data series was broken in two parts and first part i.e. June 1975-December 1977 was used for model parameter calibration and remaining data series i.e January 1978 to December 1980 was used for model validation. Simulation results are encouraging. Model efficiency (Nash-Sutcliffe) was more than 0.84 both for model calibration and validation on independent data series. As can be seen from Table 1 the efficiency differ from year to year which could be attributed to data errors and varying catchment conditions. Over all simulation both for calibration and independent data series validation can be rated very good (efficiency more than 0.84) except that some of the peaks were under simulated. From the study we conclude that the TOPMODEL can very well simulate runoff for Hemavati at Sakleshpur. However, more simulation studies are are required to ascertain applicability of TOPMODEL in this region.

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Director

S. M. Seth

Divisional Head

B. Soni
Scientist E

Study conducted by

M. K. Jain
Scientist C

Assisted by

Tanveer Ahmad
SRA