CS/AR-4/1999-2000

COMPARISON OF SINGLE AND MULTIPLE FLOW DIRECTION ALGORITHM FOR COMPUTING TOPOGRAPHIC PARAMETERS IN TOPMODEL

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PREFACE

One of the fundamental goals of scientific hydrology is to understand the response of catchments to atmospheric inputs. The development of such understanding has proved to be elusive because of the complexity of the processes, the difficulty of performing controlled experiments, and spatial and temporal variability of catchment characteristics and precipitation. Faced with this situation, it has been usual to incorporate what knowledge we have about the operation of the processes unto some conceptual model of the system. The modelling process and the development of understanding are closely related in that a comparison f model predictions with measurements is commonly used to test the hypotheses about the operation of the system being modelled.

The TOPMODEL is a conceptual model developed by Beven et. al, in 1979 based upon the concept of variable contributing area. The model uses the topographic index as one of the input for simulating the discharges in the stream. These index reflects the spatial distribution of soil moisture and saturated surface within the basin. There are different approaches to compute the topographic index, namely, Single Flow Algorithm (SDF) and Multiple Flow Algorithm (MDF). In this report, an attempt has been made to analyse the effect of these approaches on the simulation of flow and on the model parameters.

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ABSTRACT

The topography is one of the factors that most influence the physical phenomenon of rainfall-runoff dynamics. Indeed, it plays a primary role in the effects produced by the gravity drainage within a basin. In the last decade, ever-developing computer techniques associated with the greater availability of terrain data in digital form has favored the production of physically based models, which have spatial variability of topography built into their structure. The TOPMODEL developed by Beven, in 1979 is one of the many models which uses the topographic feature in simulating the flows. The topographic features are represented in the model as topographic index, ln ($a/\tan\beta$), in which 'a' represents the cumulative upslope area that drains through a point, and $\tan\beta$ is the local slope at the same point. The index reflects the spatial distribution of soil moisture and saturated surface within the basin. The topographic index, ln ($a/\tan\beta$) distribution can be computed using the two different approaches, namely, Single Direction Flow Algorithm (SDF) and Multiple Direction Flow Algorithm (MDF).

In the present study, the TOPMODEL has been applied to Malaprabha catchment. The topographic index was computed using the SDF and MDF. An attempt has been made to analyse the effect of these approaches on the simulation of flows and on the model parameters.

The results show that, the SDF and MDF have slight effect on the efficiency of the model and also on the model parameters. However, choice of these approaches does not have any effect on the simulation of flows.

1.0 INTRODUCTION

One of the fundamental goals of scientific hydrology is to understand the response of catchment to atmospheric inputs. The development of such understanding has proved to be elusive because of the complexity of the processes, the difficulty of performing controlled experiments, and the spatial and temporal variability of catchment characteristics and precipitation.

Faced with this situation, it has been usual to incorporate what knowledge we have about the operation of the processes into some conceptual model of the system. It is common that some parts of a complex conceptual model may be more rigorously based on physical theory than others. Even the most physically based models, however, cannot reflect the true complexity and heterogeneity of the processes occurring in the field. Catchment hydrology is still very much an empirical science.

The modeling processes and the development of understanding are closely related in that a comparison of model predictions with measurements is commonly used to test hypotheses about the operation of the system being modeled. Where the measurements are taken during carefully formulated and closely controlled experiments, such comparison is part of the standard scientific method. For field systems, the method is fraught with difficulties. Hydrological quantities measured in the field tend to be either integral variables (e.g., stream discharge, which reflects an integrated catchment response) or point estimates of variables that are likely to exhibit marked spatial and/or temporal variation (e.g., soil hydraulic conductivity). The result is that the scientific problem of identifying the mechanisms giving rise to observed catchment responses is poorly posed. Inspite of these difficulties, pseudophysical models of catchment dynamics provide the only vehicle for testing hypotheses in catchment hydrology, i.e., the only way to make comparisons between theory (model predictions) and observations.

The conceptual models are selected and used for the specific purposes. The use of conceptual model often involves three major issues. Firstly, the conceptual base of the model should 'capture' the major hydrological processes of the catchment. A calibrated model may reasonably reproduce observed patterns of streamflow at the calibration stage even though the basins major hydrological processes can be different from those assumed in the model. The second issue is whether the time steps used in the model are sufficiently small to represent the rate of change of the process. This problem can be particularly important in arid region where the rainfall intensity can change quickly over relatively short time scale, resulting in a sharp rise in the surface runoff. The third issue concerns the model calibration. The implementation of above mentioned procedure for testing the hypothesis in catchment hydrology is further complicated by the fact that at least some parameters in the conceptual models of catchments cannot be measured independently of inflow-outflow data, but must be fitted using the very data available for the test itself. The generally accepted way around this dilemma is to use one portion of the period of record to 'calibrate' the model and a second portion to 'validate' the model so defined.

The variable contributing area concept was introduced by Hewlett in 1961, and further clarified by Dunne and Black in 1970. Subsurface flow was gradually recognized as a major storm-flow-generating processes, by itself as 'return flow' contributions to overland flow and by its strong influence on saturation overland flow. More recent research has been oriented towards the integration of all these concepts in a continuum of subsurface processes. Increasing the complexity of conceptual perception with respect to hydrological processes appeared to be an adequate answer to an enlarged need for accurate hydrological modeling of land management impacts, water quality or climatic change assessments. Although lumped conceptual rainfall-runoff models claim to incorporate in their structures most of the processes of the hydrological cycle, they do not provide a sound scientific basis for analysing the above mentioned modeling problems. Many parameters are required if all the processes involved are to be represented. However, most of these parameters cannot be related successfully to physical catchment characteristics and must be estimated by calibration using observed hydrographs. Therefore most models show serious drawbacks in parameter identification because of their conceptual structure and data used for calibration.

The TOPMODEL is a variable contributing 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 it is 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',.

TOPMODEL performs an 'upward search for conceptualisation' from the soil column level to the catchment scale. Basin parameters are related to point estimates. The spatial variability of both soil water content and lateral drainage is related to that of soil and topographic characteristics by means of simple but meaningful assumptions. The model is also 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.

The application of TOPMODEL, requires computation of the frequency of spatial distribution of topographic index from topographic data, such as a contour map or a digital elevation model (DEM). This topographic index, which can be computed at any location x in the watershed, is $\ln(a/\tan\beta)$, where ln is the Napierian logarithm, 'a' is the upslope area per unit contour length (sometimes called the specific catchment area) from location x, and tanβ is the slope gradient at x.

In the earlier applications of TOPMODEL, the frequency distribution of ln (a/tanβ) was derived manually from contour maps. Later applications of the model used computer software and DEMs to derive the spatial and statistical distribution of ln(a/tanβ). Two types of software algorithms have been used to compute the ln(a/tanβ) distribution from DEMs; single flow direction (sdf) algorithm and Multiple flow direction (mdf) algorithms. In the sdf algorithm it is assumed that subsurface flow at every point occur only in the steepest downslope direction from any given point. In the mdf algorithm it is assumed that subsurface flow at every point occurs in all downslope direction from any given point. Quinn et al, (1991), showed that the spatial patterns and frequency distribution of ln(a/tanβ) computed using an sdf algorithm were different from those obtained when an mdf algorithm was used for the Booro-Borotou watershed in the Ivory Coast. The authors suggested that the mdf algorithm produced a more realistic looking of spatial pattern on the hillslopes of the watershed. They also speculated that the two algorithms would result in different TOPMODEL Predictions. Similar findings were reported by Moore(1995) for the Coweeta watershed in North Carolina. In addition, Moore found that compared to the sdf algorithm, the mdf algorithm resulted in a higher mean ln(a/tanβ) distribution.

In the present work, the effect of single and multiple flow algorithms on the computation of topographic index and runoff simulation using the TOPMODEL are examined in detail for Malaprabha catchment. The specific objective are (a) to compare the ln(a/tanβ) distributions computed using sdf and mdf algorithms developed by Quinn et al, (1991) and Holmgern (1994), (b) to determine how difference in the ln(a/tanβ) distribution affect hydrologic characteristics simulated by TOPMODEL.

2.0 LITERATURE REVIEW

TOPMODEL was originally developed to simulate small upland catchment in the U.K. In the first application of the TOPMODEL by Beven and Kirkby, in 1979, to Crimple Beck basin, a tributary of the River Nidd, southwest of Harrogate, Yorkshire, showed that it was possible to get reasonable results with minimum number of parameters calibration. Again in 1984, they applied to 2 more catchment namely Hodge Beck and Wye headwater in North York Moors and in central Wales respectively. In this study, forecasts were made over a period of one year based on rainfall and evaporation data. The model parameters were derived from a defined program of field measurement over a period of 2-4 weeks, and no formal optimisation procedures were carried out before comparing forecasts with the measured stream discharge record. As a result of the comparisons, the model gave a good results and seen as useful approach for ungauged catchments of up to 500 km^2 in humid-temperature climates.

Hornberger et al (1985) adapted the TOPMODEL for continuous simulation and extended to take account of observed processes in White Oak Run, a small-forested catchment in Shenandoah National Park, Virginia. Automatic calibration of the model was attempted using eight different functions. On the basis of results from a regionalised sensitivity analysis, the original model structure was greatly simplified. The parameters of the simplified model, which produced fits to the measured data very nearly as good as did the more complex model, were estimated well using a sum of square errors criterion.

In 1992, Durand et al, have applied the TOPMODEL to catchments at Mont-Lozere in the Cevennes, southern France (lies in Mediterranean ecosystems) which exhibits a high spatial and temporal variability of rainfall. They successfully simulate discharge in a wide range of climatic conditions. Some discrepancies between simulated and measured flow were observed for large events following long droughts: these were related to the dynamics of infiltration and wetting of the soils.

Iorgulescu & Jordan in 1994, tested the TOPMODEL on two subcatchments of the Haute-Mentue(Switzerland) research basin. Initially, simulations were done using the field-estimated parameters, which yielded poor results. Later, the parameters were calibrated using the rainfall and runoff data with the Nash-Sutchiffe efficiency criteria. This approach provided useful insights into the structure of the model. Even if an acceptable numerical fit was achieved. Although it was possible to verify some of the underlying concepts of TOPMODEL for the Haute-Mentue basin, the model could not be validated fully with respect to field measurements and knowledge of the physical processes involved in catchment response.

Sanghyun Kim & Delleur (1997) developed an extension of TOPMODEL for rainfall-runoff simulation in agricultural watersheds equipped with tile drains. Tile drain functions are incorporated into the framework of TOPMODEL. Nine possible flow generation scenarios are suggested for tile drained watershed and applied in the modeling procedure. In this model development, two methods of simulation of the flow in the unsaturated zone were compared: the traditional, physically based storage approach and a new approach using a transfer function. The developed model was tested using the data of catchments located in the Indian Pine Natural Field station, near the campus of Purdue University, West Lafayette, Indiana, USA. The result shows that the parameter values obtained on average were higher for the transfer function approach than when using a Monte Carlo method of parameter estimation. Since the rainfall-runoff response pattern tends to vary seasonally, seven events distributed throughout a year were used in the sensitivity analysis to investigate the seasonal variation of the hydrological characteristics.

Lamb et al, in 1997, used the simplified TOPMODEL to predict the discharge and water table. In the simplified model, the assumption of an exponential function originally made in TOPMODEL was relaxed by generalised saturated zone formulation. This saturated zone model is based on the concept of a 'discharge: relative storage' (QΔS) function which is derived empirically, using recession curve analysis, and may be of arbitrary form. The generalised formulation is applied to the Seternbekken MINIFELT catchment in

Norway, where detailed distributed water table data have been measured. These water table data are used to suggest an empirical, power Law modification of the topographic index. Results of the simulation through time of discharges and water table depths at a few locations show that the generalised saturated zone formulation is as efficient a simulator of the observed data s a conventional TOPMODEL, but requires one parameter less to be calibrated. The simulation of detailed water table distributions is only approximated in both cases. The modified power law index shows only a small improvement but provides a basis for a discussion of possible sources of error in the TOPMODEL assumptions for this site.

The TOPMODEL was applied to some of the catchments in India, namely Kolar sub-basin of Narmada basin, Hemavathy sub-basin of Kaveri basin and Malaprabha sub-basin of Krishna basin. The results obtained from these catchments showed a good agreement between the observed and simulated the flows. All of these studies, used the multiple flow algorithm developed by Quinn et al (1991) to compute the topographic index. The present study, aims at analysing the effect of different algorithms (multiple and single flow) in computing the topographic index and their effect on the simulation of the flows.

3.0. DESCRIPTION OF THE STUDY AREA AND DATA REQUIREMENTS

3.1. The Study Area

The river Malaprabha originates from Kanakumbi in the Western Ghat at an altitude of about 793 m and 16 km west of Jamboti in the Belgaum district of Karnataka State. The catchment extends between 64° 20' and 74° 30' E longitude and 15° 20' and 15° 40' N latitude. There are five raingauge stations in Malaprabha basin (Fig.1) and the river is being gauged at Khanapur. The average annual rainfall in the catchment is about 2259 mm and the mean annual evaporation is 1496.9 mm. The major part of the catchment is covered by the tertiary basaltic rock, whereas the sedimentary rocks are confined to the southeastern part of the catchment. There are only two different types of soil found in the catchment. They are red loamy and medium black soils with the depth of 0.5 m to 1 m varying across the catchment.

The vegetation cover over the study area is a complex one. The western and southwest part of the Malaprabha catchment is covered by the dry deciduous forest, which accounts for about 62.65% of the total catchment area. The northern part of the catchment is being used for the agricultural purpose and shrubs cover the sloppy area of the catchment.

3.2 Data Requirements for TOPMODEL

The TOPMODEL is topography-based model, a topographic map with contour at close interval is needed to implement the model. The topographic map is used to create a digital elevation map (DEM) of the catchment and to compute the topographic ($\ln(a/\tan\beta)$) index. The hydrometeorological data needed to run the TOPMODEL are rainfall, potential evapotranspiration and discharge at the outlet. These data are required at short time interval, say hourly. However, model can also be used for the daily data where ever the short time interval data are not available. The important model parameters required to be

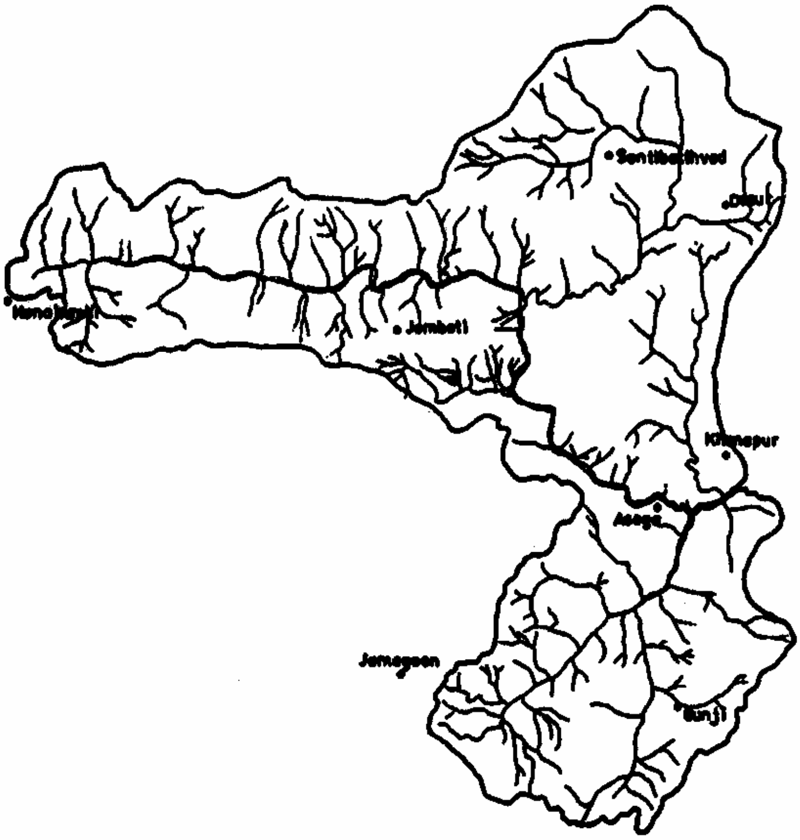


Fig..1. Malaprabha Basin Map

given as input include the value of transmissivity (m^2 /h), the unsaturated zone time delay per unit storage deficit (h), the main channel routing velocity (m/h), exponential decay factor (m), the root zone available water capacity (m) and the initial value of root zone deficit (m). Some of these parameters can be supplied from the field measurements However, in most of the cases, these parameters are calibrated to match the observed and simulated flows.

3.3 Data Availability

The base map of the Malaprabha sub-basin was prepared using the Survey of India toposheets at a scale of 1:50,000. The topographic sheets have a contour interval of 20 m.

The daily rainfall data were available at seven stations, namely Khanapur, Jamboti, Kanakumbi, Desur, Asoga, Gunji and Santibastwad, for 10 years from 1983 to 1993 and were considered for the study. In this study, the weighted average rainfall for the catchment was used. The discharge data were available at Khanapur gauging station for the same period.

4.0 BRIEF DESCRIPTION OF TOPMODEL

A brief summary of the concepts and the basic equations upon which TOPMODEL is founded are given below. Full details of the governing equations and the rationale behind the model can be found elsewhere (Beven and Kirkby, 1979; Beven,et al 1995).

TOPMODEL represents catchment topography by means of a topographic index, ln(a/tanβ), where **'a'** is the area draining through a grid square per unit length of contour and **'tanβ'** is the average outflow gradient from the grid square. The topographic index is calculated from a Digital Terrain Map (DTM) across a grid covering the catchment. The grid must be sufficiently fine to resolve important characteristics and slope formations. A high index value usually indicates a wet part of the catchment, which can arise either from a large contributing drainage area or from very flat slopes. Areas with low index values are usually drier, resulting from either steep slope or a small contributing drainage area. Grid squares with the same index values are assumed to behave in a hydrologically similar manner. As a result of this assumption, the catchment topography may be summarised by the distribution of the index values.

The TOPMODEL identifies two sources of stream water: water draining from subsurface saturated zones and water displaced from saturated and near saturated parts of the catchment. The later is generated by rainfall falling on saturated contributing areas and causing rapid movement to the stream via macropore flow, overland flow. It is distinguished from the subsurface saturated zone discharge because of its much faster movement. The saturated contributing areas will both grow and reduce during the course of a storm event. For any point on the hillslope the downhill flow from the saturated zone is assumed to decrease exponentially with depth to the water table and proportional to the local gradient;

$$qs_i = T_0 \tan\beta \exp(s_i/M) \quad \text{.............(1)}$$

where T_0 is the lateral transmissivity of the soil surface at saturation (m^2h^{-1}), M the exponential decay rate of transmissivity with depth (m), s_i the local soil moisture deficit below saturation (m) and β the local slope angle.

Two main assumptions are made here; (i) there is an exponential relationship between qs_i and s_i, and (ii) the direction of the local hydraulic gradient is parallel to the local slope (i.e. the water table is parallel to the surface). The points at which $s_i = 0$ make up the saturated contributing area. The incoming rainfall on this area produces overland flow.

The local storage deficit is linked to the mean storage deficit via the topographic index $\ln(a_i/\tan\beta)$, where a_i is the area draining through point per unit contour length:

$$S_i = S + \left[\lambda - \ln(a_i/\tan\beta)\right]M \qquad \text{........(2)}$$

where S is the mean catchment storage deficit (m) and λ is the areal average of $(a_i/\tan\beta)$.

The topographic index is derived from the digital terrain map (DTM) of the catchment. The equation (2) implicitly includes an assumption that the hydrological behavior of every part of the catchment is adequately described by this index. In other words, all the points with the same index values are modeled as having identical storage deficits at each time. This assumption makes it possible to summarize the catchment topographical features by the distribution of the index. However, it is possible to take into account the spatial variability of soil properties by subdividing the catchment into homogeneous subcatchments, or by integrating T_0 into the topographic index.

At each time step t (24 hours in the present case) , S(t), the storage at time t, is calculated from S(t-1) and from the estimated movements of water through the root zone, the unsaturated zone and the saturated zone. The net rainfall first fills up the root zone. If the amount of rain falling is sufficient to fill up the root zone capacity then the water will move to the unsaturated zone. The maximum storage capacity of the root zone, SRMAX, is considered to be equivalent to the field capacity of the soil. The water moves vertically from the unsaturated zone to the saturated zone and this flow is modeled using an exponential relation as in equation.(1)

$$qv_i = K_0 \exp(s_i/M) \qquad \text{...........(3)}$$

where K_0 is the vertical conductivity of the soil at the surface (mh^{-1}). S(t) is calculated after summing the local vertical and lateral flows;

$$S(t) = S(t-1) + QS(t) - QV(t) \qquad (4)$$

Where QS(t) is the runoff from the saturated area in any time step t, and QV(t) represents the total recharge to the water table in any time step t.

In brief, the inputs to the model are rainfall, potential evaporation at daily steps and the distribution of the topographical index derived from the DTM. The outputs are the average soil moisture and local soil moisture deficits below saturation, and the discharge, separated into two components (surface runoff on the saturated area and subsurface flow/groundwater discharge). The parameters of the model are the soil hydrodynamic properties at the surface, T_0, the lateral transmissivity; K_0, the vertical conductivity; M, the exponential decay rate of these properties with depth: and SR_{MAX}, the maximum storage capacity of the root zone, and it is interpreted here as the soil moisture at field capacity. This makes up a basic structure on which a series of variations can be built to adapt TOPMODEL to specific catchment and specific modelling purposes

TOPMODEL is mathematically and parametrically simple and relies on the preprocessing of digital terrain data to calculate the catchment distribution function of a topographic index ln(a/tanβ) where 'a' is the cumulative upslope area draining through a point (per unit contour length) and tanβ is the slope angle at the point. The ln(a/tanβ) index reflects the tendency of water to accumulate at any point in the catchment (in terms of a) and the tendency for gravitational forces to move that water downslope (expressed interms of $\tan\beta$ as an approximate hydraulic gradient). The calculated values of both a and $\tan\beta$ will depend upon the analysis of flow pathways from the DTM data and the grid resolution used. There are two procedures available for calculating the $\ln(a/\tan\beta)$, namely single flow direction and multiple flow direction. In the present analysis both the procedures have been used to calculate the topographic index ($\ln(a/\tan\beta)$) values. The procedure is described below.

4.1 Physical significance of the parameters and their range

The concepts underlying TOPMODEL have thus far involved just the topographic index and five parameters: **M**, T_0, SR_{max}, T_d and SR_0. to transform the rainfall into runoff. Out of these five parameters, first 4 parameters i.e. **M**, T_0, SR_{max} and T_d play an important role in the transformation of rainfall into runoff. The physical significance of these three parameters are described below.

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 $\mathbf{T_0}$, which defines the transmissivity of the profile when saturated to the surface. A larger value of M effectively increases the active depth of the soil profile. A small value, especially if couple with a relative high T_0, generates a shallow effective soil, but with a pronounced transmissivity decay. This combination tends to produce a well-defined and relatively shallow recession curve response in the model hydrograph.

The parameter $\mathbf{T_d}$, the unsaturated zone time delay per unit storage deficit accounts for the changes in unsaturated zone fluxes with local unsaturated zone storage and depth to the water table (or storage deficit), and it is being related with the storage in the unsaturated zone and the local saturated zone deficit due to gravity drainage, and dependent on the depth of the local water table.

The vegetation interception capacity is represented by a reservoir with a capacity of SR_{max}. The water is extracted from the reservoir at potential evapotranspiration rate; the net precipitation in excess of the capacity SR_{max} reaches the soil and forms the input for the subsequent model component.

The parameter SR_0 represents the initial value of the root zone deficit, and it is related to the initial soil moisture available at the beginning of calibration period.

Table.1 . The TOPMODEL parameters and their acceptable range

Parameters of the Model	**Unit**	**Acceptable Range**
The exponential storage parameter (M)	Mts.	0.01-1.0
The mean catchment value of $\ln(T_0)$	M^2/hr	0.01-2.25
The unsaturated zone time delay per unit Storage deficit (T_d)	hrs	0.01-24
The root zone available water capacity (SR_{max})	Mts.	0-0.300
The initial value of root zone deficit (SR_0)	Mts.	0.001-0.1

5.0 Application of TOPMODEL

5.1 Processing of Spatial Data

The ILWIS (Integrated Land and Water Information System) GIS software was used in this study. The ILWIS can be used on a PC platform. It provides the user with the capabilities of data gathering, data input, data storage, date manipulation and analysis and data output. It merges and integrates various conventional GIS procedures with image processing and can handle both vector and raster graphics data.

5.2 Creation of Spatial Database

The process of creation of database for the basin through the ILWIS involved collection of relevant data, converting these data in digital format through digitization, error checking and correction, polygonisation of segment files and finally conversion of data acquired in vector structure to raster format.

The topographic map of the catchment was prepared using the Survey of India toposheets at the scale of 1:50,000 having a contour interval of 20 m. The contour and the stream network were traced on a transparent sheet from the toposheets and these were then digitized on a PC through the ILWIS GIS package. A DEM of the catchment was prepared from the digitised data. The grid size of the DEM can be selected by the user. As a larger grid size is chosen, some information is lost due to discretization.

Quinn et al (1995) have pointed out that grid sizes of around 100m are considered too large for application of the topographic index which requires a finer grid resolution to depict the topographical form of the individual hillslopes. Large grid cells exhibit a bias towards large index values. DEMs with fine resolution should be used to test internal state processes as 50m data are too coarse for point field data to validate. Small channels are hidden within the large-scale grid cells and a loss of resolution gives a loss of boundary information. A grid size of about 20m or less is considered necessary to obtain a realistic simulation. However, it is important to note that:

1. Fine grid scale digital terrain models are usually not available
2. A reduction in grid size leads to huge increase in volume of data to be handled, even for a small catchment.
3. Interpolation errors may be introduced while creating fine grid maps from the data of coarse grids.
4. More pixels involve considerably more processing time.

In the present case, initially the grid size adopted in the horizontal plane was 300m*300m. However, if the grid size was reduced, the number of grids became very large, as pointed out above. This required handling of very big data files as the catchment size was big, thus necessitating more computer resources. Moreover, as the contour interval was 20m, a smaller grid size did not lead to improved representation of topography in terms of elevation differences. Therefore, the grid size of 300m * 300m was finally used.

After the DEM was generated, an ASCII file of grid elevation was created using the format conversion module in which the elevations of the pixels were written. In a natural catchment, unless there is a lake inside the catchment, all the points should send the flow to the outlet. However, due to large grid size and contour interval of the topographic map, local sinks or pits where the elevation is below the elevation of all surrounding pixels, are generated when DEM is created. The calculation of the topographic index requires computation of contributing area at a point. Thus, it is necessary that these sinks are removed so that the index is computed correctly. The sinks can be removed by artificially increasing the elevation of the sinks such that elevation of the sink pixel becomes higher than the elevations of the surrounding pixels.

Once the local sinks or pits are removed, the next step is to compute the topographic index from the regular raster grid elevation data of the catchment. The topographic index can be computed using the different algorithms, namely multiple flow algorithm and single flow algorithm. In the present study, both the approaches are used to compute the topographic index. The computational procedure is described below.

5.3 The Computation Of Topographic Index Distribution Used in Topmodel

An analysis of catchment topography is required in order to derive the a/tanβ distribution function. The computation of topographic index (a/tanβ) values requires the information on topography of the catchment. Early development of TOPMODEL, relied upon the manual analysis based on map information of local slope angles, upslope contributing areas and cumulative areas. Beven and Krikby (1979) outlined a computerised technique used to derive the topographic distribution function based on the division of the catchment into sub-basin units. However, Quinn (1991) developed a group of Digital Terrain Analysis programmes, based on raster elevation data, with the aim of investigation their utility in deriving the topographic information required by TOPMODEL. Application of these techniques to catchment modeling studies has been described by Quinn et. al., (1991) and Quinn and Beven (1993). Quinn et.al., (1991) describe an multiple flow direction algorithm that is based on the distribution of area to all down slope grid elements; Wolock (1993), on the other hand, uses an algorithm based on a single flow direction with the greatest slope. Other techniques have also been used; most raster DTMs have been derived from contour data digitised from existing maps and Moore et al., (1986) have use DTA techniques based on flow paths derived directly from contour data to calculate the a/tanβ index.

The topographic index reflects the spatial distribution of soil moisture and saturated surface within the basin. The distribution of ln(a/tanβ) can be directly considered in terms of storage patterns, since it gives the corresponding quantity of area that contributes directly to runoff for a given values of the topographic index. The correct definition of such an index therefore has an extremely important role in rainfall-runoff transformation processes, since for analogous index values, the greater quantity of the contributing area A_c produces an increase in available runoff in relation to the basin outlet (Mendicno et al., 1997).

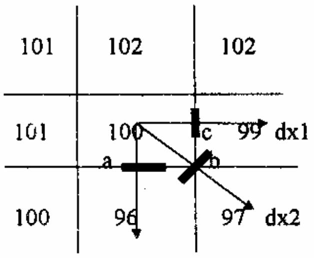
There are various procedures directed at the identification of the spatial distribution of the topographic index. They can vary both as a function of the structure type of the topographic data, and in relation to runoff schematization during the propagation phase along the slopes (Moore et al., 1993). However, in the present study, the procedure developed by Quinn et al., (1991) has been employed to compute the spatial distribution of $\ln(a/\tan\beta)$ for both single and multiple flow direction.

5.3.1 Calculating the Topographic [$\ln(a/\tan\beta)$] Index

In an attempt to represent the convergence or divergence of flow under the control of topographic curvature, Quinn et al. (1991) developed a multiple flow direction algorithm to calculate accumulated contributing areas across adjacent pixels. This routine was written to work on 50 m resolution DTMs. The routine is effectively a form of subgrid interpolation which share contributing area in accordance with the shape of the contours passing through a given grid cell relative to those of its neighbors.

Figure 2 shows the original multiple direction flow sharing algorithm for a example DTM with 50 m grid resolution. The main variable in the slope algorithm are the angle between the adjacent pixels, the postulated contour length depending on flow direction (0.5 weighting for cardinal direction and 0.35 for diagonal weighting) and the flow lengths dx1 and dx2. Length dx1 is set to 50 m and dx2 to 70.1 m to account for the longer flow path between downslope diagonal pixels. When summed across a series of downslope cells it is in contact with, the algorithm produces a series of weighted flow proportions. The current accumulated are in each cell is then passes to its neighbors using these calculated proportions.

The single flow direction algorithm does not require a contour length term as every pixel has the same contour length. However, multiple flow direction algorithms have variable outflow directions that are dependent on a cell's neighbors, hence the contour length must be taken into consideration.



a=0.5*tan((100-96)/dx1) = 65.55%
b=0.35*tan((100-97)/dx2) = 23.01%
c=0.50*tan((100-99)/dx1) = 15.44%

Figure .2. Multiple flow direction appropriating algorithm (Quinn et al, 1991).

There is another method for computing the topographic index , which is much more powerful to adjust the amount of water that flows across a particular flow direction dependent on its slope. Holmgren (1994) gives an algorithm where the amount of flow in any one direction is calculated as

$$d_i = cld(\tan\beta)^h$$

where d_i= the flow proportion in the ith downslope direction and

cld= is the contour length

Thus h=1 is equivalent to the original multiple flow direction algorithm of Quinn et al. (1991). Values in excess of h=10 tend to given more of a single flow direction approximation. A value around 100 is equivalent to the single flow direction algorithm.

By the simple introduction of this power, the pattern can be radically changed. Even if two outflow directions are similar, the effect of a high h power will cause a marked bias towards the steeper angle. This formulation was built into the existing algorithm. Figure 3 shows the worked example that is based on figure 2. It has been assumed here that the contour length has not changed in size. It could be argued that if the flow were leaving a cell through only one direction, then a reduction in the contour length would occur. However, this would affect the index pattern in the same way as achieved by increasing the power term only. In fact, if the contour length is allowed to vary inversely with $(\tan\beta)^h$, then the contour length can become infinitesimally small, leading to index values of 100 plus or to computer overflow errors. It is thought that the original contour length algorithm should be the benchmark for analysis and should remain unchanged. The alteration of flow is adequately achieved by using the Holmgern power term (Quinn et al.,1995).

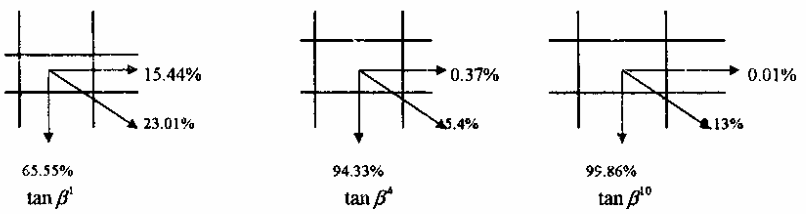


Figure.3. Effect on the flow apportioning route when raising tanβ to power h (Quinn et al, 1995)

6.0. Analysis of Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) Developed for Malaprabha catchment was used to calculate 'a' and 'tanβ' for each grid cell in the catchment. To do so required the calculation of the total area draining into each cell (A), as well as the contour length (C) and the slope gradient (tanβ) along which drainage from the dell occurs (a= A/C). Drainage from a cell was assumed to occur in only the steepest downslope direction for sdf algorithm and was assumed to occur in all downslope direction for the mdf algorithm. Both the sdf and mdf algorithm required removal of local depressions in the elevation data. In this study, elevation data representing local depressions were filled using the Digital terrain model developed by Quinn et al (1991), also the same model is used to calculate the topographic index of the catchment. The analysis of topographic index obtained for both the algorithms is given below.

6.1. Differences in The ln(a/tanβ) Distributions computed With the Single Flow And Multiple Flow Direction Algorithms.

There are various procedures directed at the identification of the spatial distribution of the topographic index. They can vary both as a function of the structure type of the topographic data, and in relation to runoff schematisation during the propagation phase along the slopes (Moore et al. 1993). In a recent paper, Moore (1996) showed by means of a methodological analysis of the problem, that several of these procedures allow better estimation of the spatial distribution of some hydrological characteristics. These evaluations can be quantitatively explained by referring to the spatial distribution information content of the topographic index estimated as an entropy measure according to the theory proposed by Shanon and Weaver. In the present study, an attempt is made to compare the spatial distribution of topographic index computed using single and multiple flow algorithms proposed by Quinn et al (1995) and Holmgren (1994).

The figure.4,5a ,5b . show the cumulative frequency distribution of topographic index and spatial distribution of topographic index computed from single flow and multiple flow algorithms for Malaprabha catchment. The values of ln(a) is a measure of the amount of upslope drainage area and local flow convergence or divergence: and ln(1/tanβ) measure the local gravitational gradient. Values of ln(a/tanβ) are highest where ln(a) is highest (large upsloped areas and flow convergence) and ln(1/tanβ) is highest (gentle slopes). The cumulative frequency distribution of topographic index for Malaprabha catchment shows that the sdf algorithm computes the more cumulative area for the same topographic index than that of the multiple direction algorithms (figure.4).

The spatial distribution of ln(a/tanβ) values generated by the sdf algorithm looks different than the one generated by using mdf algorithm. The sdf algorithm produces a spatial distribution with more discrete, rougher pattern, and the mdf algorithm produces a distribution with a smoother pattern. These results agree with those of Quinn et.al (1991), who showed that the spatial distribution patterns of upslope drainage area and of the ln(a/tanβ) values are smoother for their mdf algorithm than for their sdf algorithm. Also, Moore (1995) showed that the spatial distribution pattern of upslope area per unit contour length was more linear and less smooth for the sdf algorithm than the pattern derived from the mdf algorithm. The smoothness in the pattern of the spatial distribution computed using the mdf algorithm occurs because the upslope area is partitioned to multiple downslope-neighboring cells.

Recently, Costa-Cabral and Burges (1994) compared the spatial distribution patterns of upslope drainage area computed with sdf and mdf algorithm for idealised geometric surfaces. They showed that the mdf algorithm produced more accurate patterns of upslope drainage area compared to the sdf algorithm. They also demonstrated that even the mdf algorithm was prone to error under some conditions, and they described an alternative method to compute upslope drainage area based on aspect angles.

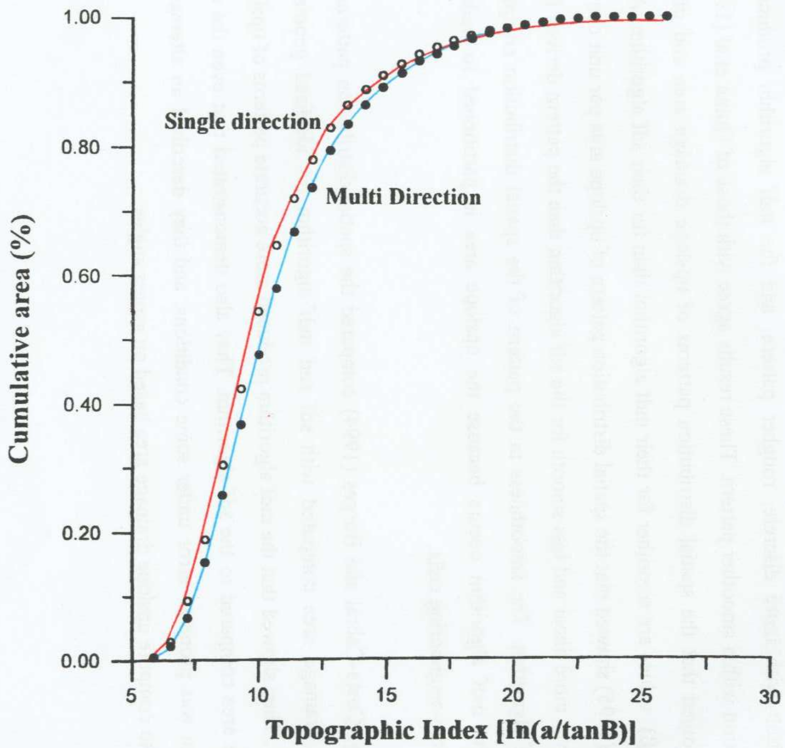


Fig. 4 Cumulative Frequency Distribution of Topographic Index for Malaprabha Catchment

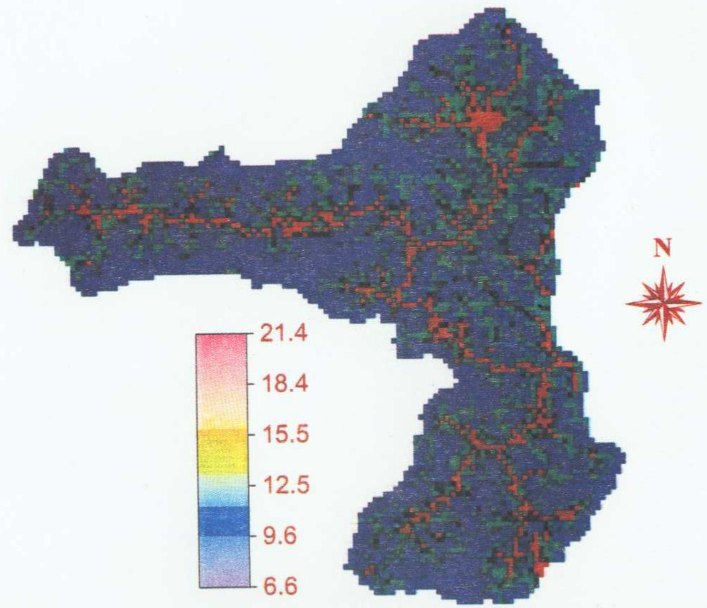


Fig.5a . Spatial Distribution of Topographic Index computed using Single Direction Algorithm

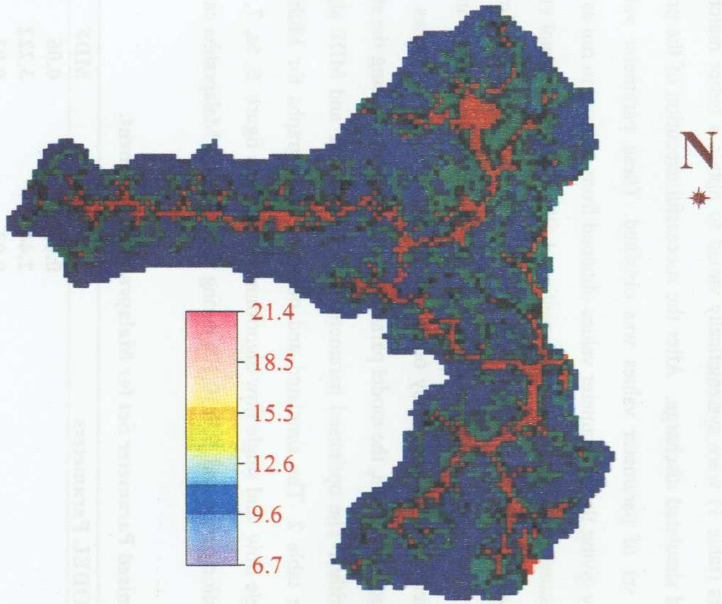


Fig.5b. Spatial Distribution of Topographic Index computed using Multiple flow Direction Algorithm

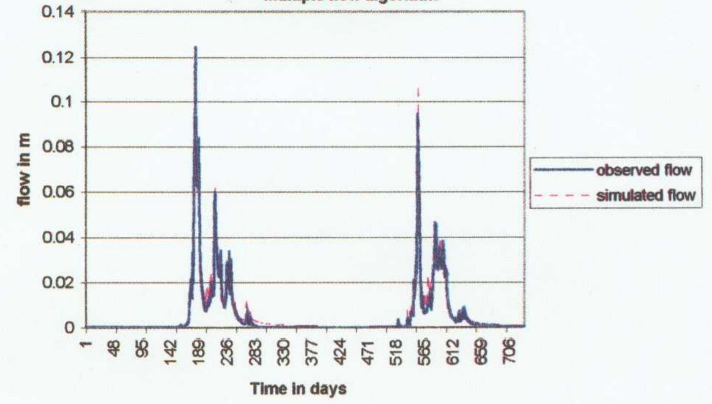
7.0. RESULTS AND DISCUSSION

The data required to run the model were compiled in the required format besides deriving the topographic data and the distribution function of the topographic index [$\ln(a/\tan\beta)$]. The statistics of the topographic index [$\ln(a/\tan\beta)$] were derived using the single flow and multiple flow direction algorithms. The statistics were used along with the continuous data of 5 years for calibration and 5 years of validation for Malaprabha catchment. The topmodel is capable of providing the results that can be mapped in space to verify their correctness in a spatial context. However, in the present study, the field measurements were not available to carry out the verification of the model parameters. The only variable, which could be verified, was the discharge measured at the outlet of the catchment. The model parameters (table 1) were systematically varied to obtain a better match between the observed and simulated discharge. After the successful execution of the program on calibration, one set of parameter values was obtained. These parameter values were further refined by giving these parameter values obtained from calibration run as the initial values for the second run. The procedure is continued till we get the optimal values. The best parameter sets obtained for multiple flow algorithms to Malaprabha catchment, were used for single flow algorithm with out recalibration. This exercise gives an insight into how the optimised set of parameter by one algorithm will produce the flows under the other type of algorithm. Then, the model parameters were optimised using the statistics of single flow algorithm. The optimised parameter set for both SDF and MDF algorithm is presented in the table 2. The simulated and observed hydrographs for Multiple flow, uncalibrated single flow and single flow algorithm are shown in figure 6, 6a, 7, 7a, 8 and 8a during calibration period and 9,9a10,10a during validation for Malaprabha catchment.

Table. 2 . Optimised Parameter Set for Malaprabha Catchment.

Sl.No	TOPMODEL Parameters	SDF	MDF
1	M	0.079	0.06
2	Ln(T0)	2.444	3.222
3	T_d	0.03	0.03
4	SR_{MAX}	0.0999	0.0999
5	SR_0	0.09	0.09

Fig. 6.0. Comparison of observed and simulated flow for calibration period of Multiple flow algorithm



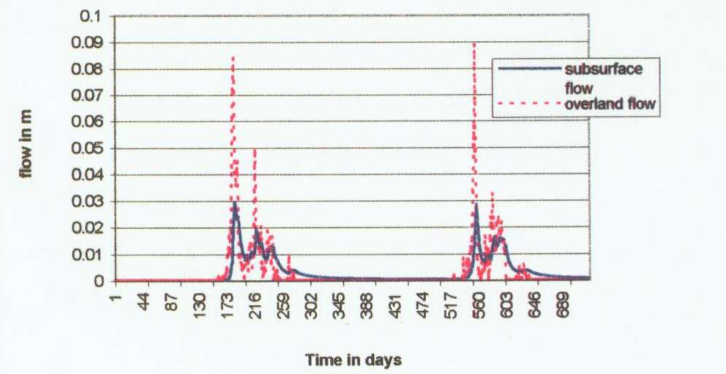
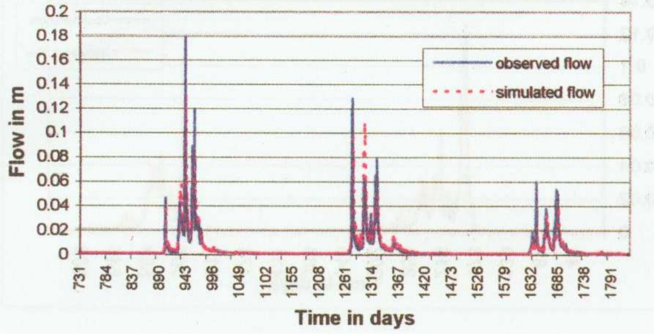


Fig.6a. Comparison of observed and simulated flow for calibration period of Multiple flow Algorithm



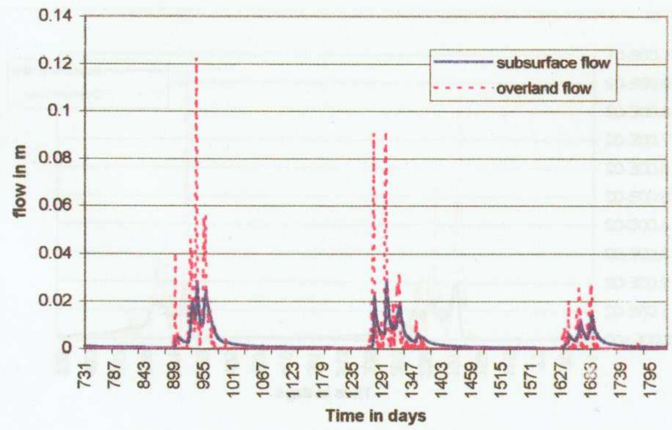
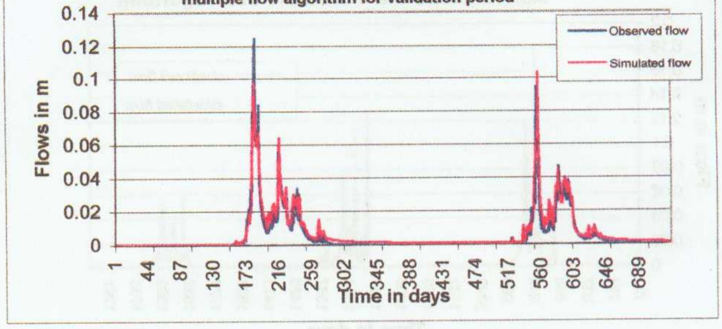


Fig.7.0 . Comparison of observed and simulated flows from uncalibrated multiple flow algorithm for validation period



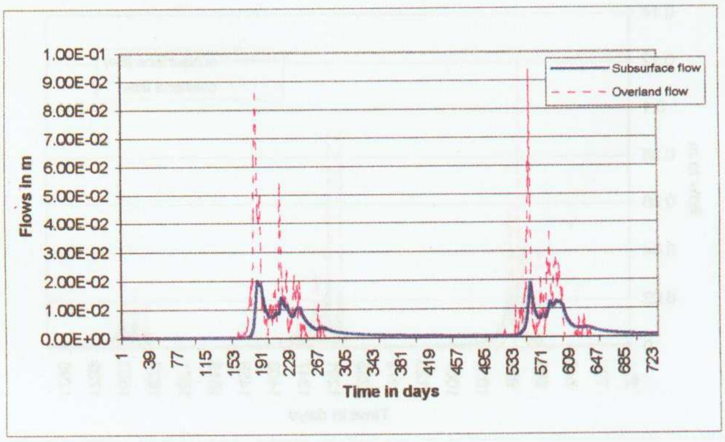
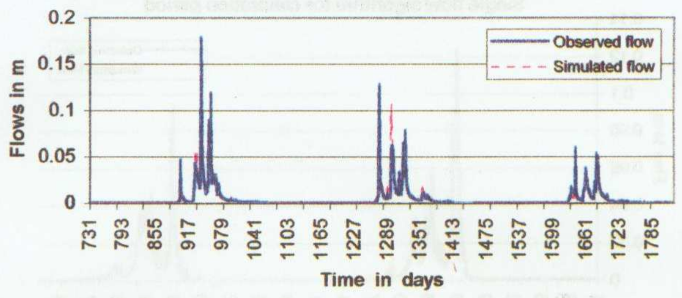


Fig.7a. Comparison of observed and simulated flows from uncalibrated multiple flow direction algorithm for validation period



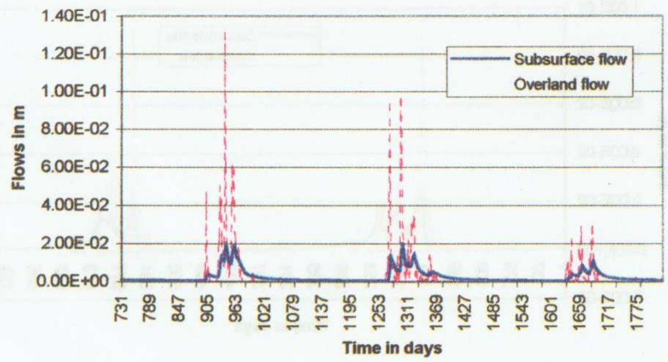
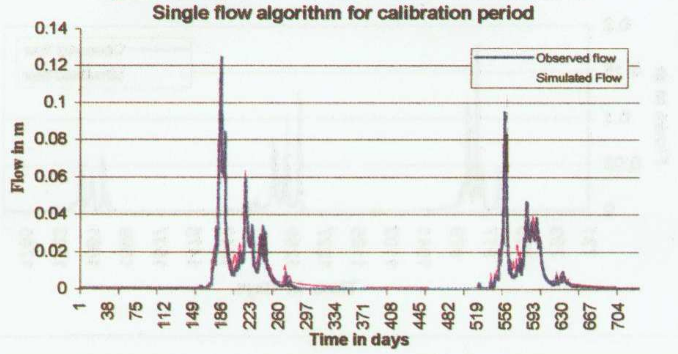


Fig.8.0 . Comaprison of observed and simulated flow for Single flow algorithm for calibration period



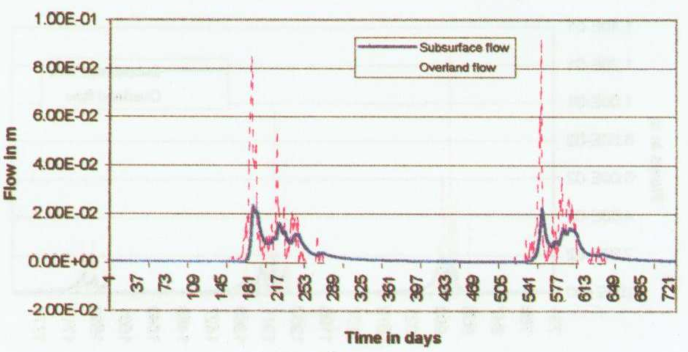
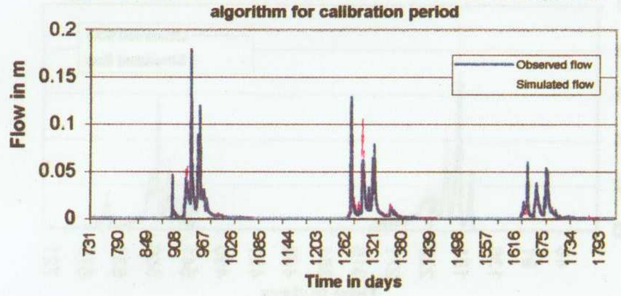
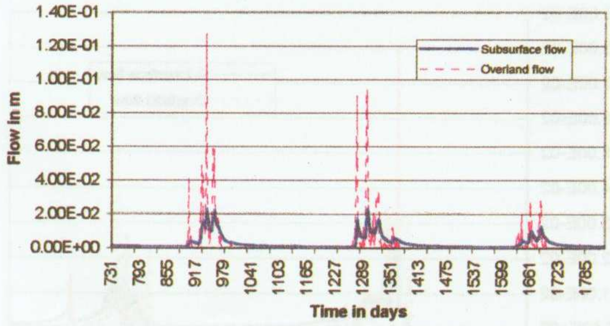


Fig.8a . Comparison of observed and simulated flow for Single flow algorithm for calibration period





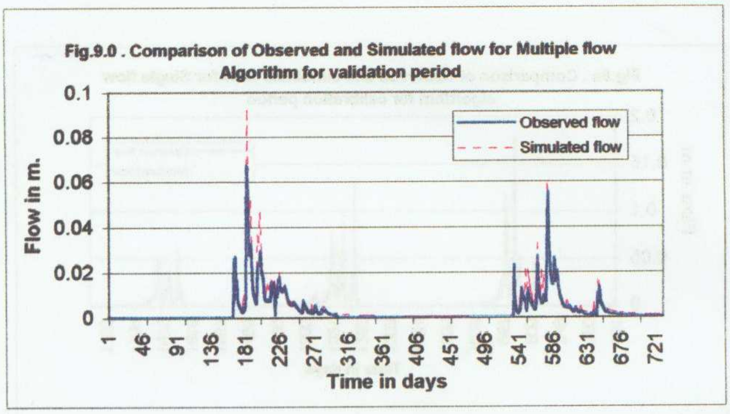
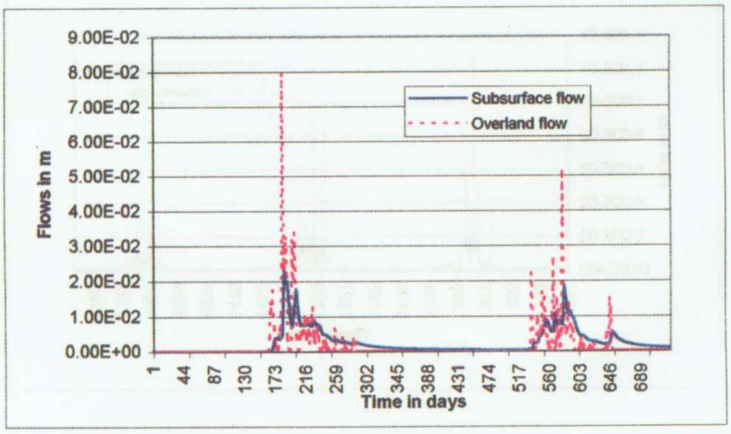


Fig.9.0 . Comparison of Observed and Simulated flow for Multiple flow Algorithm for validation period
Flow in m.
Time in days
Observed flow
Simulated flow
0.1
0.08
0.06
0.04
0.02
0
1
46
91
136
181
226
271
316
361
406
451
496
541
586
631
676
721


Flows in m
Time in days
Subsurface flow
Overland flow
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
1
44
87
130
173
216
259
302
345
388
431
474
517
560
603
646
689

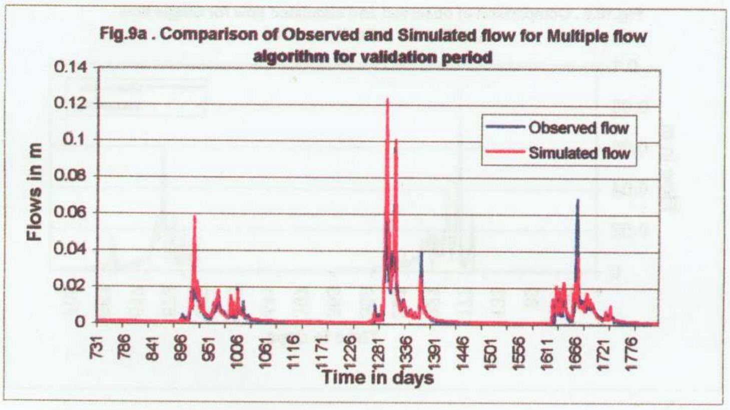


Fig.9a . Comparison of Observed and Simulated flow for Multiple flow algorithm for validation period
Flows in m
Observed flow
Simulated flow
Time in days

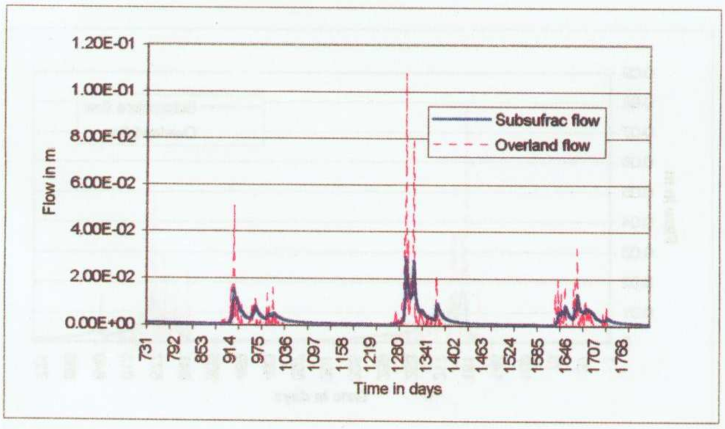
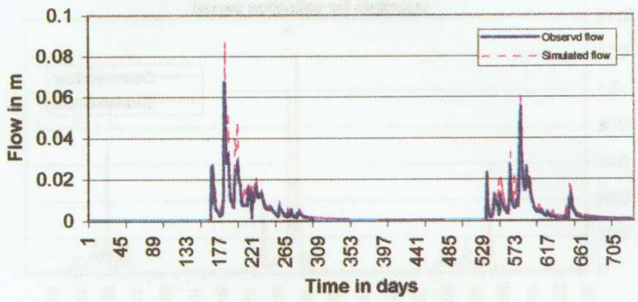

Flow in m
Subsufrac flow
Overland flow
Time in days

Fig.10.0 . Comparison of observed and simulated flow for Single flow algorithm for validation period



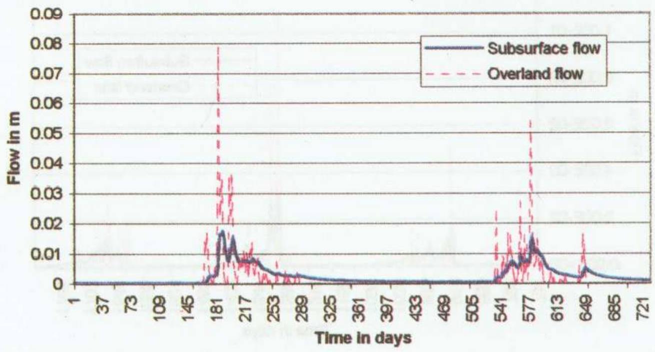
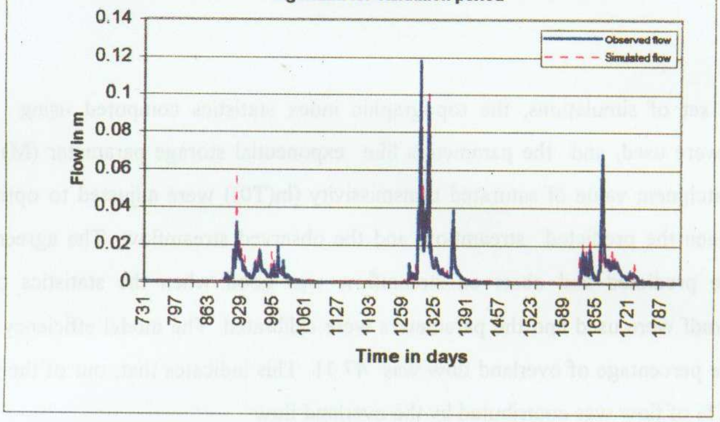
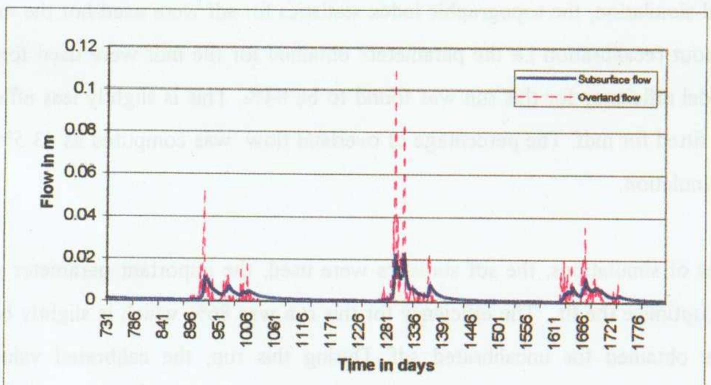


Fig.10a . Comparison of observed and simulated flow from Single flow algorithm for validation period





7.1. Comparison of TOPMODEL Simulations Using the Single and Multiple Flow Direction Algorithms.

TOPMODEL was applied to Malaprabha catchment to determine the effects on hydrologic simulation due to differences in the ln (a/tanβ) distribution statistics computed using the sdf and mdf algorithms. The TOPMODEL was run using these two sets of topographic index and the 5 years of daily data for calibration and 5 years of data for validation.

In the first set of simulations, the topographic index statistics computed using mdf algorithm were used, and the parameters like exponential storage parameter (M) and the mean catchment value of saturated transmissivity (ln(T0)) were adjusted to optimise the fit between the predicted streamflow and the observed streamflow. The agreement between the predicted and observed streamflow was good when the statistics of ln (a/tanβ) of mdf were used and the parameters were calibrated. The model efficiency was 90% and the percentage of overland flow was 47.31. This indicates that, out of the total flow, 47.31% of flow was contributed by the overland flow.

In the second simulation, the topographic index statistics for sdf were used but the model was run without recalibration i.e the parameters obtained for the mdf were used for this run. The model efficiency for this run was found to be 84%. This is slightly less efficient than the one fitted for mdf. The percentage of overland flow was computed as 43.5% for the second simulation.

In the last set of simulations, the sdf statistics were used, the important parameter were calibrated to optimise the fit. The efficiency for this run was 86% which is slightly better than the one obtained for uncalibrated sdf. During this run, the calibrated value of saturated transmissivity (ln(T0)) was decreased from 3.222 to 2.449. The lower the value of Ln(T0) means that, the soil is less transmissive thereby increasing the percentage of overland flow. The table 3 presents the calibrated model parameter values, percentage of overland flow and model efficiency for the three cases discussed above. The results obtained for this study suggest that the sdf and mdf algorithm yield almost identical results in optimising the fit between observed and simulated flow. The model efficiency for mdf and sdf algorithm is 90% and 86% respectively. It further suggests that the flow paths simulated for these two cases, are very similar. However, using the different topographic index computation algorithms, may cause the optimisation routine to find very diffeient saturated hydraulic parameters for good agreement between the observed and simulated streamflow. Thus, the TOPMODEL simulates the same streamflow but compensates for different topographic parameter by slight change in the parameter values.

Table.3. Topmodel Simulation Results for Malaprabha Catchment using ln(a/tanβ) distribution computed using Single flow Direction and Multiple flow Direction Algorithms.

Simulation	Model Efficiency	M mt	L_0 m^2/hr	Percentage of Overland Flow
Calibrated sdf	86	0.079	2.449	56.10
Uncalibrated sdf	84	0.06	3.222	43.5
Calibrated mdf	90	0.06	3.222	47.31

8.0 CONCLUSION

From the study, the following conclusion are drawn:

1. The single direction flow algorithm computes the more cumulative area for the same topographic index value than the multiple direction flow algorithms.

2. The use of sdf and mdf algorithm results in different spatial distribution of the topographic index computed from the DEM's.

3. The use of sdf and mdf algorithms causes only marginal difference in the model efficiency and simulated flow paths. The mdf algorithm gives slightly better results.

4. The use of sdf and mdf algorithms has some effect on the model parameters, especially on m (the decay parameter) and $\ln T_0$ (the transmissivity of the soil profile under saturation).

Finally, it can be concluded, the choice of algorithm, will effect the simulated spatial distribution of hydrologic characteristics such as soil moisture content. Therefore, if TOPMODEL is being used to simulate the spatial pattern of hydrologic characteristics, then the mdf algorithm can be preferred than the sdf algorithm. If the model is used for simulation of streamflow, the choice of any algorithm makes no difference.

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