RAINFALL RUNOFF MODELLING USING TOPOGRAPHY BASED DISTRIBUTED MODEL (TOPMODEL)

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled: **"RAINFALL RUNOFF MODELLING USING TOPOGRAPHY BASED DISTRIBUTED MODEL(TOPMODEL)"** in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in water resources development, in Water Resources Development and Management Department, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during the period from July 2006 to June 2007, under the supervision and guidance of Dr. S.K. Mishra and Dr. M K. Jain.

The matter embodied in this Dissertation has not been submitted by me for the award of any Degree.

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ABSTRACT

The formation of runoff occurs, in most cases as the result of combination of causes including rainfall intensity exceeding the infiltration capacity and available water capacity in the soil being exceeded by the total amount of rainfall. Topography is recognized as an important factor in determining stream flow response of watershed to precipitation. The TOPMODEL, Topography based Hydrological model, is a variable contributing area conceptual model. Due to it's structural simplicity and a few number of parameterization, TOPMODEL has become more popular for land surface process study using digital elevation models (DEMs). TOPMODEL simulates runoff at the catchment outlet based on the concept of saturation excess overland flow and subsurface flow. It utilizes topographic index as an indicator of likely spatial distribution of rainfall excess generation in the catchment.

The present work aims at to evaluate the TOPMODEL applicability to the forest and sub-Himalayan watershed. Such an evaluation does not appear to have been reported in literature. In this study TOPMODEL was applied to simulate continuously the runoff hydrograph of Chaukhutia watershed of Ramganga catchment. The objectives were to relate hydrological responses to runoff generation mechanisms, operating in the catchment and to estimate the uncertainty associated with runoff prediction. The Topographic Index values within the catchment were determined using digital elevation (DEM) data. Select parameters in TOPMODEL were calibrated using an iterative procedure to obtain a set of parameters to produce minimum sum of square of errors between observed and computed hydrograph. The calibrated parameters are the transmissivity decay parameter, m, the surface transmissivity $\ln(T_0)$, the root zone water available capacity, SR_{max}, initial moisture deficit in root zone, SR_{init} and channel velocity, ChVel. Observed data for the period (1975 – 78) was used for calibrating model parameters and response of the model with calibrated parameters was verified using data for (1979 – 81).The generalized likelihood (GLUE) framework was used to assess the performance of the model with randomly selected parameter sets. The TOPMODEL did not perform as a good simulator for Chaukhutia watershed, which is characterized by its land use as: forest=50%, agriculture and pasture=27%, and barren land=8%. Efficiency of the model in calibration period was of the order of 0.58 and in validation period was of the order of 0.649. Although model simulated well the base flow portion of the observed hydrograph but the model efficiency has been deteriorated due to the underestimation of peaks by the model, which is not unusual as most of the long-term rainfall-runoff models perform poorly, especially in forested watersheds and often underestimate peak flows.

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CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

The flow of water on the surface of the earth has long perplexed the human mind. The desire to understand the movement of water has mainly arisen from the need to evaluate the amount of water available at a particular location to meet local demand as well as risk of flooding due to excess water. Hydrological processes within a catchment are complex involving macropores, heterogeneity and local pockets of saturation. Catchment direct runoff response to rainfall involves generation of rainfall excess (runoff response) and the transfer of this excess to the catchment outlet via land surface and through linked channels (channel response). The representation of runoff formation process has been accomplished, over the decades, with methods which vary according to the purpose and application of the model. These range from simple calculation of design discharge to the two dimensional representation of various processes, based on suitably conditioned mass balance, energy and momentum equations and to the three dimensional representation of all exchanges.

Runoff in wet region is mainly produced by saturation excess runoff. This means that the spatial distribution of soil moisture storage will result in different surface runoff production. For a large area, the saturation excess runoff will occur in a certain portion of the area, where there is no soil moisture deficit, say, ground water goes upto ground surface. Both models and data have shown that within a catchment substantial soil moisture heterogeneity exists at almost any scale and that a major control on the distribution of soil moisture is topography. Even though there are many surface runoff models based on saturation excess runoff mechanism, only a few models take the topography influence on the spatial distribution pattern of soil moisture into consideration and in turn on runoff production.The TOPMODEL(Beven,1986a) 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 soil with the vertical distance from ground level.

The TOPMODEL is one of the few conceptual models, in which physical reality is represented in a simplified manner, 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. It is a topography based watershed hydrology model that has been used to study a range of topics, including spatial scale effects on hydrological process, topographic effects on stream flow, the identification of hydrological flow path etc.

1.2 OBJECTIVE

The overall objective of this study is the runoff estimation of Chaukhutia watershed of Ramganga catchment using TOPMODEL. To attain the above objective following subsidiary objective needs to be satisfied:

- To generate digital elevation model (DEM) for watershed under study.
- To calculate the Topographic index from DEM for use in TOPMODEL.
- To calibrate and validate TOPMODEL for the watershed under study.
- To perform the sensitivity analysis of model parameters using Monte Carlo Simulations and analysis of results obtained.

CHAPTER – 2

REVIEW OF LITERATURE

2 .1 BACKGROUND

The literature contains many works which summarize the current level of understanding of physics of the complex process of rainfall-runoff transformation, and still more work is continuing to bring in possible improvements in schematizing the whole process so as to develop mathematical models(Todini 1988). In fact the representation of runoff transformation processes has been accomplished, over the decades, with models which vary according to the purpose and application.

The fundamental characteristic of catchment hydrology is in the form of mass balance equation for a specified time interval and is represented by:

$$R = P - ET - \Delta S \qquad \text{-----------(2.1)}$$

Where P is precipitation, R is runoff, ET is evapotranspiration and ΔS represents change in storage which includes surface water, soil moisture, groundwater and snow pack. Over short periods, ground water storage and spatial distribution of soil moisture content will change in response to the prevailing inputs and climate. Consequently, investigation of hydrologic processes on these time scales require detailed knowledge of water including fluxes, changes in storage, and transfers throughout the catchment.

Mathematical models in hydrology are useful for accessing the conceptualization of dominant hydrologic processes operating in a catchment. A model, once calibrated and verified on a catchment, provides a multi-purpose tool for further analysis. The model can be used to test hypotheses and gain a better understanding of how the catchment behaves under different conditions in future, that is to make predictions. Models also represent a means of integrating measured data collected spatially and temporally from the catchment and can be used to provide estimates for missing data. Whichever type of model is selected for a catchment, the final structure necessary represents a simplification of reality.

2.2 RAINFALL RUNOFF MODELLING APPROACHES

Most hydrologic systems are extremely complex, and we cannot hope to understand them in all detail. Therefore, abstraction is necessary if we are to understand or control some aspects of their behaviour. Abstraction consists in replacing the system under consideration with a model of similar but simpler structure. The basic purpose of a model is to simulate and predict the operation of the system that is unduly complex and the effect of changes on this operation. This use of hydrologic models for prediction purposes arises largely because of the inadequate availability of hydrologic data (Dooge, 1973). The increasing effect of human activity on elements of hydrologic cycle will tend more and more to render hydrological data of limited use for the direct prediction of corresponding behaviour in future.

Runoff models are classified based on:

(i) Process description (deterministic, conceptual, stochastic)

(ii) Domain representation (lumped, semi-distributed, distributed)

(iii) Temporal scale (annual, monthly, daily, hourly)

(iv) Solution technique and model application.

A mathematical model expresses the system behaviour by a set of equation, perhaps together with logical statements, expressing relationships between variables and parameters. Mathematical models are sometimes divided into:

(i) Theoretical or physical models

(ii) Conceptual models

(iii) Empirical models.

Theoretical models presumably are the consequences of most important laws governing the phenomena. A theoretical or physical model has a logical structure similar to the real world system and may be helpful under changed circumstances. Physically based model's parameters can be measured directly in-situ. Watershed runoff models based on St. Venant's equation are the example of physical models e.g. SHE (System Hydrologique European) model (Abbott et al.,1986) and others.

An empirical model is not based on physical laws. It merely presents the facts, that is, it is a representation of data. If the conditions change, it has no predictive capability e.g. rational method, unit hydrograph models, etc.

For a conceptual model, the physical reality is represented in simplified manner. Conceptual models consider physical laws but in highly simplified form. So conceptual models are intermediate between theoretical and empirical models. Examples of conceptual models may include rainfall-runoff models based on the spatially lumped form of continuity equation and the storage discharge relationship. Models of Nash (1958) and Dooge (1959) are conceptual models.

Theoretical models aid in understanding a process and generally yield information in greater detail in both time and space. Empirical models do not aid in physical understanding. Conceptual models provide useful results efficiently and economically for some problems. They contain parameters, some of which may have direct physical significance and can therefore be estimated by using concurrent observations of input and output.

TOPMODEL (Topography based hydrologic MODEL) is a conceptual model and was first introduced by Kirkby and Weyman (1974) and refined by Beven and Kirkby (1979) to simulate runoff from a catchment based on the concept of saturation excess overland flow and subsurface flow and places emphasis on the role of catchment topography in the runoff generation process. An implicit assumption is that the local groundwater table has the same slope as the watershed surface. This allows for the modeling of sub-surface flow using the surface topographic slope.

2.3 REVIEW OF TOPMODEL APPLICATIONS

TOPMODEL represents a set of modeling tools that combines the computational and parametric efficiency of a lumped modeling approach with the link to physical theory. TOPMODEL has been successfully used in humid temperate regions (Beven and Wood, 1983; Homberger et al., 1985; Beven, 1993) Robson et al., 1993, Lamb et al, 1998; Guintner et al., 1999) and drier Mediterranean regimes (Durand et al., 1992; Pinol et al., 1997), small humid tropical catchments; the Booro catchment in Irovy coast (Quinn et al., 1991) and a forested head water catchment of a river Sinnamary in French Guiana (Molicova et al., 1997). TOPMODEL was applied to simulate continuously the runoff Hydrograph of medium sized humid tropical catchment (Campling, 2002). The model simulated well the fast subsurface and overland flow events superimposed on seasonal rise and fall of the baseflow. A study of rainfall-runoff response for a catchment in the upper reaches of Yangtze river is done by Shufen (2004) using TOPMODEL coupled with the simple water cycle model. TOPMODEL works well in simulating the runoff of the Soumoun river catchment. The rainfall-runoff response of the Tygarts Creek catchment in eastern Kentucky is studied using TOPMODEL by Nageshwar &. Brummett (2005). The calibration results obtained in this study are in general agreement with the results documented from previous studies using TOPMODEL.

Molicova et al., (1997) used the TOPMODEL for modeling the hydrological patterns within a humid, tropical catchment. They tested its validity in modeling the stream flow dynamics (hydrograph) in a 1 ha tropical rain forest catchment in

French Guiana. The field validation of the temporal and spatial hydrodynamics across a rainfall-runoff event revealed that TOPMODEL might be suited for applications to this particular rain forest environment. In fact, this was the first successful application of such a model within the humid tropics. The main reason for success of the model was low hydraulic conductivity of subsoil, coupled with the absence of an additional deep ground water body, the contribution from which has caused difficulties in application of topographic based runoff models elsewhere in humid tropics.

Pinol et al. (1997) applied the distributed TOPMODEL concepts in an application to the strongly seasonal contributing area responses in two adjacent small Mediterranean catchments in the Parades region of Catalonia, Spain. A perceptual model of hydrological response in these catchments was used to suggest possible modifications in the model, in a hypothesis testing framework, including an attempt to modify the topographic index approach to reflect the expansion of effective area of subsurface flow during the wetting-up sequence. It was found that slight improvements in modeling efficiency were possible but that different model parameter distributions were appropriate for different parts of the record. The model was much more successful for the catchment producing the higher runoff volumes.

Campling et al. (2002) applied the TOPMODEL to simulate the runoff hydrograph of a medium sized humid tropical catchment (379 km^2). The objectives were to relate hydrological responses to runoff generation mechanisms operating in the catchment and to estimate the uncertainty associated with runoff prediction. Field observations indicated that water tables were not parallel to the surface topography, particularly at the start of wet season. A reference topographic index λ_{REF} was therefore introduced into the TOPMODEL structure to increase the weighting of local storage deficits in upland areas. The model adaptation had the effect of depending water tables with distance from river channel. The generalized likelihood uncertainty estimation (GLUE) framework was used to asses the performance of the model with randomly selected parameter sets, and to set simulation confidence limits. The model simulated well the fast subsurface and overland flow events superimposed on the seasonal rise and fall of the base flow. The top ranked parameter sets achieved modeling efficiencies of 0.943 and 0.849 in 1994 and 1995 respectively. The GLUE analysis showed that exponential decay parameter m, controlling the base flow and local storage deficit, was the most sensitive parameter. There was increased uncertainty in the simulation of storm events during the early and late phases of the season which was due to a combination of errors in detecting the rainfall depths for conventional rainfall events, the treatment of rainfall as a catchment areal value, and the strong seasonality in runoff response in humid tropics.

Shufen & Huiping (2004) used the TOPMODEL to study the rainfall-runoff response in a catchment (around 2500 km^2) in the upper reaches of Yangteze river. They developed a simple water cycle model, for estimating other components of the surface water cycle, which was implemented into the TOPMODEL to integrate the water cycle of the catchment. Using the output of a

DEM from 100m x 100m resolution data and a single flow direction algorithm, the index distribution function was calculated for the catchment under different channel initiation thresholds. Finally the daily and monthly rainfall-runoff response from 1960 to 1987 for Soumon River Catchment (a tributary of the Yangtze River) in China was simulated with TOPMODEL. To evaluate the general quality of model, percentage of efficiency E of each year from 1960 to 1987 with Channel Initiation Threshold (CIT) equal to 0.01 km^2, 0.1 km^2 and 5.0 km^2 was calculated. The coefficient E didn't show a large variation from each other with different CIT values except for a very small CIT. For CIT = 0.5, 1 and 5 km^2, the values for E are almost the same. They found that E values are large for most years which means TOPMODEL works well in simulating the runoff of Soumon River catchment. Hence, it is concluded that TOPMODEL works well in catchments with a hill slope region, with moist soil, and with a shallower ground water table.

The rainfall-runoff response of the Tygarts Creek Catchment, which is a mountainous catchment, was studied using TOPMODEL by Bhaskar et al. (2005). Unlike the traditional application of this model to continuous rainfall-runoff data, the use of TOPMODEL in single event runoff modeling, specifically floods, was explored by them. The topographic index values within the catchment were determined using the digital terrain analysis procedures in conjunction with digital elevation model (DEM) data. Select parameters in TOPMODEL were calibrated using an iterative procedure to obtain the best fit runoff hydrograph. The calibrated parameters included the surface transmissivity

T_o, the transmissivity decay parameter m, and initial moisture deficit in root zone, S_{ro}. These parameters were calibrated using three additional storm events. Overall, the calibration results obtained in this study were in general agreement with the results documented from previous studies using TOPMODEL. However, the parameter values did not perform well during the verification phase of study consequently, a universal set of TOPMODEL parameters could not be recommended for simulating runoff from Tygarts Creek Catchment. The topographic index curves obtained for the Tygarts Creek Catchment and each of its sub-catchments were in close agreement, as were the average index values. However, the average index values were higher than those documented from previous studies, partly due to the large grid size of 83 m used for analysis. Since the parameters 'm' and T_o, the average topographic index value, and the resulting stream flow values were all directly connected, the large grid size also affected the calibrated values of 'm' and T_o.

Nachabe(2005) proposed an equivalence between TOPMODEL and NRCS curve number method in predicting variable runoff source areas. By his approach he had shown that NRCS equation can be used to describe the probability distribution function of moisture deficit in a catchment, as calculated by TOPMODEL approach. His approach was to constrain 'S' parameter in the Natural Resources Conservation Service(NRCS) method by the physical soil and topography characteristics of the catchment and depth to water table. By giving a clear physical meaning for 'S' he provided better estimation of this parameter in humid vegetated landscape where runoff production is controlled by rising water table. By his analysis it was shown that a distributed model might be equivalent to a lumped parameter model, when the objective is to predict a spatially integrated response, like runoff at catchment outlet.

Wang et al. (2006) used the TOPMODEL'S rainfall – runoff hydrologic concept, based on soil saturation process, in representing hydrograph recession curve by power function decay of hydraulic conductivity with soil depth. In their study a power function formulation of Green and Ampt infiltration equation was developed to represent field measurements in Ward Pound Ridge watershed in New York City drinking water supply area. They used power function decay to compute Topographic Index distributions of soil saturation of TOPMODEL studies and found that soil hydraulic conductivity values had power function decay with soil depth. They also found that differences between linear, exponential and power function infiltration scenarios are sensitive to relative difference between rainfall rates and hydraulic conductivity. Using a low frequency 30 minute design storm with 48cm/hr rain for n=2 power function formulation had given a faster decay of infiltration and more rapid generation of runoff.

2.3.1 Application of TOPMODEL to Indian Catchment

TOPMODEL was applied to Malaprabha catchment (520 km^2) in Karnataka by Venkatesh and Jain (2000) to simulate the daily flows at Khanapur. The topographic index for Malaprabha catchment was derived by developing a digital elevation model (DEM) by interpolating the contours in the basin at 300 m grid size. The results indicated that the model could be used to simulate the flows in the catchment quite accurately. The efficiency of model was 0.89 and 0.79 respectively in calibration and validation. Also model was able to simulate the timing and magnitude of the peak flow satisfactorily.

Rainfall-runoff modeling for Hemavathy catchment in Western Ghats was studied by Jain (1996).Raster DEM input for the model was generated through ILWIS after digitization contour maps from topographic maps. In all 5 years of data was used for simulation study. Calibration and validation of TOPMODEL was carried out by breaking the available data series in two part. The first part, i.e. June 1975 – December 1977, was used for model parameter calibration and the remaining data series i.e. January 1978 to December 1980 was used for model validation. Model efficiency (Nash-Suteliffe) was more than 0.84 both for model calibration and validation on independent data series.

Above review of literatures reveal that concepts of TOPMODEL have been tested on widely differing catchments having different size, climate and land cover conditions. In India, very few studies are reported in literature using TOPMODEL concepts, particularly no study we could find in forested Himalayan catchment. This study is an attempt to fill this gap.

2.4 TOPMODEL LIMITATIONS

(i) TOPMODEL only simulates watershed hydrology.

(ii) TOPMODEL can be applied most accurately to watersheds that do not suffer from excessively long dry periods and have shallow homogeneous soil and moderate topography.

(iii) Model results are sensitive to grid size, and grid size < = 50 m is recommended.

CHAPTER – 3

TOPMODEL DESCRIPTION

TOPMODEL is a set of conceptual tools that can be used to reproduce the hydrological behaviour of the catchments in a distributed or semi-distributed way, in particular the dynamics of surface or subsurface contributing areas.

The model simulates hydrologic fluxes of water (infiltration excess, overland flow, infiltration, subsurface flow, evapotranspiration and channel routing) through a watershed. The model simulates explicit groundwater / surface water interactions by predicting the movement of water table which determines where saturated land surface areas develop and have the potential to produce saturation overland flow

3.1 TOPMODEL ASSUMPTIONS

(i) The hydraulic gradient of subsurface flow is equal to the land surface slope.

(ii) The actual lateral discharge is proportional to specific watershed area (drainage area per unit length of contour line).

(iii) The redistribution of water within the subsurface can be approximated by a series of consecutive steady states.

(iv) The soil profile at each point has a finite capacity to transport water laterally down slope.

(v) The saturated hydraulic conductivity decreases exponentially as depth below land surface increases.

3.2 TOPMODEL THEORY

In TOPMODEL the topography dominated rainfall excess generation process is described by using a topographic index $\lambda_i = \ln (a_i / \tan \beta_i)$, where a_i is upslope catchment area per unit contour length draining to a point 'i' in the catchment and $\tan \beta_i$ is the local surface topographic slope (assumed equal to hydraulic gradient of saturated zone) at the same location. This index is used to calculate the average moisture deficit over the entire catchment and the local moisture deficit at any location 'i' within the catchment. Hence it can be used to characterize how the moisture deficit at any particular location within the catchment deviates from the average moisture deficit of entire catchment. So the main goal of TOPMODEL is the computation of storage deficit on water table depth at any location for every time step. The theory relates mean watershed storage deficit to local storage deficits using the local value of a function of the topographic index.

The TOPMODEL parameters in runoff simulation examined in the past studies are surface transmissivity 'T_o' and transmissivity decay parameter 'm'. According to Beven (1997), the concept of transmissivity, as used in TOPMODEL does not have the traditional meaning of groundwater mechanics, where transmissivity refers to the rate at which water is transmitted through a unit width of aquifer under unit hydraulic gradient. The transmissivity values obtained using

TOPMODEL are for downslope subsurface flow, where the unit hydraulic gradient is equal to surface topographic slope. The other TOPMODEL parameter 'm' reflects the decay rate of assumed transmissivity profile (relationship between the subsurface transmissivity, T, at any depth to the surface transmissivity, T_o). The slope of stream flow recession curves during period of no recharge to the groundwater table can be analyzed to get an initial estimate of parameter 'm'. In original version of TOPMODEL, the soil hydraulic conductivity on the soil transmissivity is assumed to decay following a negative exponential law. In this case, the expression that estimates the value of local storage deficit or water table depth is given in terms of topographic index $\ln (a / \tan \beta)$. Other forms of soil hydraulic conductivity decay function lead to different index functions. When distributed values of soil transmissivity, T_o, are known, a soil topographic index may be considered, $\ln (a/T_o \tan\beta)$.

3.3 RUNOFF PRODUCTION IN TOPMODEL

Runoff generation at a point depends on

(a) Rainfall intensity or amount

(b) Antecedent soil moisture conditions

(c) Soils and vegetation

(d) Depth to water table i.e. topography

(e) Time scale of interest.

These vary spatially which suggest a spatial geographic approach to runoff estimation. The soil profile is defined by a set of stores. The upper one is the root zone storage where rainfall infiltrates until the filed capacity is reached. In this store, evapotranspiration is assumed to take place at the potential rate to decrease at a linear rate when the root zone becomes depleted. Once the field capacity is exceeded, a second store starts filling until the water content reaches saturation. The gravity drainage store links the unsaturated and saturated zones, according to a linear function that includes a time delay parameter for vertical routing through the unsaturated zone. When the deficit in the gravity drainage store or water table depth equals zero, the saturation condition is reached and the rainfall produces direct surface runoff.

TOPMODEL primarily generates estimates of runoff at the catchment outlet from the saturation excess at the surface and from the subsurface flow. The rainfall runoff equations used are derived from

(i) Darcy's law

(ii) The continuity equation

(iii) The assumption that the saturated hydraulic conductivity decreases exponentially as depth below the land surface increases.

Darcy's law in TOPMODEL takes the form

$$q_i = T_o (\tan \beta_l) \exp (-S_i / m) \qquad (3.1)$$

where index 'i', refers to a specific location in the catchment, q_i = The down slope flow beneath the water table per unit contour length (m^2/h); $\tan \beta_l$ = Average inflow slope angle; T_o = Surface transmissivity (m^2/h) at location I; m = transmissiivity decay parameter; S_i = Moisture deficit at location i in (m)

The continuity equation is represented by quasi-steady state recharge rate to the water table.

$$q_i = r_i a_i \tag{3.2}$$

where r_i is the recharge rate (m/h) to the water table a_i is the upslope contributing area per unit contour length (m^2/m) at any location i in the catchment.

Combining these two equations (3.1) and (3.2) and rearranging gives an expression for moisture deficit S_i at any particular location i within the catchment.

$$S_i = - m \ln (r_i a_i / T_o \tan \beta_I) \tag{3.3}$$

The variable S_i in the above equation can be expressed in terms of average moisture deficit, $\bar{S}$, for the entire catchment or sub catchment as

$$S_i = \bar{S} - m[(\lambda_i - \lambda) - (\ln T_o - \ln T_e)] \tag{3.4}$$

where $\lambda_I = \ln (a_i / \tan \beta_i)$ is the local topographic index and T_e is the average transmissivity value for the entire catchment or sub-catchment and is equal to

$$T_e = \left(\frac{1}{A}\right)\sum \ln T_o \qquad (3.5)$$

where A is entire area of catchment; λ = the catchment average topographic index value and is given by

$$\lambda = \left(\frac{1}{A}\right)\sum_i \ln(a_i / \tan\beta_i) \qquad (3.6)$$

Equation (3.4) is the fundamental equation for describing runoff production within TOPMODEL because it defines the degree of saturation for each topographic index value λ_i at any location within the catchment.

By assuming T_e equal to T_o, S_i depends on $\bar{S}$ and the deviation of the local topographic index, λ_i from λ. Since small values of S_i are associated with larger values of the topographic index λ_i, the higher the topographic index value at any location in the catchment, the smaller amount of moisture that will be needed to saturate the soil profile for that location.

In the TOPMODEL, it is assumed that the hydraulic conductivity, K, decreases exponentially with depth. The hydraulic conductivity and transmissivity have the relation T = bK, where b is assumed average depth of soil moisture deficit zone. Hence the transmissvity below the catchment surface can be expressed as

$$T = T_o \exp^{(-S_i/m)} \qquad (3.7)$$

Where T (m^2/h) is the transmissivity value for a local moisture deficit, S_i. This relationship is used in the development of equation (3.4).

There are three main soil profile zones, namely root zone, unsaturated zone and saturation zone. When the root zone exceeds the field capacity of the soil, excess moisture contributes to moisture storage is the unsaturated zone. Beven (1995) describes the equation describing the flow through the unsaturated and saturated zones in TOPMODEL, which are:

(i) The vertical flux through the unsaturated zone is represented by

$$q_{vi} = S_{uz} / S_i t_d \tag{3.8}$$

where q_{vi} has units of (m/h), S_{uz} is the moisture storage in unsaturated zone at each time step at location i (m), S_i is moisture deficit in the unsaturated zone at location 'i' at each time step in (m), t_d is the time delay per unit depth of deficit (h/m). The term $S_i t_d$ represents a time constant that increases with the soil moisture deficit.

(ii) The recharge rate to the saturated zone at any time step from the unsaturated zone is $q_{vi}A_i$ where A_i is the fractional area associated with topographic index class 'i'. This recharge is summed over the total number of topographic index classes, n, to get the total recharge to the saturated zone Q_v.

At current time step, Q_v (m/h) = $\sum_i q_{vi} A_i$ (3.9)

Once Q_v enters the saturated zone, the flow in the saturate zone on subsurface flow, Q_b (m/h), is

$$Q_b = Q_o \exp^{(-\bar{S}/m)} \tag{3.10}$$

The flow Q_b can also appear at the surface when the soil profile is fully saturated, such as at the bottom of a hill slope, Q_o (m/h) in equation (3.10) is the subsurface flow when the soil is fully saturated (i.e. when S = 0)

$$A_o = Ae^{-Y} \tag{3.11}$$

Where Y is the average soil-topographic index; A is the total catchment area. The average soil topographic index Y is given by

$$Y = \frac{1}{A}\sum \ln(a_i / T_o \tan\beta_i) \tag{3.12}$$

For constant transmissivity T_o, within the catchment

$$Y = \frac{1}{T_o} \tag{3.13}$$

The recharge rate to the saturated zone, Q_v and subsurface flow from the saturated zone, Q_b, are used to update the value of average moisture deficit, in the catchment at each time step at (h). This is represented by

$$\overline{S}_t = \overline{S}_{t-1} + (Q_{b,t-1} - Q_{v,t-1}).\Delta t \qquad (3.14)$$

where the subscript t represents the current time interval. The initial value of $\overline{S}$ (i.e. when t = 0) is calculated from equation (3.10) using the initial value of the observed hydrograph as Q_b. The total contribution to the catchment outlet at any time step, Q_i (simulated flow), is the sum of subsurface flow, Q_b, and the saturation excess overland flow, Q_{ovr}.

The overland flow Q_{ovr} is calculated as the product of the depth of saturation excess and the fractional area of topographic index values that are generating the saturation excess.

Routing is necessary to recognize the effects of travel time within the catchment. The routing method used in TOPMODEL resembles Clark's (1945) method, which is a time area routing method. In the time area method of catchment routing, the travel time in the catchment is divided into equal intervals. At each time interval, it is assumed that the area within the catchment boundaries and the specific distance increment will contribute to the flow at the catchment outlet. The partial flow at the catchment outlet from each sub area is equal to the product of the rainfall excess produced times the area of the contributing portion of the catchment. Summing the partial flows of all contributing areas at each time step gives the total flow at the catchment outlet for each time step in the hydrograph (Ponce 1989).

3.4 DESCRIPTION OF COMPUTATIONAL PROCEDURE FOR ln(a/tanβ) INDEX IN EACH GRID SQUARE

In order to calculate ln (a/tan β) Index in each grid square, the contributing area for that grid square must be calculated and then divided by the tangent of the slope relevant to that grid. Only the downward direction is considered below. If it is assumed that all the directions have the same water transportation probability, then the area drained by unit length of contour can be calculated as

$$a = \frac{A}{nL} \tag{3.15}$$

where n = number of downward stream direction, L = effective contour length orthogonal to the direction of flow; A = Total area drained by current grid square (total upslope area).

The value of tan β can be computed as

$$\tan\beta = \frac{1}{n}\sum_{i=1}^{n}\tan\beta_i \tag{3.16}$$

where tan β_i is the slope of the line connecting the current grid square with the further most grid square in the i-th downstream direction. Therefore,

$$\frac{a}{\tan\beta} = \frac{A}{L\sum_{i=1}^{n}\tan\beta} \tag{3.17}$$

and $$\ln\left(\frac{a}{\tan\beta}\right) = \ln\left[\frac{A}{L\sum_{i=1}^{n}\tan\beta i}\right] \tag{3.18}$$

The amount of area A that contributes in each ith downstream direction is thus calculated as:

$$\Delta A_i = \left[\frac{A_i\tan\beta_i}{\sum_{i=1}^{n}\tan\beta_i}\right] \tag{3.19}$$

The procedure is repeated on all cells of the DEM proceeding downstream.

3.4.1 Different Approaches used for Computation of Topographic Index

Various procedures have been implemented to determine the spatial distribution of the topographic index ln (a/tan β). The development of these procedures can be attributed to the manifold potential of the geographic information systems (GIS) which by means of its integration with hydrological modules greatly facilitates the estimation of the index in catchment areas.

Topographic index using single flow direction algorithm proposed by Jenson and Dominique (1988) is the most commonly used method of computing topographic index due to its simplicity and wide availability in most of the GIS systems. In this method, starting from a digital terrain model (DTM), the cumulative upslope area drained through a generic cell of the DTM is computed by allowing flow of water to occur in one of the possible eight neighbouring cells by means of a moving window of 3 x 3 points centered on the analysis point (I, j) (commonly known as D8 algorithm) which, along the direction of maximum slope, moves sequentially from higher to lower DTM levels. At the end of this elaboration, it is possible to associate the cumulative upslope area that has drained through the element considered, the theoretical path taken by flow and the topographic gradient in the direction of maximum slope to each DTM element (I, J).

Greater detail can be obtained by introducing a stochastic component inside the D8 algorithm, along the N-E, S-E, S-W and N-W directions (Fairfield and Leymarie, 1991). This improvement, known as Rho8 procedure, is more often found more suitable in those moderately sloping areas along which the automatically extracted channel network would tend to runoff in parallel along the preferential directions, according to the D8 approach. The D8 and Rho8 procedures produce similar distribution function of topographic index, however, the same procedures do not represent completely the flow path of surface runoff, especially in those areas typified by divergent surfaces.

Freeman and Quinn et al., (1991) introduced a multiple direction approach ,defined as FD8,for theoretical evaluation of the concentration of surface runoff by considering the accumulated upslope area for any one cell is distributed amongst all those of downstream direction according to weighted percentages relative to the slope. The same Authors have, however demonstrated that FD8 algorithm cannot simulate well in certain topographic conditions, such as those found in alluvial plains. In these circumstances a pronounced expansion of surface runoff along the alluvial plains is noticeable instead of well-delineated stream channels. The FD8 algorithm, therefore, has to be modified according to the river network and local soil depth variations.

A mixed scheme namely, FRho8 (Mendicino and Sole, 1997) allows the evaluation of theoretical path of flow related to the permanent drainage system. Runoff coming from slopes (scheme FD8), after having reached one of the channels of the river network, must remain in it (scheme Rho8) until it reaches the basin outlet.

Quinn et al (1995) suggested a specific procedure for hydrological applications using TOPMODEL. This is based on the analysis of distribution functions of the topographic index obtained for different value of channel initiation threshold, CIT which is minimum drainage area required to initiate a channel. Variations in the CIT produce different resolution levels of the channel network because of different cataloging of a certain number of DTM cells ("Channel" cell, on "slope" cells).

Therefore, different procedures imply variation in the shape of the topographic index distribution function, channels of the network are characterized by a greater concentration of surface runoff with respect to the slopes, and, therefore, by higher values of topographic index. If a high starting value of CIT is selected (low network resolution level), and ever decreasing values are considered (level increase), the 'channel' cells propagate upwards involving the 'slope' cells that contain a channel, and which are thus characterized by lower index values. This leads to a small increase in the peak of the topographic index distribution function. These variations are contained upto a threshold value of CIT for which there is a rapid rise and a noticeable shift of the distribution peak towards lower index values. This threshold values according to Quinn et al. (1995) should be more suitable for the identification of the permanent channel network in the case of hydrological applications conducted exclusively with TOPMODEL, relative to basic resolution of current DTM.

In the above procedures there are two important restrictions; the first involves the formation of runoff within the DTM, which, as well as having a pixel, origin, is routed downwards by means of a line (one dimensional); the second refers to runoff directions, which are limited to the eight possibilities of the neighbouring points of cell under consideration. These problems can be overcome by a DTM cell is routed downwards by means of a surface, analogous to that produced by the procedure proposed by Costa-Carbal and Burger (1994), called DEMON. In this procedure, according to contour based stream tube approach used originally by Beven and Kirkby (1979), runoff is generated by area and not by a pixel origin. Runoff produced by DTM cell is routed downwards by means of a surface, analogous to that produced by the projection of a stream tube on to a plane. Different stream tubes, or flow paths, are identified locally as line intersection points, traced in aspect direction, with the edges of the DTM cell. The width will vary according to morphology in the DTM, increasing for divergent surfaces and decreases in relation to convergent surfaces.

Currently a digital terrain model (DTM) or digital elevation model (DEM) is extensively used to calculate the spatial distribution of the topographic index in a catchment (Saulnir et al., 1997). However, there are two factors which affect the pattern of the topography index distribution; the resolution of the topography used in the DTM and the way to define a grid as containing the river channel or not in a catchment. If a grid, which originally is one containing a river channel by one threshold setting, which is used to decide whether the grid contains the river channel or not, is considered as one of the water collection area without the river channel by another threshold setting, the number of grids with high topography index will increase and the distribution of the topography index in a catchment will move to the end of high value and in turn the average topography index of the catchment will enlarge. In order to reduce the effect of the way to consider a grid as containing the river channel on not, a channel initiation threshold (CIT), is set up. If a grid with area 'a' draining water through it greater than CIT, the grid is considered as one containing water channel; otherwise the grid is considered as

CHAPTER - 4

THE STUDY AREA AND DATA AVAILABILITY

The Chaukhutia watershed, located in Almora and Chamoli districts of the State of Uttrakhand, has been selected for the present study. This watershed is the uppermost subwatershed of Ramganga reservoir catchment. The Chaukhutia watershed of Ramganga reservoir catchment lies between 29^0 46' 35" to 30^0 6' 11"N latitude and 79^0 11'23" to $79^0$31'21"E longitude in the Shivalik range of Himalayas, having an area of 572.81 sq km. Mainly Chaukhutia watershed is extended from Dwarahat (Almora) in south and Gairsen (Chamoli) in north. Entire Chaukhutia watershed falls under Kumaon region of Western Himalayas. The outlet of Chaukhutia watershed is located in Chaukhutia block headquarter under Ranikhet sub division of Almora district.

4.1 TOPOGRAPHY

The Chaukhutia watershed is hilly catchment of the river Ramganga. The maximum and minimum elevations within this watershed are 3097.5 and 939.4m above mean sea level respectively. The outlet is situated at an elevation of 939.4m in west-southern boundary of the watershed as shown in location/index maps (Fig.4.1). This watershed consists mostly of rolling and undulating topography having very steep irregular slopes.

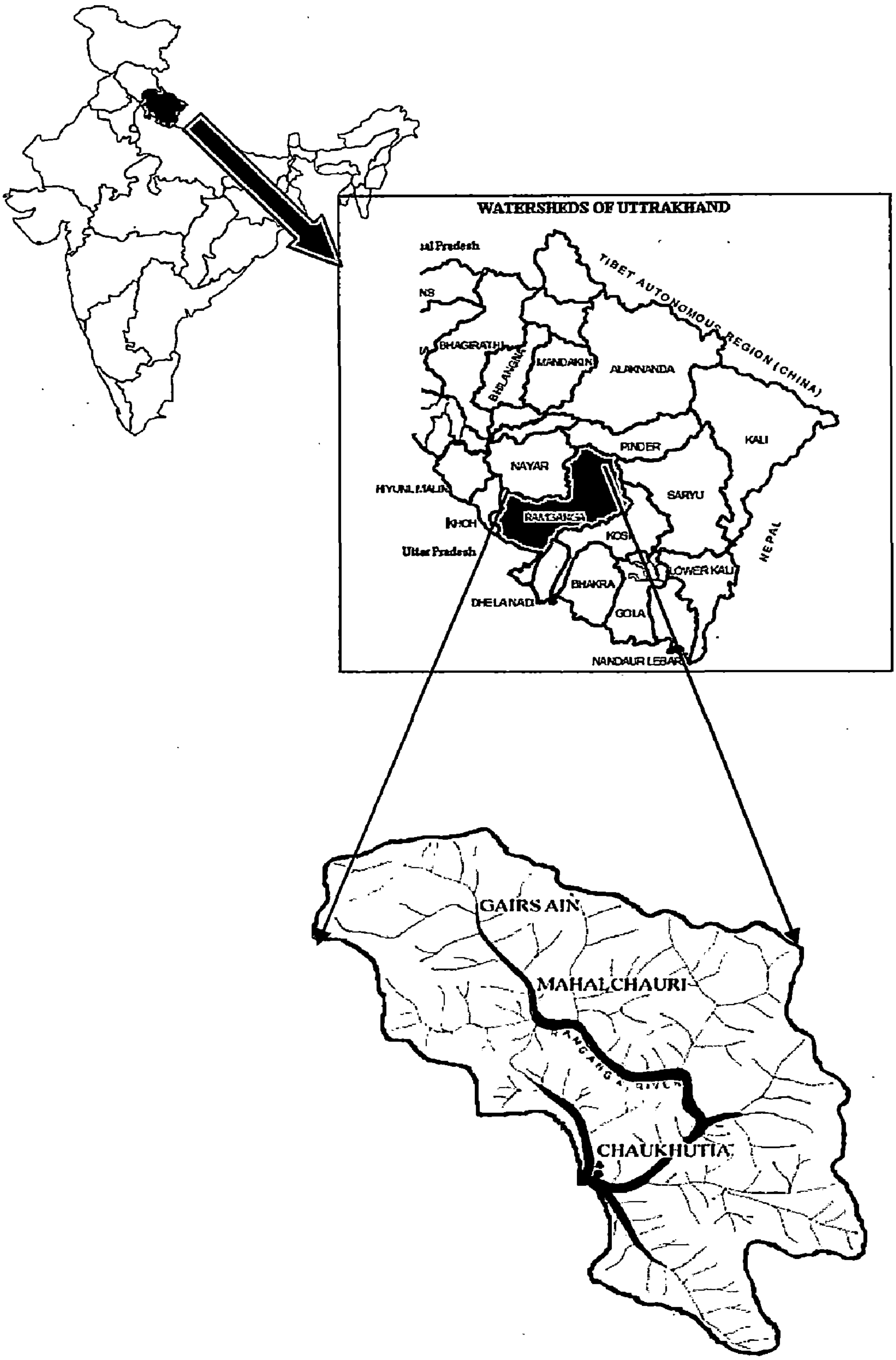

Fig. 4.1 Location Map of Chaukhutia watershed

4.2 GEOLOGY

Chaukhutia watershed consists of crystalline and sedimentary rocks of Calc zone. Crystalline occurs as vast sequence of low to medium grade metamorphics associated with coarse to medium grained granites. A thin zone of porphyritic rocks exposed along the Almora fault is known as Chaukhutia Quartz Prophyry. These rocks are highly crushed and fine grained with prophyro-blasts of quartz and feldspar, and also show development of schistose structure. Sedimentary rocks of Calc zone is found north of Dwarahat around Dhunagiri hill and Ramganga valley near Mehalchauri. South of Mehalchauri north-east trending open faults of large wavelength are superimposed by the tight isoclinical folds trending north-west. A series of gently plunging open folds of 27.432 m to 36.576m wavelength are exposed in the Ramganga valley south-east of Mehalchauri. Tightness of folds increases in upper level and assumes a recumbent to overturned posture towards Chaukhutia. Regional trend of folds is from north to north-west which are reoriented and refolded near the contact with Almora crystallines.

4.3 SOIL TYPE

Soils in Chaukhutia watershed vary in texture, depth and slope. Broadly soils of this watershed may be classified as loamy soils. Depth of soil varies from shallow to deep and slope varies from steep to very steep. Hydrologically, soils

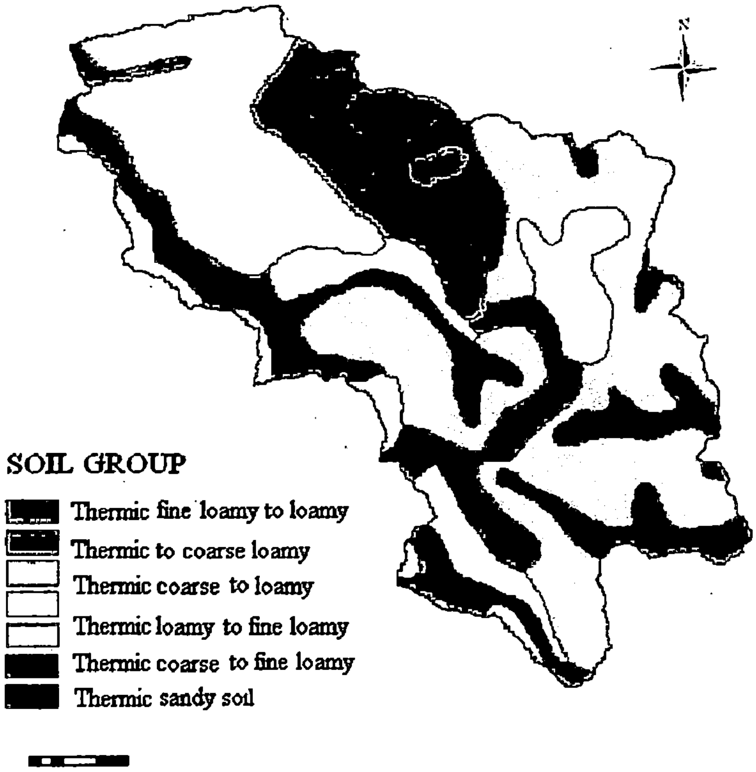

Fig. 4.2 Soil Map of Chaukhutia watershed

present in the watershed can be grouped from A to C as per SCS (1956). Fig. 4.2 depicts the soil map (NBSSLUP, 2004) of the watershed.

4.4 LAND USE

In terms of land resources, the Chaukhutia watershed is covered with Forest, Pasture, Agriculture, Settlement, and Fallow/Rocky/Waste lands. Forests present in Chaukhutia watershed are dominated by dense mixed jungle mainly having Pine and Banj, Chir pine (Pinus Roxburghii) and broad-leaved Banj (Quercus Leuchotrichophora). Most of the forest areas are under Reserve Forest. The forest cover of Chaukhutia watershed is about 50% of the total area of this watershed and falls under the jurisdiction of Divisional Forest Office (Soil Conservation), Ranikhet, Almora, Uttrakhand. Agriculture is mainly practiced on hill-slopes as level terrace cultivation and valley cultivation. The percentage of agriculture land area is about 12.0% of the total area of this watershed. About 15% area of the watershed is covered under pasture land.

The area covered by urban and rural settlements in this watershed is about 8.0% of the total area. Mostly settlement is along Ranikhet – Badrinath state highway which crosses the Chaukhutia watershed from its southern boundary to northern boundary. The rural economy under this watershed is characterised by subsistence agriculture, mainly on rainfed conditions. In addition to this, the area under different types of road is about 2.0% of the total area. Besides above, other land types such as water bodies (about 5.0%) and

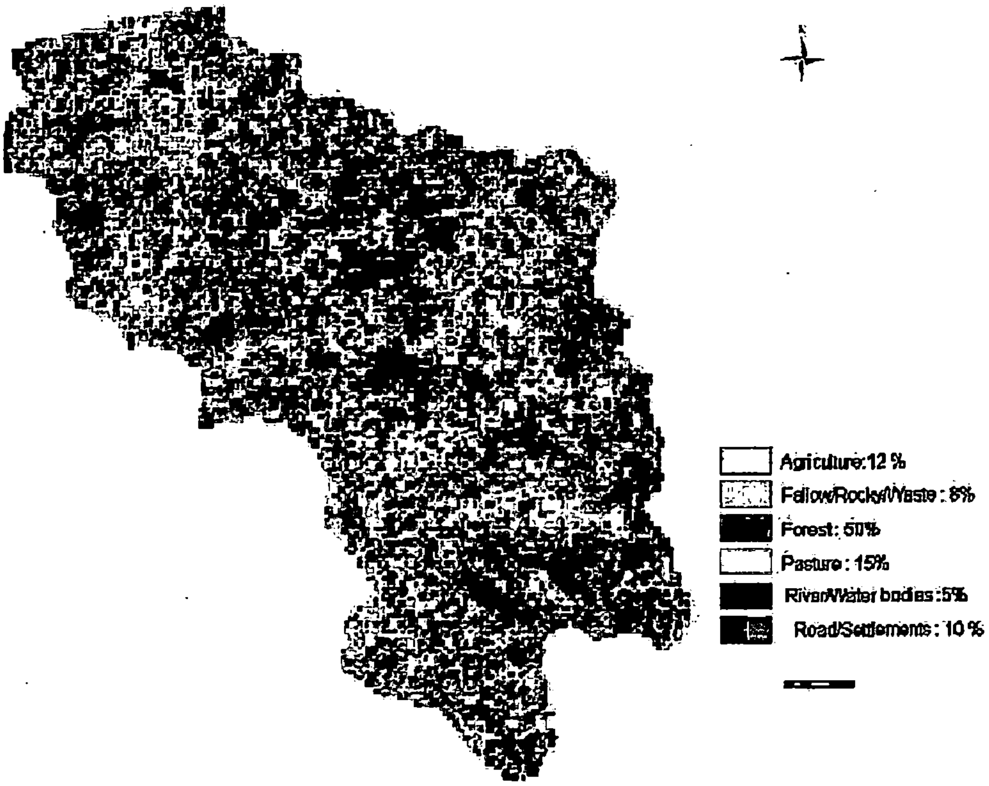

Fig.4.3 Land use Map of Chaukhutia watershed

area under Fallow/Rocky/Waste land is about 8.0% of the total area of this watershed. Land cover map of the watershed obtained after classification of LISSIII satellite image of IRS system is shown in Fig. 4.3.

4.5 CLIMATE

The Chaukhutia watershed lies in Sub Himalayan zone of Western Himalaya. The variation in altitude influences the climate of the watershed. The climate of this watershed varies from sub-tropical in the lower region to sub-temperate and temperate in upper region with a mean annual temperature of about 22^0C.

4.6 STREAM NETWORK

The watershed is drained by a dense river network having high slopes. The length of Ramganga River up to Chaukhutia outlet is about 37 km. There are two major streams that meet the river Ramganga at Chaukhutia namely Kurhlar Gad which is 16km long meeting main river from south-east direction and Khachyar Gadhera which is about 14km long and meet the main streams north direction of Chaukhutia. In addition to these two major streams, several other major and minor streams also meet river Ramganga and its tributaries. Drainage map of Chaukhutia watershed is shown in Fig. 4.4.

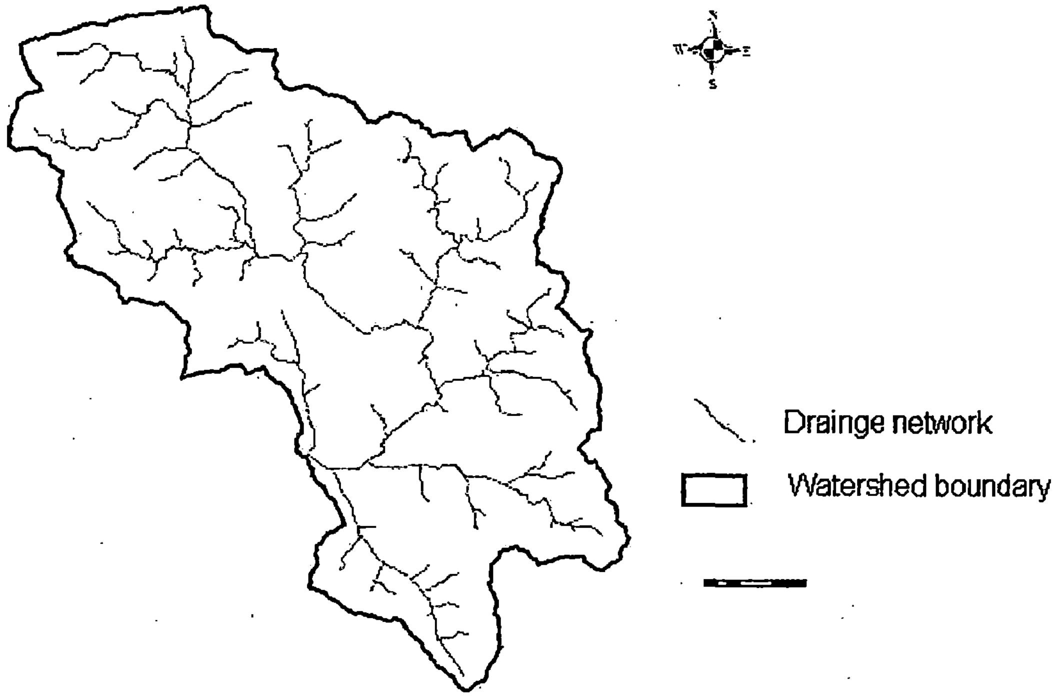

Fig.4.4 Drainage Map of Chaukhutia watershed

4.7 RAINFALL

Significant portion of total precipitation in the form of rainfall in the watershed occurs mainly during the four months of the monsoon i.e. from June to September with a mean annual total precipitation of 1388.7 mm. On an average, the monsoon contributes about 74% of the total annual rainfall. Wide variations in total annual rainfall have been observed in past 30 years (967.9 mm (1981) to 1985.1mm (1998)). Mean monthly rainfall varies from 6.9 mm in the month of November to 344.3 mm in the month of July. The entire hydro-meteorological characteristics of the watershed are characterized by the high precipitation generating peak monsoon flows and low precipitation during the dry season resulting in low flows.

4.8 DATA AVAILABILITY

Basic topographic details were available from the Survey of India toposheets (No. 53N4, 53N8, 53O1, 53O5 and53O9) at the scale of 1:50000. Daily rainfall and runoff data, for the years 1975-78 and June1979-May1981, was available. Temperature data of watershed, for the corresponding period, was also available which was used for calculation of daily evapo-transpiration values of the watershed due to non availability of observed evapo-transpiration data.

CHAPTER - 5

DATA PROCESSING, ANALYSIS AND DISCUSSION OF RESULTS

Application of TOPMODEL involves (a) generation of digital elevation model (DEM), (b) determining the Topographic index distribution of watershed from generated DEM, after making it sink free, (c) preparing the necessary Input and Catchment data files from Hydrological and Topographic index distribution data, (d) calibrating and validating of the model, and (e) sensitivity analysis of model parameters.

5.1 DTM GENERATION AND ANALYSIS

In the present study scanned topographic maps in scale of 1:50000 were used to derive spatial information such as contours, drainage, spot height etc. Georeferencing of scanned topographic maps was done using ERDAS IMAGINE Image processing system (ERDAS, 2001). The objective of Georeferencing is to provide a rigid spatial framework by which positions of the real world features are measured, computed and analysed in terms of length of a line, size of an area and shape of a feature. The primary aim of a reference system is to locate a feature on earth surface. All these maps were first registered in Geographic coordinate system(lat, long) and then re-projected in polyconic projection system with reference spheroid as Everest 1956 (Indo-Nepal) by invoking Geometric correction function of Data preparation menu of ERDAS IMAGINE. Then all the point features, line features, such as contours and streams, and area features, such as lakes, ponds etc, were digitized as vector layer in ERDAS. All these files were exported to ArcGIS (ESRI, 2000) to assign associated attribute information elevation of contours etc. and further processing.

The digitized contour map was interpolated using interpolation tools available in ArcGIS to produce DEM of Chaukhutia watershed. By using Topo to raster option of Raster Interpolation menu, hydrolgically correct DEM at a finer resolution of 20m was made. Generated DEM was further aggregated to 100 m pixel size to fit into rows and column limits imposed in TOPMODEL program. Aggregated DEM of 100m resolution was analysed further by TauDEM terrain analysis extension to ArcGIS (Tarboton, 1997). Using terrain analysis functions available in TauDEM extensions, a sink free DEM was generated. Location of the outlet of watershed was marked on sink free DEM. For this, a shape file with point feature class was created in ArcMap and outlet was located on the stream path by selecting Editor/Start and Stop Editing and save edits options of ArcMap. Selecting this output file in Network Delineation menu watershed was delineated. After masking operation Raster Digital Elevation was masked and all pixels lying outside of watershed were assigned a value greater than 9999.0m. The masked DEM of watershed is shown in Fig. 5.1.

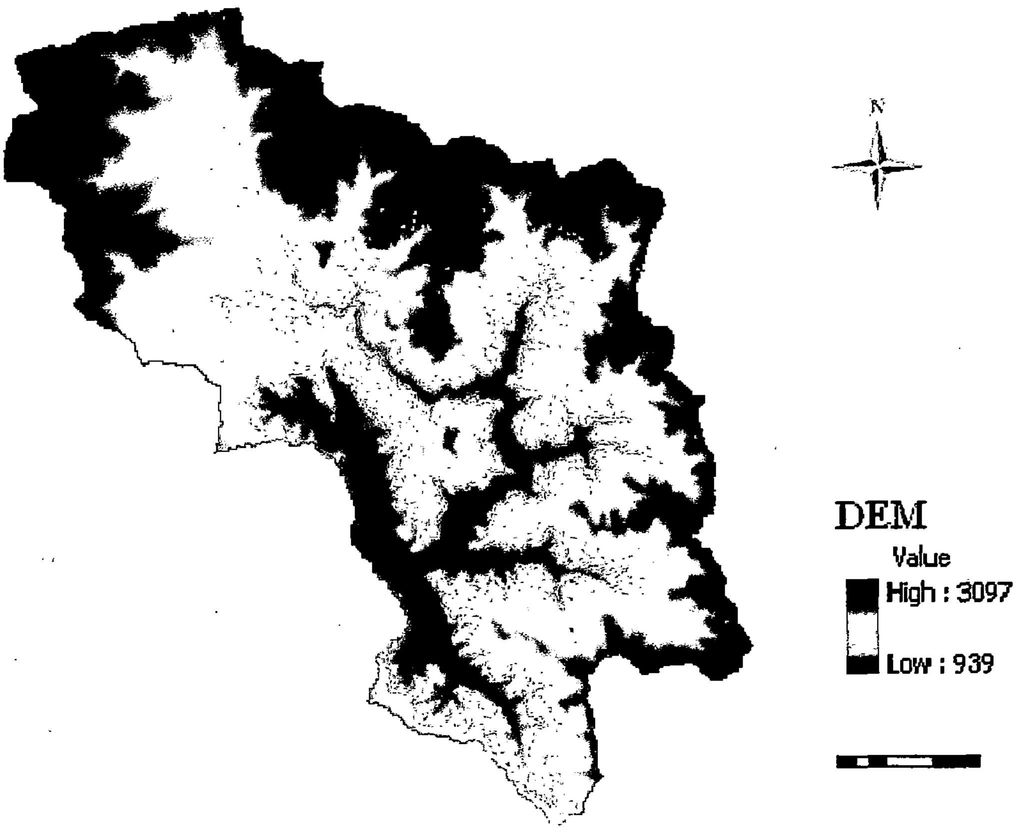

Fig.5.1 DEM of Chaukhutia watershed

5.2 DETERMINING THE TOPOGRAPHIC INDEX

The generated DEM was exported to ASCII format for inputting into DTM analysis program of TOPMODEL. The input elevation file is a file of elevation in meters, listed in order from bottom left hand (South West) corner, row by row, working northwards. Only the elevation of points within the catchment is used, all other values in the matrix is set to a value greater than 9999.0 (m), for Topographic Index calculation.

Values of topographic index ln(a/tanβ) were calculated using single and multiple direction flow algorithm (Quinn et al., 1995). By choosing Topographic Index distribution option of the program, output files, with information of topographic index ln(a/tanβ), % contributing area $\Delta A_c/A$, cumulative contributing area and number of sinks and lake pixels, was obtained. The single flow direction 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 contour length is also considered for this flow direction. For this weighting factor of 0.5 was considered for cardinal directions and 0.35 for a diagonal direction for partitioning of flow (Quinn et al. 1991). These topographic index distribution values were reclassified into 27 classes to fit in dimensional limitation of less than or equal to 30 classes of the TOPMODEL program available. Fig. 5.2 shows the spatial distribution of Topographic Index in the catchment computed using single and multiple flow direction algorithms. Fig. 5.3 shows cumulative frequency distribution of

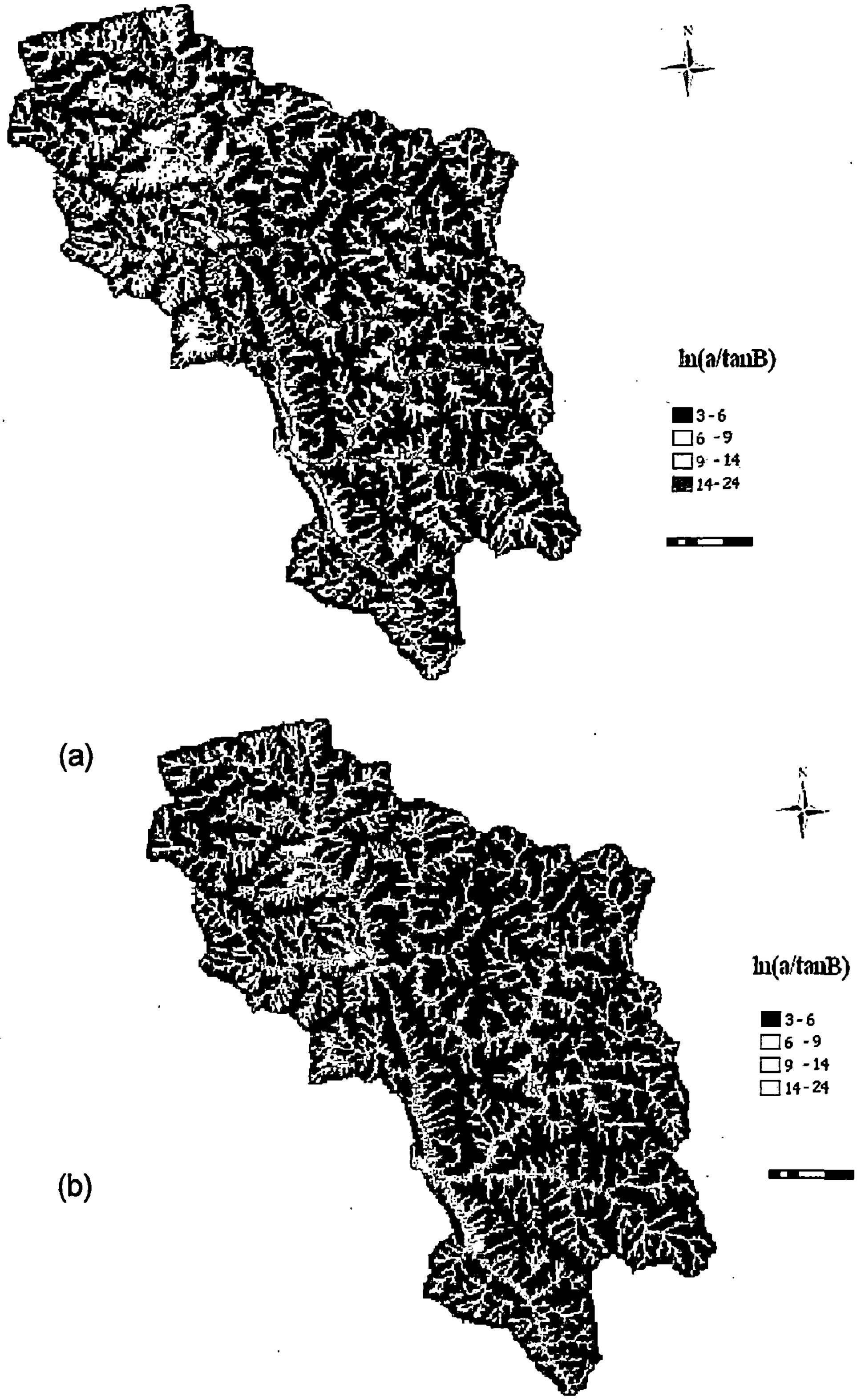

Fig.5.2 Topographic Index Map of Chaukhutia watershed (a) Multiple direction of flow, (b) Single direction of flow

Topographic Index $\ln(a/\tan\beta)$ for single and multiple flow direction algorithm. As can be seen from Fig. 5.3, the curves showing cumulative frequency distributions for single and multiple flow direction have same shape but index values computed by single flow direction algorithm have higher values near channel cells due to concentration of flow which can be seen clearly from this figure. Overall the distribution of topographic index well spread across the catchment and nearly all high index areas are located near the streams. In general, the index map corresponds well with the catchment wetness.

5.3 PREPERATION OF INPUT FILES

For setting up of a model for a watershed, input data files are required to be prepared. The input files for application of the TOPMODEL consist of project file of the watershed having information of text description of application, Catchment Data file name, Hydrologic Input Data file name and Topographic Index Map file name. The Catchment data file was prepared with all necessary data regarding $\log(a/\tan\beta)$ distribution class values, stream channel distance increment with contributing area for channel routing and five model parameters, namely, parameter of exponential transmissivity function (m), the natural logarithm of effective transmissivity of the soil when just saturated ($\ln(T_o)$), the profile storage available for transpiration (SR_{max}), initial storage deficite in root zone (SR_{int}), and effective surface routing velocity for scaling the distance/area (ChVel), with initial, minimum and maximum values of the parameters.

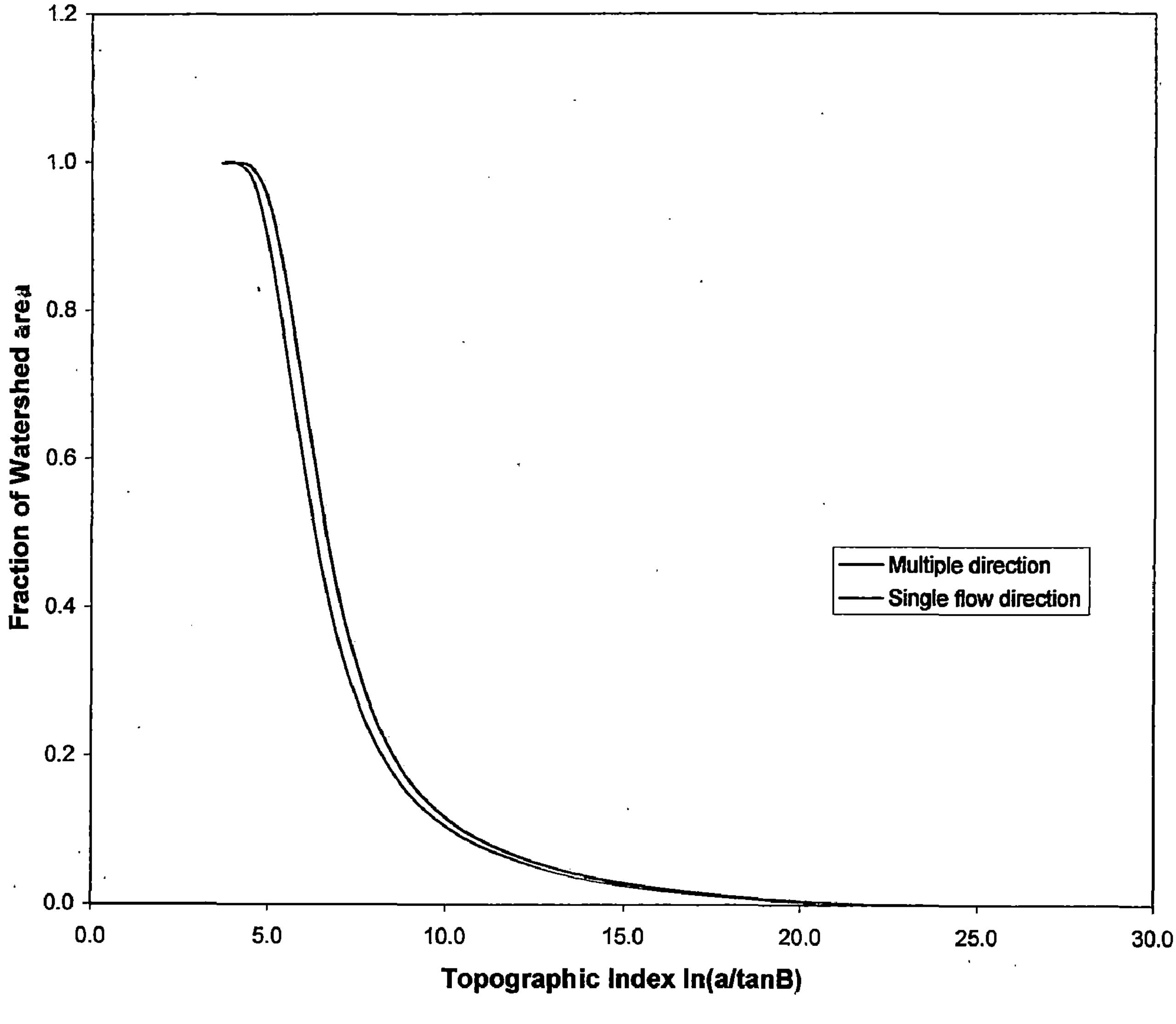

Fig. 5.3 Cumulative frequency distribution of Topographic Index

for Single and Multiple direction of flow

Hydrological input Data file was prepared with the available daily rainfall, runoff and temperature data of the watershed. As reported previously, daily potential evapo-transpiration data was not available, therefore monthly Potential evapo-transpiration was calculated by an empirical formula given by Blaney and Criddle (1962). In this method potential evapo-transpiration is estimated by correlating it with sunshine hour and temperature. Sunshine at a place is dependent on latitude of the place and varies with month of the year. PET for a crop during it's growing season is given by:

$$PET = \sum K*F$$

where K is monthly crop coefficient determined from experimental data and F is monthly consumptive use factor, given by

$$F = (0.0457T_m + 0.8128)\ P$$

Where PET, the potential evapo-transpiration in cm; T_m, the mean monthly temperature in ^oC and P, the monthly percentage of bright sunshine hour in the year.

5.4 MODEL CALIBRATION AND VALIDATION:

For calibrating and validating of the model parameters, available observed data was split into two groups, the first group of data for years 1975 to 1978 was used for calibration of the model and the remaining data for years 1979 to 1981 was used to validate the model results.

5.4.1 MODEL CALIBRATION

Each formulation of the TOPMODEL may present an individual parameter set to be calibrated, however in the version of the TOPMODEL used in the present study, there are five critical parameters that directly control model response. These are:

1. 'm' : the parameter of exponential transmissivity function or recession curve (units of depth, m)
2. $\ln(T_o)$: The natural logarithm of effective transmissivity of the soil when just saturated. A homogeneous soil throughout the catchment is assumed.
3. SR_{max} : The soil profile storage available for transpiration i.e. available water capacity (units of depth, m)
4. SR_{init} : The initial storage deficit in the root zone (units of depth, m)
5. ChVel : Effective surface rooting velocity for scaling the distance/area or network width function. Linear routing is assumed (units of m/hr).

The model was applied on a continuous basis over a period of 4 years (Jan75 to Dec78) for calibration of model parameters for the watershed. A time step of 1 day was selected for computations to calibrate the model. As detailed earlier, all five parameters were assigned with initial values. The calibration of parameters was systematically performed starting with parameter 'm'. The value of parameter m was varied, holding values of remaining four parameters at initial value and value of parameter m was determined which yields the highest Nash and Sutcliffe efficiency value, 'EFF'. Subsequently, the parameter m was assigned just determined value and next parameter $\ln(T_0)$ was varied with an effort to further maximize efficiency. This was repeated for remaining parameters in succession to arrive at a set of parameters which gave highest value of efficiency EFF. These parameters were further refined by giving computed parameters as initial guess in second round of execution runs with narrow band of upper and lower limits and in this way a set of parameter was chosen which gave highest value of EFF. After each run of the model, four indices of goodness of fit were considered for evaluation. These are:

- The Nash and Sutcliffe efficiency, EFF = $(1 - \sigma_i^2/\sigma^2_{obs})$ where σ_i^2 is residual variance and σ^2_{obs} is the observed variance
- Sum of squared errors, SSE = $\sum_1^n (Q_{obs} - Q_{simu})^2$
- Sum of squared log error, SLE = $\sum_1^n \{\log(Q_{obs}) - \log(Q_{simu})\}^2$
- Sum of absolute errors, SAE = $\sum_1^n |Q_{obs} - Q_{simu}|$

The calibration of model parameters was done by considering values of topographic index computed by single as well as multiple flow direction algorithms. For computation of topographic index using single flow direction, weighing factor 'H' was taken equal to 5.0 and for multiple flow direction 'H' was taken as 1 for 100 m pixel size used in the present analysis (Quinn et al.,1995). The values of model parameters obtained through calibration and values and error statistics for entire calibration period obtained using topographic index values for single and multiple direction algorithms are shown in Table 5.1. Yearly values of Nash-Sutcliffe efficiency using multiple direction flow algorithm based topographic index are shown in Table 5.2. As can be seen from Table 5.2 the efficiency of model vary from year to year with a high value of 0.86 for year 1976 and lowest value for year 0.33 for year 1978.

TABLE – 5.1 Values of calibrated parameters and error statistics for calibration run.

Flow direction	m	$Ln(T_0)$	SR_{max}	SR_{init}	Chvel	EFF	SSE	SLE	SAE
Multiple (H =1.0)	0.005	2.0	0.0015	0.001	3600	0.584	9.27E-6	3.73E+2	0.058
Single (H = 5)	0.0048	2.0	0.0015	0.001	3600	0.583	9.29E-6	3.58E+2	0.057

TABLE – 5.2 Yearly values of Nash-Sutcliffe efficiency for calibration run.

Calibration year	Efficiency
1975	0.73
1976	0.862
1977	0.605
1978	0.336

The result shows that there is little variation in efficiency as well as value of the parameters in both single and multiple direction flow suggesting insignificant effect on computed results due to choice of computation method used for deriving topographic index. Figs. 5.4, 5.5, 5.6, and 5.7 show the simulated and observed hydrographs for calibration period for years 1975, 1976, 1977 and 1978 respectively. As can be seen from Fig. 5.4 the match of observed and simulated runoff is very good however the observed and simulated runoff shown in Fig. 5.7 does not give good matching.

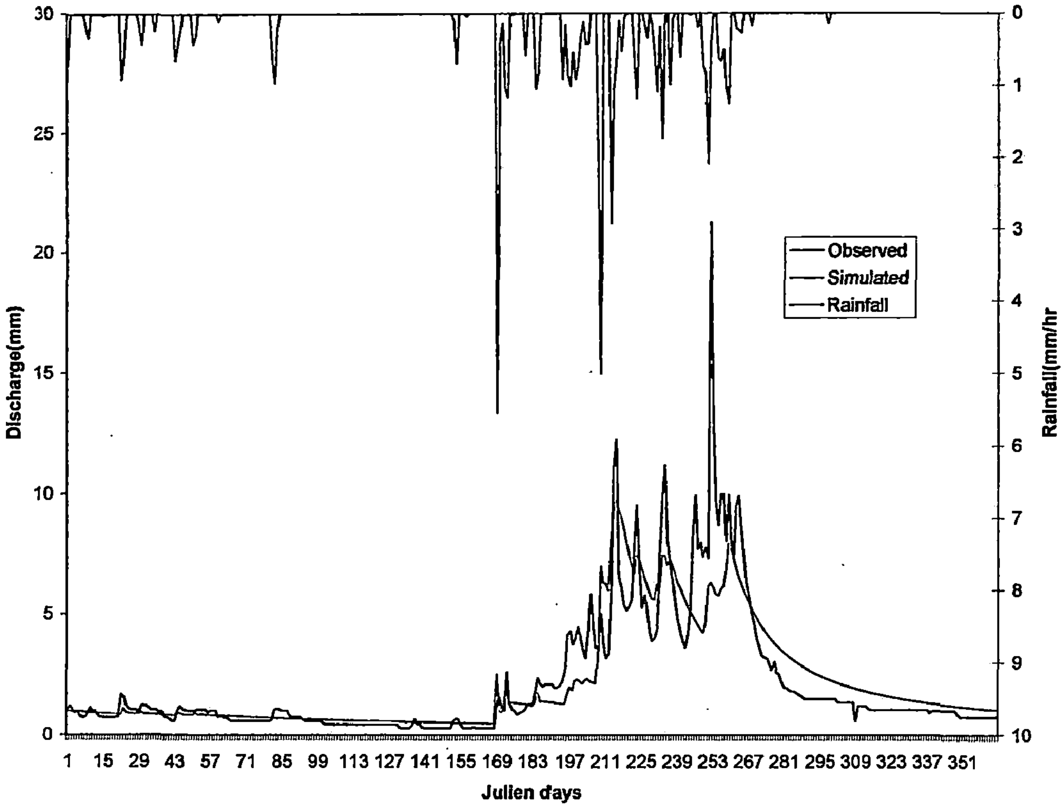

Fig.5.4 Observed and simulated hydrograph of chaukhutia watershed (calibration year 1975)

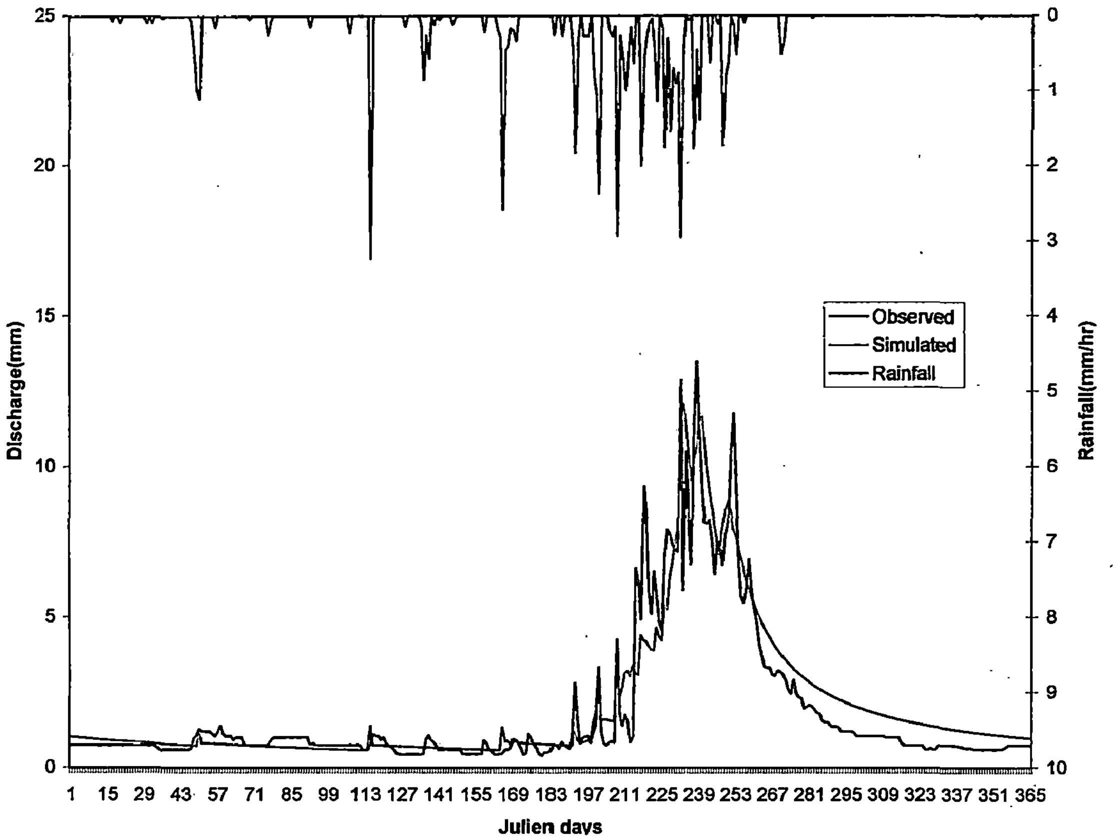

Fig.5.5 Observed and simulated hydrograph of Chaukhutia watershed (calibration year1976)

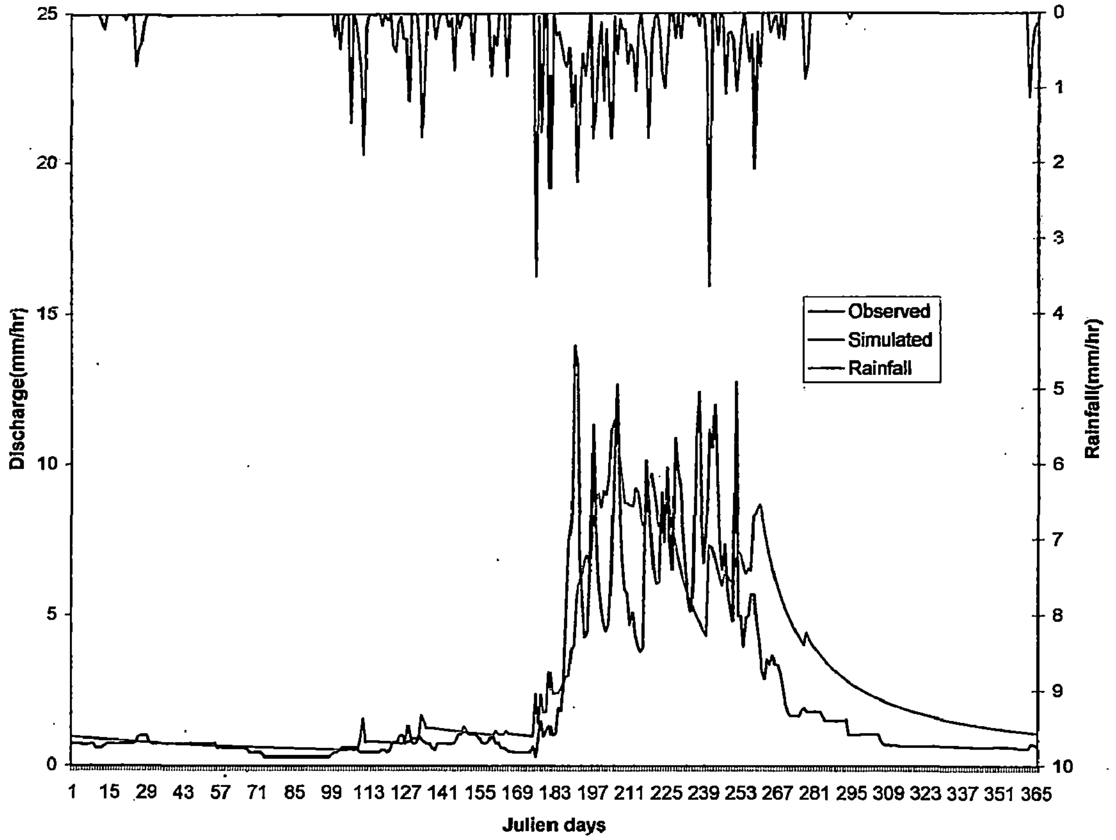

Fig.5.6 Observed and simulated hydrograph of Chaukhutia watershed (calibration year1977)

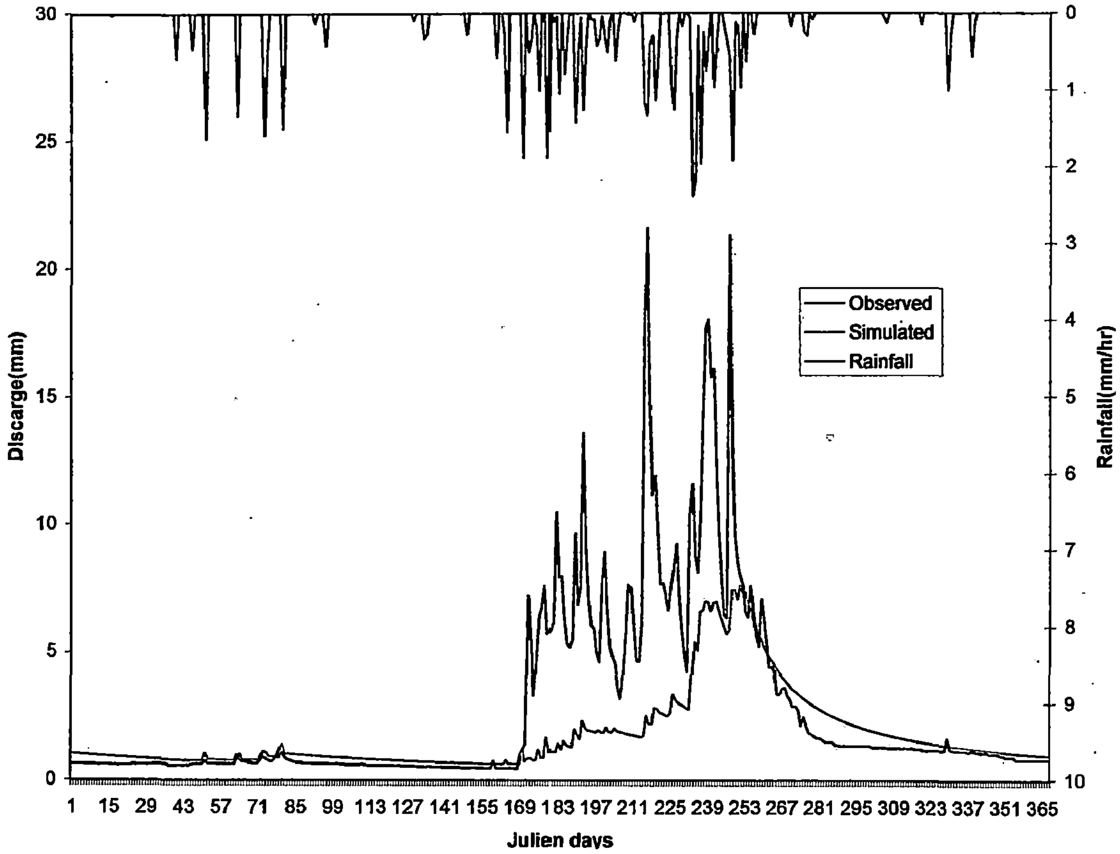

Fig.5.7 Observed and simulated hydrograph of Chaukhutia watershed (calibration year 1978)

5.4.2 MODEL VALIDATION

The model was run further with above parameter set for validation data series and the resulting efficiency was compared with the calibration efficiency. Validation was carried out for the period different from the one used for calibration. Same set of optimized parameters as found during calibration were used to run the model. The average values efficiency and other goodness of fit indices for validation period are given in table 5.3. Yearly values of Nash-Sutcliffe efficiency using multiple direction flow algorithm based topographic index are shown in Table 5.4 for validation period. As can be seen from Table 5.4 the efficiency of model vary from year to year with a high value of 0.695 for year 1980-81 and lowest value of 0.419 for year 1979-80. Figs. 5.8 and 5.9 show the simulated and observed hydrographs for validation period for years 1979-80 and 1980-81 respectively. As can be seen from Fig. 5.9 the match of observed and simulated runoff is very good however the observed and simulated runoff shown in Fig. 5.8 does not give good matching.

TABLE – 5.3 Values of error statistics for validation run.

Flow direction	EFF	SSE	SLE	SAE
Multiple (H=1.0)	0.649	4.27E-6	2.64E+2	0.028
Single (H=5)	0.665	4.07E-6	2.52E+2	0.027

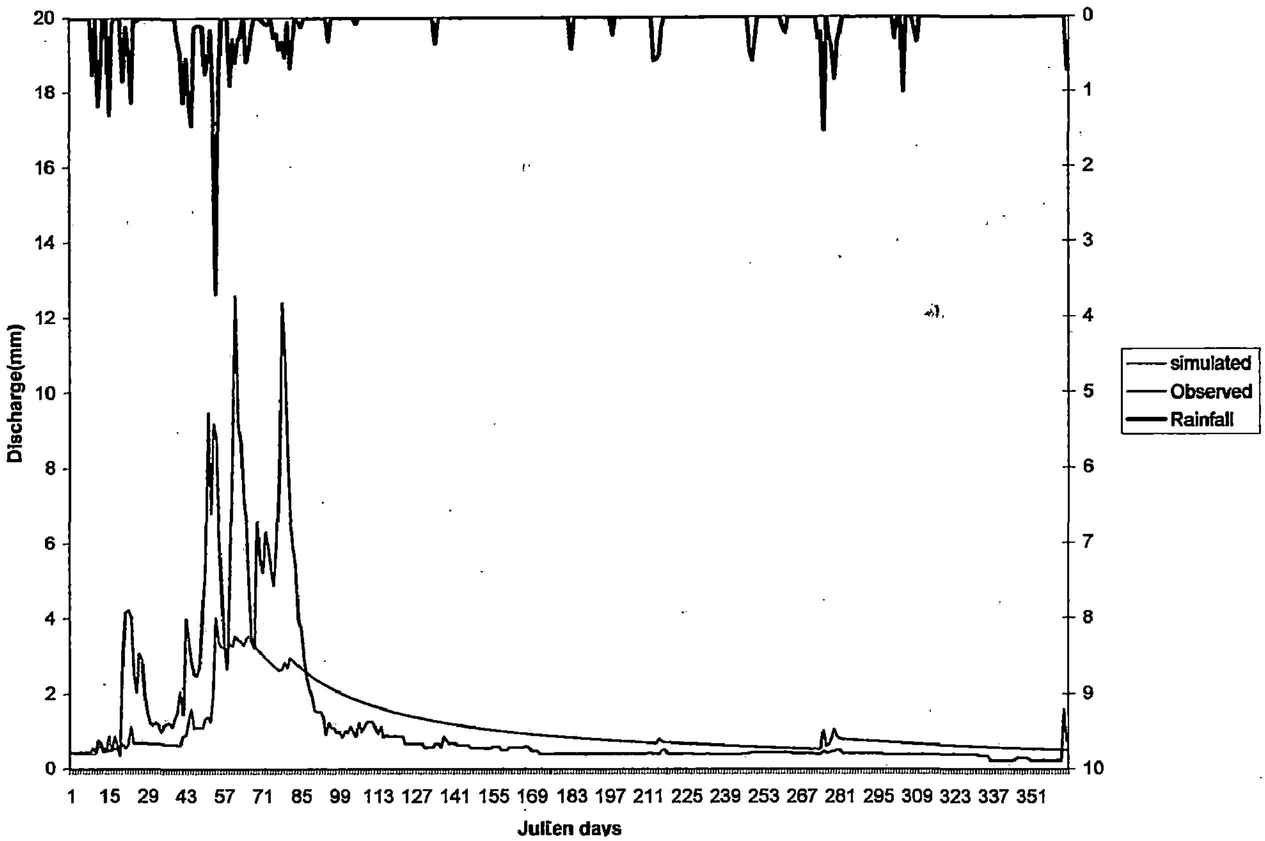

Fig.5.8Observed and simulated hydrograph of Chaukhutia watershed (Validation year 1979-80)

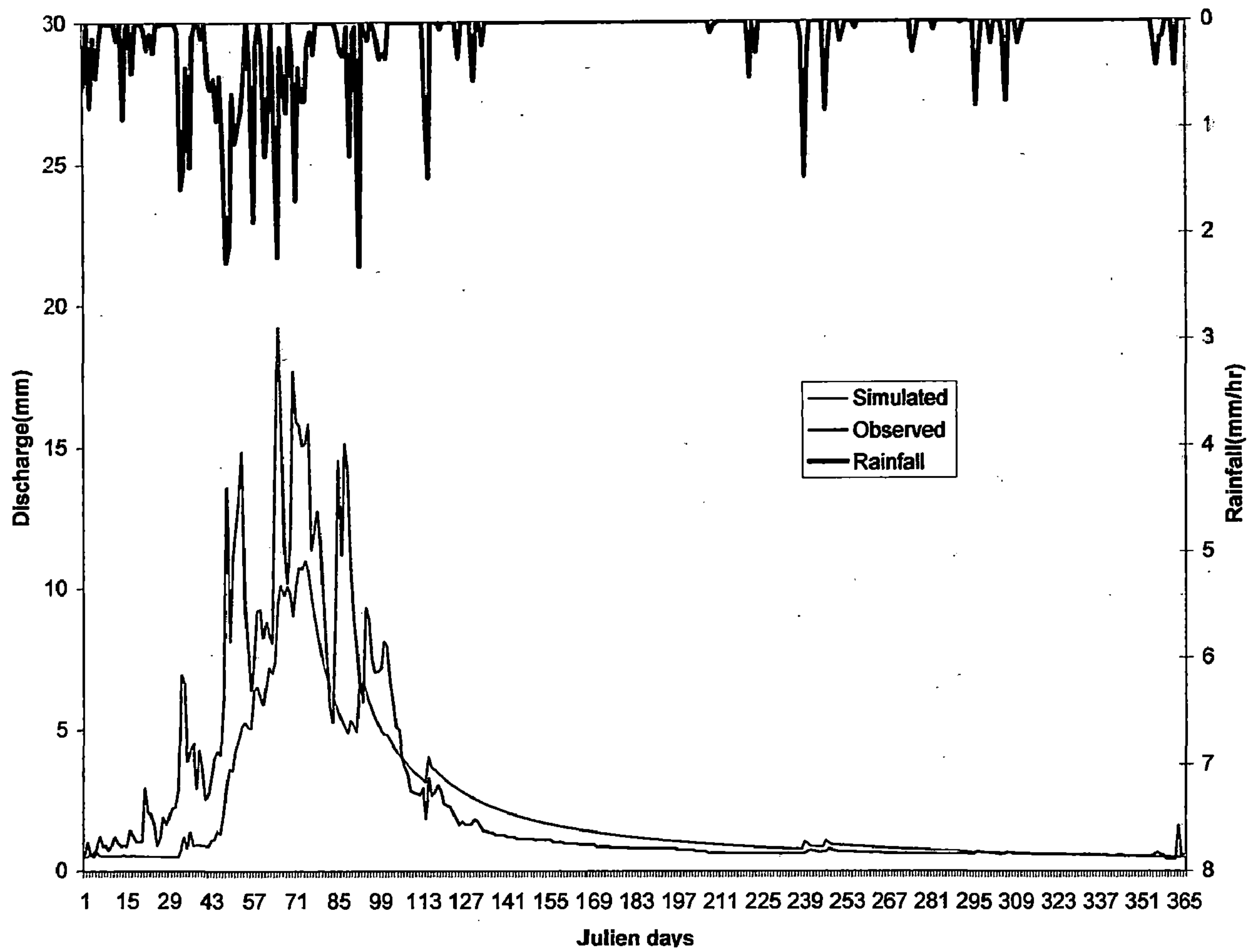

Fig.5.9 Observed and simulated hydrograph of Chaukhutia watershed

(Validation year 1980-81)

TABLE – 5.4 Yearly values of Nash-Sutcliffe efficiency for validation run

Validation year	Efficiency
1979-80	0.419
1980-81	0.695

5.5 DISCUSSION OF RESULTS

It is evident from the results of model's performance based on efficiency and other goodness of fit indices that there is a minor difference in efficiency for single and multiple direction flow. This may be due to marginal difference in values of topographic index distribution in single as well as multidirectional flows.

Topographic index indicates the propensity of landscape areas to become wet. The maximum Topographic Index class was 25.0 and minimum Topographic Index class was 3.5. High index values are associated with river channel and low with upland areas which do not contribute directly to runoff. From the Topographic index distribution Map of Chaukhutia watershed it can be seen that most of the watershed areas are in lower index class values. This is due to coverage of watershed with deep forest (about 50%) which contributes a little towards infiltration excess runoff. This may be one reason behind the low average Nash and Sutcliffe efficiency value of 0.58, for calibration and 0.649 for validation periods.

The model simulated the rise and fall of seasonal base flow through the season with superimposed overland and fast subsurface flow events. Simulations improved as the rainfall events became more frequent and contributing areas were more established through wetting up. The calibration period plot of observed and simulated hydrographs showed that the model reproduced the rise and fall of seasonal base flow but under-estimated some of the high runoff producing storm events. This phenomenon was also visible in validation period plot of observed and simulated hydrographs. This resulted in overall low efficiency of model. It is also observed during calibration run that influence of parameter like SR_{init} and ChVel on runoff estimation is negligible. It may be due to coverage of watershed by deep forest with the large moisture holding capacity. Deep forest also causes more evaporation. This causes less initial root zone deficit to occur at the start of next rainy season.

5.6 SENSITIVITY ANALYSIS

The Sensitivity Analysis was carried out to evaluate the sensitivity of the objective function due to change in the values of model parameters in predefined range. An initial run of the model was made with the current value of parameters and efficiency as objective function. Then value of each of the parameters was altered in specified lower and upper limits of the parameters and results for different combinations of parameters set were obtained. A result for plots of efficiency with change in values of individual parameters is shown graphically in

Fig. 5.10. As can be seen from Fig. 5.10, only three parameters namely 'm', $ln(T_o)$ and SR_{max} are affecting model efficiency and change in values for parameters SR_{ini} does not affect model efficiency

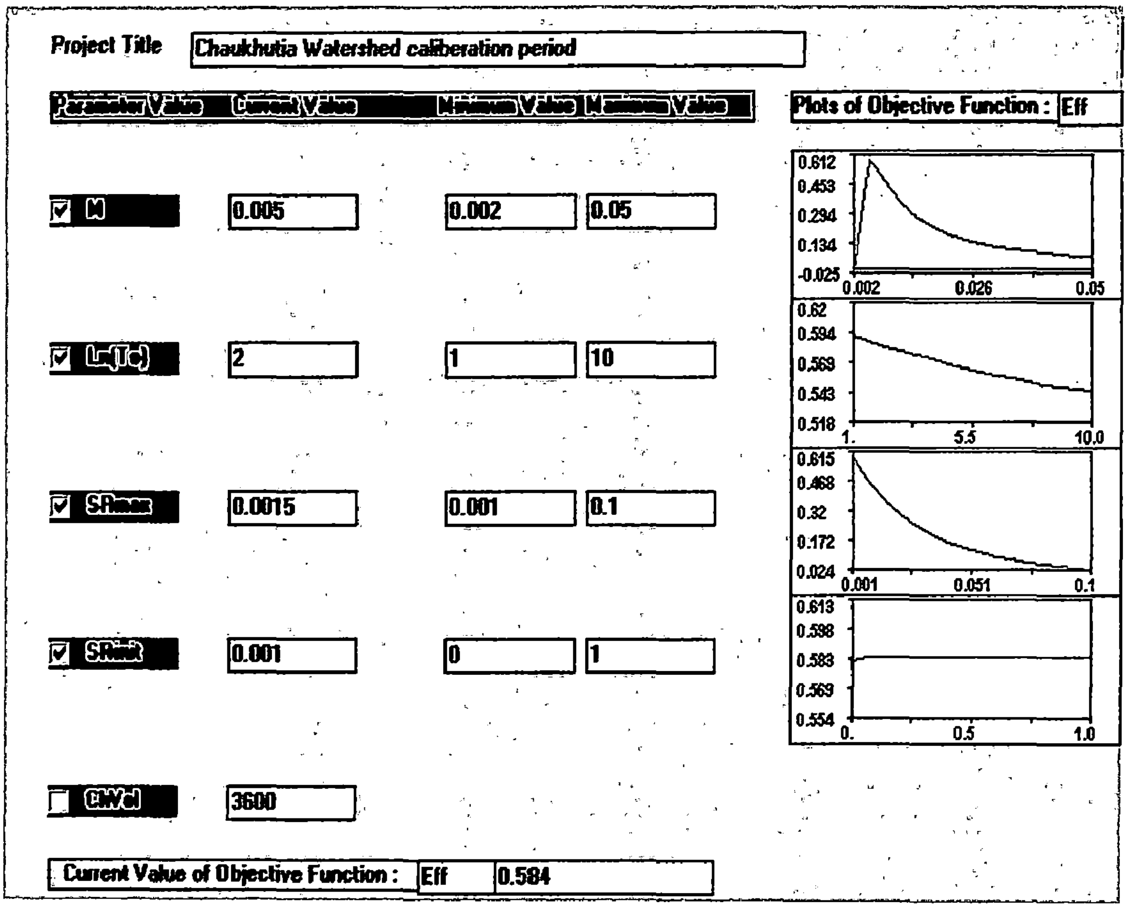

Fig.5.10 Sensitivity analysis of parameters of Chaukhutia watershed

5.7 MONTE CARLO ANALYSIS

To evaluate model performance further, Monte Carlo simulation runs were made using uniform random samples of the parameters chosen for inclusion in the analysis. Values of the other parameters were kept constant at their current values. The result was analysed by GLUE program

5.7.1 GLUE

The purpose of model calibration was to determine uncertainty associated with model prediction estimates derived from simulation for the entire season. The GLUE procedure requires a number of choices to be made (Beven and Binley,1992):

1. Sampling a range for each parameter;
2. Methodology for sampling the parameter space;
3. A likelihood measure of model performance;
4. A criterion for acceptance or rejection of models; and
5. A methodology for updating likelihood measures.

Random values of parameters m, $\ln(T_0)$, SR_{max}, SR_{init}, and Ch Vel were drawn from uniform distributions over specified ranges. 1000 sets of five randomly generated parameters were supplied to TOPMODEL. The likelihood measure to evaluate model performance was the modeling efficiency of Nash and Sutcliffe(1970):

$$L(\Theta_i \mid \underline{Y}) = [1 - \sigma_i^2/\sigma^2_{obs}]$$

Where $L(\Theta_i|\underline{Y})$ is the likelihood measure for the 'i'th model conditioned on the observations, σ^2_{obs} is the observed variance for the period under consideration, and σ_i^2 is the associated error variance for the 'I'th model. The 1000 parameter sets were selected for calibration period. The criterion for behavioural parameter sets was selected as E> 0.5; all others rejected.

From the result of Monte Carlo Analysis run, scatter plots of maximum likelihood versus different parameters were obtained. Dotty plots of 'E' versus parameters

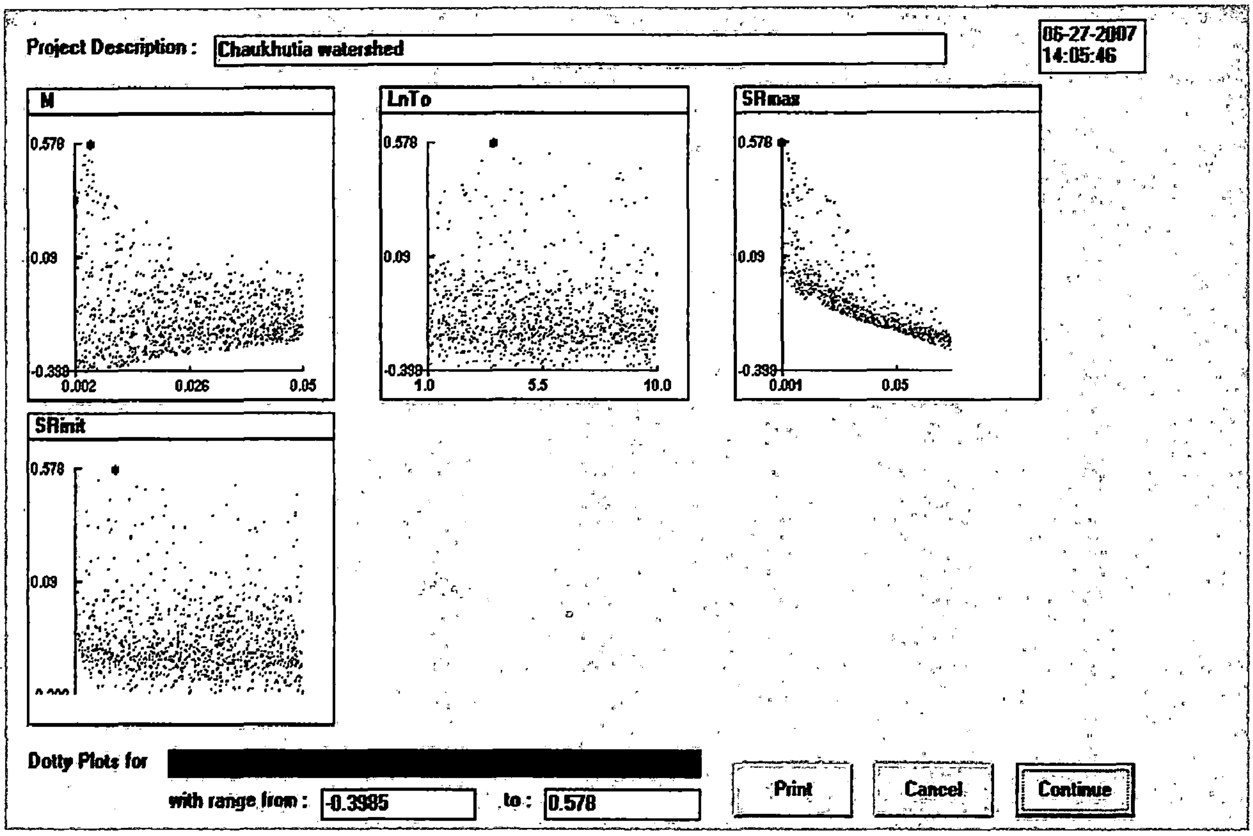

Fig. 5.11 Dotty plots of parameters of Chaukhutia watershed for Efficiency

(Fig, 5.11) were used to assess the sensitivity of parameters to model performance. All the parameters have showed good or bad simulations over wide ranges of parameter space. It can be concluded from plots that 'm' and ' SR_{max}' parameters are sensitive to simulation due to clustering of dots in a certain range of parameter space. Based on Monte Carlo analysis list of top 20 ranked parameter sets are shown in Table 5.5. Among these twenty sets, only four parameter sets have efficiency E > 0.5. This indicates that model simulated the daily flows of Chaukhutia watershed little less than satisfactorily.

TABLE 5.5 List of top ranked parameter sets as per Monte Carlo simulation

Rank	m	$Ln(T_0)$	SR_{max}	SR_{init}	Efficiency
1	0.005	3.626	0.001	0.179	0.578
2	0.004	5.823	0.003	0.102	0.533
3	0.005	4.409	0.004	0.701	0.509
4	0.006	3.12	0.004	0.269	0.504
5	0.004	4.652	0.007	0.312	0.493
6	0.004	7.382	0.006	0.386	0.491
7	0.005	9.329	0.005	0.974	0.473
8	0.006	3.034	0.006	0.236	0.449
9	0.005	0.562	0.007	0.151	0.447
10	0.003	8.481	0.012	0.664	0.426
11	0.006	8.649	0.005	0.399	0.419
12	0.005	2.415	0.011	0.051	0.398
13	0.006	6.436	0.008	0.966	0.391
14	0.007	4.281	0.006	0.963	0.379
15	0.005	2.915	0.014	0.604	0.378
16	0.002	2.448	0.013	0.394	0.377
17	0.003	1.714	0.001	0.342	0.373
18	0.008	2.564	0.006	0.715	0.368
19	0.005	4.712	0.013	0.146	0.368
20	0.009	2.496	0.003	0.177	0.36

CHAPTER – 6

SUMMARY AND CONCLUSIONS

The present work aims at to evaluate the TOPMODEL applicability to the forest and sub- Himalayan watershed. Such an evaluation does not appear to have been reported in literature. TOPMODEL, a distributed, topographically based hydrological model was applied to simulate continuously the runoff hydrograph of Chaukhutia watershed of Ramganga catchment. It is a variable contributing area conceptual model in which topography controls the soil water storage and runoff generation. 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 consideration of only a few parameters.

Calibration and validation of the TOPMODEL was carried out on Chaukhutia watershed. Raster DEM input for the model is generated through Arc GIS after digitization contour map from Survey of India toposheets. Available data was split into two groups, the first set (1975 – 78) was used for calibration of the model and the other set (1979 – 81) was used to validate model. The model efficiency was 0.58 in calibration and 0.649 in validation period. The simulations provided an insight into the response of the catchment at different periods of the season. TOPMODEL performed only reasonably well as a continuous hydrograph simulator in the Chaukhutia watershed. The model simulates well the base flow events but most of the peaks were under simulated. Although top ranked parameter sets achieved modeling efficiency of E = 0.57, simulation results are less than encouraging. This may be due to topography of watershed area which has a moderate to steep sloping surface covered with deep forest whereas TOPMODEL is suitable for moderate topography only. Also deep forest contributes less to saturation excess runoff.

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