HYDROLOGICAL STUDIES OF DISTURBED MOUNTAINOUS WATERSHEDS

A THESIS

submitted in fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

HYDROLOGY

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JUNE, 1995

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**HYDROLOGICAL STUDIES OF DISTURBED MOUNTAINOUS WATERSHEDS**" in fulfilment of the requirement for the award of the Degree of **Doctor of Philosophy**, submitted in the Department of Hydrology of the university is an authentic record of my own work carried out during a period from January 1988 to June, 1995 under the supervision of **Dr. B.S. Mathur** and **Dr. M.S. Rama Mohan Rao**.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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28/5/96 28/5/96 28.5.96

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ACKNOWLEDGEMENTS

I feel privileged to express my deep sense of gratitude and sincere regards to Dr. B.S. Mathur, Professor, Department of Hydrology, University of Roorkee, Roorkee, for his keen interest, excellent guidance, invaluable and timely suggestions, and ceaseless encouragement throughout the course of the present study.

I express my gratitude and indebtedness and thankfully acknowledge the guidance, suggestions and constant encouragement that I received from Dr.M.S. Rama Mohan Rao, Dr.V.V. Dhruva Narayana, Ex- Directors and Dr.J.S. Samra, present Director of the Central Soil and Water Conservation, Research and Training Institute, Dehradun, during the present study.

I wish to express sincere thanks to Dr.Ranvir Singh, Professor and Head, Dr.D.K. Srivastava, Dr.Deepak Kashyap, Professors, Dr.N.K. Goel, and Dr.Himanshu Joshi, Readers, Department of Hydrology, University of Roorkee, Roorkee, for their encouragement and co-operation throughout the course of the study.

I express my gratitude to Dr.W.D. Striffler, Emeritus Professor, and Dr.Freeman M. Smith, Professor, Department of Earth Resources, College of Natural Resources, Colorado State University, Fort Collins, Colorado, U.S.A. for their valuable suggestions and encouragement.

I am thankful to the authorities of CSWCRTI, Dehradun (India) for providing me the necessary data for my research work and study leave. Without their co-operation this work could never be taken up.

I pay a respectful homage to the memory of my father who had a long cherished goal of making me a good researcher. I would be ever grateful to him for the support which he extended to me.

I would like to express my deep sense of indebtedness to my mother, sister-in-law and brother-in-law who inspired me to continue the course of research work. I am thankful to Mr. Vivek who helped me in the compilation of my thesis.

I am thankful to my wife Parvati for her help in typing the manuscript and managing the household affairs in my absence. I am also thankful to my children for bearing the agony of being parted for a long time.

I am grateful to Mr.G.P. Juyal, Sr. Scientist (Engg.), Mr.G. Sastri, Head of Division (H & E) and Mr.R.K. Arya, Technical Officer (Engg.) CSWCRTI, Dehradun for their timely help in my thesis.

I am also thankful to Dr.K.D. Singh, Head, Dr.S.N. Prasad, Ex-Officer-in-charge, other scientists and Mr.P.R. Raibole, Draftsman CSWCRTI, Research Centre Kota, for their help and encouragement during the course of the present study.

I am thankful to my colleagues Mr. R.S. Kurothe, Mr. G.P. Roy, Mr. M.L. Gaur, Mr S.K. Tyagi, Dr. M.R.N. Shahri, Dr. Md. Mubarak Hossain, Mr. Asadullah, Dr. Saleem Ahmed, Dr. A.K. Tiwari and other friends and relatives for their co-operation and encouragement during the course of this study.

I acknowledge the co-operation of Mr. D.P. Sharma in charge of computer lab.

Roorkee (Vidya Sagar Katiyar)

SYNOPSIS

In this research work, some currently used hydrologic models have been studied with the objective to modify them so that they can account for the hydrological processes of disturbed, mountaineous, small watersheds of the himalayan region (Chapter-I). The literature survey conducted during the study (Chapter-II) revealed that in case of mountainous watersheds there are two extreme ends of runoff generation mechanisms viz, the Hortonian overland flow and the subsurface stormflow. On the other hand, some researchers (Freeze, 1980; Beven, 1986, 1991) believe that the channel flows need be simulated through saturation excess runoff, interflow and groundwater flow mechanisms.

Three hydrologic models viz. the time-area, variable source area and physiographically distributed models have been used to study the hydrologic behaviour of disturbed, mountainous, small watersheds. The description of two such watersheds is given in chapter-III alongwith availability of data. The availability of meteorologic (i.e. 25 storm events of Jhandoo-Nala and 5 storm events of Bhaintan watershed) and hydrologic data have been discussed.

The descriptions of the proposed (above mentioned) models are given in Chapter-IV. It was found that the Time-Area model did not produce satisfactory results if the time of concentration was computed using empirical relationships (i.e. Kirpich formula etc.). However, it produced better results when the time of concentration is computed using the concepts of S-hydrograph (chapter-V).

The proposed Variable Source Area model gave quite satisfactory results. It simulated runoff through four components namely the direct flow, the saturated area flow, the interflow and the groundwater flow. Three nonlinear reservoirs have been used for the conceptual representation of the runoff mechanism for each of these components of flow. The relationships of variable source area `extent' with API, rainfall intensities, interflow, baseflow and saturated flows which were arrived at in this study may be of practical use. The relationship of runoff factor with baseflow may help in determining the runoff volume.

In the proposed Distributed Physiographic model (Chapter-V) the watershed is divided into tributary and main channel subwatersheds. The runoff process for each of these subwatersheds is conceptually taken care of with the help of two nonlinear reservoirs. The upper nonlinear reservoir provides an output which is termed as `surface supply ' (S_s). The lower nonlinear reservoir receives its input through infiltration. Its output is termed as groundwater supply (S_g). These two components (viz. the S_s and S_g) form the total supply (St) to the channel in the form of lateral inflow. The kinematic wave theory is applied for routing of flows through the channel reaches. An implicit finite difference scheme is used for routing flows to the outlet. At confluences, the concept of continuity is used for flow synthesis.

The model has produced satisfactory results (Chapter-V). It has the capability of taking into account the changes in hydrologic behaviour due to soil conservation treatments in different parts of the watershed under consideration.

For the proposed Varible Source Area model, as well as for the Distributed Physiographic model detailed sensitivity analyses have also been carried out. In the last Chapter (Chapter-VI), summary of the work is presented and the results have been discussed.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description
A	Area of watershed, subwatershed, reservoir
Ac	The channel cross-sectional area of flow
AEVAP1	Evaporation from the canopy
AEVAP2	Evaporation from the soil
ARMS(N)	Area of N^{th} main channel subwatershed
ARTR(N)	Area of N^{th} tributary subwatershed
ARWS	Total area of the watershed
CEPMAX	maximum interception capacity
C_g	Groundwater supply coefficient
CMAX	actual interception capacity
C_r	Channel conveyance coefficient
CSMAX	Sum of maximum soil zone and groundwater storages
C_s	Surface supply coefficient
dhg	Change in groundwater storage reservoir
dhs	Change in surface storage reservoir
dt	Change in time (time step)
EFF	Model efficiency
EVAP	Potential evapotranspiration
EVPT	Actual evapotranspiration
f	Infiltration rate, capacity
f( )	Function of
F	Sum of difference between observed and computed runoff rates
fc	Final infiltration rate
FCAN	Canopy development function

FFS	Drainage to groundwater
FFU	Drainage from upper soil zone
fo	Initial infiltration rate
FS	Groundwater recession coefficient
FU	Soil water conductivity coefficient
g	Acceleration due to gravity
h_g	Average depth in groundwater storage
h_s	Average depth in surface storage
i	Variable grid value along distance line
I	Rainfall intensity
Ii	Rainfall intensity during i^{th} time interval
$I_{(j)}$	Intensity of rainfall excess during the j^{th} time step
INCEP	Actual interception
INFL	Infiltration into the ground
j	Variable grid value along time line
k	Iteration number
K1	Fraction of soil zone drainage becoming interflow
K2	Fraction of groundwater drainage becoming baseflow
K3	Fraction of upper zone storage contribution to expansion of source area
K4	Fraction of ground zone storage contributing to expansion of source area
Kc	Channel conveyance
KS	Groundwater recession exponent
KU	Soil water conductivity exponent
KW	Kinematic wave
L	Watershed length measured along the channel
m	Channel conveyance exponent, metre

min	Minute
n	Total number of time steps, observations
n_{ar}	Number of time areas in a catchment
n_m	Manning's roughness coefficient for channel
NTR	Number of tributaries in a watershed
p	Wetted perimeter of channel
PA	Extent of saturated area as fraction of watershed area excluding PCAR
PB	Fraction of watershed area contributing surface runoff in the form of RUNO1 and RUNO2
PCAR	Fraction of area always contributing to direct runoff
PPT	precipitation
q	The lateral inflow per unit length of channel
Q	Channel discharge rate
$\bar{Q}$	Mean discharge
QBF	Discharge rate at the outlet of the watershed at the onset of storm
Qmax	Maximum discharge ordinate
QMS(N, 1)	Discharge rate at the N^{th} confluence (i.e. at the outlet of N^{th} main channel subwatershed) at the first time step
Qo	Observed discharge rate
Qp	Observed peak discharge rate
Qs	Simulated discharge rate
QTR(N, 1)	Discharge rate at the outlet of N^{th} tributary subwatershed at the first time step
QTS(N, 1)	Discharge rate contributed by the nonlinear reservoirs (surface and subsurface) of the N^{th} main channel subwatershed at the first time step

R	Hydraulic radius of the channel
R^2	Coefficient of determination
RFALL1	Throughfall or precipitation minus interception
RUNO1	Source area (or saturated area) runoff
RUNO3	Interflow
S_Φ	Sorptivity
SAC	Source area exponent
SC	Source area coefficient
Sc	Bed slope of channel
Se	The weighted uniform or equivalent slope of the watershed
Sf	Friction slope (of overland or channel)
S_g	Volumetric groundwater supply rate per unit area
So	Bed slope of overland
S_s	Volumetric rate of surface supply per unit area
SSIN	Actual water volume in groundwater storage
t	Time instant
Tc	Time of concentration for the watershed
THETA	Weight factor for baseflow contributions
t_r	Time since commencement of rainfall
USIN	Actual water volume in upper soil zone
USZT	Maximum amount of water that can be stored in soil profile
x	Distance measured in the direction of flow
X	Baseflow/average rainfall intensity
X1	Total rainfall depth of event
X2	Antecedent precipitation index
X3	Baseflow at the beginning of storm event

X4	Average rainfall intensity
Y1	Extent of saturated area
Y2	Net saturated area
ti	Time from beginning of storm to the i^{th} time interval
Δt	Time step
Δx	Space step
α	Kinematic wave parameter
αs	Multiplication factor to step size when failure is encountered in optimisation process
β	Inverse of channel conveyance exponent
βs	Multiplication factor to step size when success is encountered in optimisation process
γg	Exponent for groundwater storage
γs	Exponent of surface supply rate
∂	Partial derivative operator
λ	Non-dimensionalised parameter defined by Beven et al., 1984
λs	Step size in optimisation process
ϕ	Continuing loss rate
θ	Soil moisture

ABBREVIATIONS

API	Antecedent Precipitation Index
CSWCRTI	Central Soil and Water Conservation Research and Training Institute
TAC	Time-Area-Concentration
VSAS	Variable Source Area Simulator
VRIM	Variable Rainfall Infiltration Model

LIST OF PHOTOGRAPHS

CHAPTER I

INTRODUCTION

1.1 PRELIMINARY REMARKS

Due to population explosion in most parts of the tropics, water now is a scarce natural resource and needs careful planning for its conservation and use. Though useful to the society, many a times it poses problems by way of floods, droughts, erosion, sedimentation etc.

The relationship between rainfall and runoff has been one of the central themes of hydrological research for many years. With the advent of digital computers in the fifties and sixties, a tremendous upsurge in hydrological modelling took place. However, hydrological modelling, involving the hydrologic processes, namely, rainfall, infiltration, surface runoff and baseflow continues to be a difficult task. Although significant research work has been carried out for large catchments resulting in the development of useful models, similar research efforts involving small watersheds of the tropics are still lacking. In India the small mountainous watersheds have received even less attention and only a few hydrological studies involving small hilly watersheds have been reported, that too quite recently (Sastry and Dhruva Narayana 1986; Hossain, 1989; Putty and Rama Prasad, 1992; Shahri, 1993). The detailed review of literature reported in the next Chapter reveals that very little information has so far been generated on the complex hydrological behaviour of the small watersheds of the Himalayan region.

Recently International Centre for Integrated Mountain Development (ICIMOD) has been established at Kathmandu, Nepal, which has bought out some technical publications. (Carson, 1985;

Ives, 1986; Dunsmore, 1988; Bandyopadhyay, 1989; Aitken et al., 1991; Alford, 1992). However, very little research work could be traced out in the field of hydrologic modelling of steep sloped small mountainous watersheds of the Himalayas. It may be worth noting that some hydrological research work has been done in the western parts of the Himalayas towards the far end towards the Hindukush side for some of the rivers of Pakistan but these studies have perhaps been carried out for the real time flow analysis as well as for forecasting of river flows of some major river basins. No research study could be traced out for small watersheds in those areas too.

1.2 IMPORTANCE OF HYDROLOGICAL STUDIES OF MOUNTAINOUS WATERSHEDS

Much emphasis is currently being placed on the development of the water resources of the country to meet the growing demands for domestic and agricultural sectors as well as for hydroelectric power generation. In very steep sloped Himalayan watersheds, slopes may go to the extent of beyond 70 degrees. Even on one face of the mountain a number of small watersheds may be delineated. Their studies become important as the flash floods may wash away the roads and disturb the communication lines. The overall runoff studies become important for storage as well as diversion of water which serve as a source for the contour canals being planned in the hills to meet the demands of irrigation and domestic water supplies. These days, the studies of small mountainous watersheds have also become important with the planning and development of microhydel schemes in the hilly regions of the Himalayas.

The problem of rainfall runoff studies gets further complicated because of indiscriminate exploitation of high mountainous watershed resources. This includes deforestation as well as mining for rocks and minerals. The developmental activities like road construction, implementation of irrigation projects, construction of buildings for rural and urban dwellings and tourist resorts have been additional sources of disturbance. Whatever be the reasons, hydrological regimes are badly affected, which disturb the hydro-environment of ecological regimes of uplands. In order to restore the same, the soil conservation works of various types and nature are needed to be taken up on small watersheds. The Central Soil and Water Conservation Research and Training Institute Dehradun (India) took up two pilot projects for the restoration of Himalayan ecology of these two disturbed mountainous watersheds. The details of these watersheds are given in Chapter-III.

1.3 HYDROLOGICAL PROBLEMS OF SMALL MOUNTAINOUS WATERSHEDS

Access is not the only difficulty with the small mountainous watersheds .The very nature of the mountain environment further complicates matters seriously.These include the high variability of precipitation, temperature, infiltration due to changes in topography, soils, geology and vegetation.

In the U.P. Himalaya soils of cultivated and forest areas are generally gravelly (open structured). There are holes made by rats, rodents and decayed roots which cause pipe flows. High content of humus in open structured forest soils result in high infiltration rates. Therefore, the subsurface stormflows form the dominant part of runoff. The hydrological data recorded at Bhaintan and Jhandoo-Nala watersheds (Appendix-D1) reveals that the surface runoff (1.4 to 8.7 per cent of rainfall) is very little as compared to subsurface runoff (27 to 58.9 per cent of rainfall).

Rainfall does vary temporally and spatially in the mountainous areas. However due to orographic effect the amount of rainfall has been found to vary from 70 to 160 percent of the mean rainfall value in a small watershed of 272 ha (Bhaintan watershed) (Katiyar, 1982).

High altitude upland watersheds are impervious and devoid of thick vegetation where major part of the rainfall is converted into runoff. In these areas surface runoff (i.e. overland flow) form the dominant part of runoff. Mountainous streams are flashy and turbulent which pose difficulties in hydrological measurements. Velocity of flow beyond 15m/sec are not uncommon.

Accumulation of water in unsaturated zone nearly cause perched water table like situations and increased bank storages which release water over a longer period of time i.e. the recession limbs are found to be many times longer than the rising limbs of hydrographs (Appendix-D2). For the mountainous watersheds in different parts of the world, hillslope hydrological models of complex nature have been developed (Freeze, 1971; Hewlett and Troendle, 1975; Beven and Kirkby, 1979; Beven et al., 1988; Calver and Wood, 1989; Ormsbee and Khan, 1989; etc.). However, the aim of the present study is to propose models which may be simple and economic in applications and have the capabilities to take into account the effects of soil conservation treatments which are carried out to restore the ecological regimes of disturbed mountainous watersheds of the Himalayas.

Keeping the above in view the following objectives were set for the present study.

1.4 OBJECTIVES

The main objectives defined for the present dissertation are given as under.

i) To study different runoff generation mechanisms (i.e. different approaches in hydrologic modelling).

ii) To suitably modify hydrologic models to suit the disturbed mountainous small watersheds of Himalayan region.

iii) To calibrate models onto two small mountainous test watersheds.

iv) To test the suitability of proposed models by applying the same onto the test watersheds.

v) To test the sensitivity of model parameters, and

vi) To draw suitable conclusions from the experience of application of the models onto these two small, disturbed, mountainous watersheds of U.P. Himalaya.

1.5 THE APPROACH

The mechanics of the runoff process has been studied through three hydrologic modelling approaches which use different runoff generation mechanisms, viz., the Hortonian Overland Flow Concept (i.e. for a Time-Area based model), the Variable Source Area Concept (i.e. for a Variable Source Area model) and the Physical Process based modelling approach (i.e. for a Distributed Physiographic model). These three approaches (models) have been used to study the hydrologic behaviour of disturbed, mountainous, small watersheds.

1.6 PLANNING OF THE DISSERTATION REPORT

The chapter wise planning of the present dissertation is as under.

The next Chapter is titled as "Review of Literature". Here terminologies and concepts pertaining to the approaches used in the past have been discussed. A description of the approaches/models developed by different researchers is presented in chronological order.

In **CHAPTER-III** a brief description is presented for the two natural, disturbed, small mountainous watersheds on which different models were applied. The availability of data for the two natural watersheds has also been discussed.

CHAPTER-IV is devoted towards the description and development of the hydrologic models. Mathematical formulations based on the Time-area concept, Variable source area and Kinematic wave theory are explained. Solution technique of KW equations has also been discussed. The proposed distributed physiographic model configuration is also described in this chapter.

CHAPTER-V deals with "Application of Models". The proposed models have been applied onto the two mountainous test watersheds (viz. Bhaintan and Jhandoo-Nala). The capabilities of the proposed models by way of predicting runoff for various storm events have also been shown.

Lastly, the **CHAPTER-VI** has been devoted towards "Discussion of Results and Conclusions". In this chapter the calibration and simulation results using the three proposed models have been discussed. Based on the experience of the computations carried out, suitable conclusions have been drawn.

CHAPTER-II

REVIEW OF LITERATURE

2.1 INTRODUCTION

In this chapter, progress in studies pertaining to runoff generation mechanisms and some of the concepts, terminologies basic equations related to the study will be discussed. A few currently used watershed models for mountainous areas alongwith their important features and applications have also been described.

Modelling of the rainfall-runoff process is of scientific and practical importance. Many of the currently used mathematical models of hydrologic systems were developed during the fifties and later. Much of the efforts since then have been focused on refining these models rather than on developing new ones. Some of the concepts used in hydrological modelling are given in following sections.

2.1.1 Time-Area Methods

The rainfall-runoff relationship has been one of the main themes of hydrological research for many years. Mulvaney (1851) developed the `rational method' which represented the first formal relationship for predicting design (peak) discharge from rainfall. This method was based on the concept of `time of concentration'. In the early part of twentieth century, efforts were made to modify the rational method to account for the nonuniform distribution (i.e. in space and time) of rainfall and watershed characteristics. The rational method was further modified by introducing the concept of isochrones (i.e. lines of equal travel time). This provided the base for the concept of the time area diagram and its mathematical derivative i.e. the time area concentration curve. The original rational method, was meant to predict peak discharges but its application through time-area method turned out to be the first model capable of predicting time-dependent responses of a watershed due to input rainfall.

2.1.2 Unit Hydrograph Theory

Sherman (1932) proposed the concept of `unit graph' based on the principle of superposition. A notable era, in rainfall runoff modelling, began with the introduction of unit hydrograph theory. For predicting the runoff from an ungauged watershed, the response parameters were related to watershed characteristics which led to the concept of the synthetic unit hydrograph.

With the advent of computers during 1960's the hydrologists started using systems engineering for the study of the unit hydrograph. The impulse response function in a linear time invariant system was considered as the basis for designing an instantaneous unit hydrograph (IUH). Subsequently the IUH can be explained in terms of a series of linear or nonlinear reservoirs and linear channels. Their combinations led to the development of conceptual models. The best known conceptual model is the cascade of linear reservoirs (Nash, 1958).

2.1.3 Explicit Soil Moisture Accounting Models

The Stanford Watershed Model (SWM1) was introduced in 1960. This, Explicit Soil Moisture Accounting (ESMA) model, comprises of an infiltration function, a unit hydrograph and recession function to yield the mean daily flow using daily rainfall. Flemming (1975) describes the details of 19 ESMA models of varying degree of complexity. The SWM1 underwent further modification (Crawford and Linsley, 1962, 1966) to account for total catchment response rather than storm runoff. The modified model was named as SWM4.

2.1.4 The Optimisation Approach

Model calibration in 1960's was somewhat a subjective process carried out by determining the values of parameters through the results of successive model runs. This led to the need of paying special attention for increasing the accuracy in matching the computed discharges with observed ones. Dawdy and O'Donnel (1965) proposed a criterion based on minimizing the following objective function through the successive automatic adjustment of the model parameters.

$$F^2 = \sum_{i=1}^{n} (Q_{oi} - Q_{si})^2 \quad \ldots \quad (2.1)$$

where,

F^2 = index of disagreement or objective function,

Q_o = observed streamflow rate,

Q_s = simulated streamflow rate and

n = number of observations.

Dawdy and O'Donnel used the Rosenbrock's (1960) method of optimisation that does not require the evaluation of derivatives of F^2. The nature of response surface was found to present problems, which resulted in premature convergence away from the optimum. It was also found that the error function F^2 was insensitive to changes in some parameter values. They suggested that parameter sensitivity might be assessed by changing each parameter value in turn while holding the remaining parameters constant at the end of optimisation run. Ibbitt (1970) carried out extensive study of the performance of optimisation techniques using Dawdy and O'Donnell and SWM models. He observed that a modified version of the Rosenbrock technique performed the best for the models which were considered. However, several problems were encountered, notably the undesirable effects of threshold parameter values on the response surface and the existence of multiple optima in the parameter space. Local search techniques such as the Rosenbrock method are not designed to find a global optimum. In this work, a split sample testing procedure was suggested in which a part of the available flow record not used in model calibration (i.e. model fitting) was used to assess the prediction efficiency of the model.

Nash and Sutcliffe (1970) defined model efficiency as given under :

$$EFF = \frac{\sum_{i=1}^{n} (\bar{Q}_o - Q_{oi})^2 - \sum_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n} (\bar{Q}_o - Q_{oi})^2} \quad .... \quad (2.2)$$

where,

EFF = Model efficiency or coefficient of determination

Q_o = observed discharge rate

$\bar{Q}_o$ = mean observed discharge rate

Q_s = simulated discharge rate.

The other numerical criteria often used and also utilised in the present study are the following :

$$F = \sum_{i=1}^{n} (Q_{oi} - Q_{si}) \quad .... \quad (2.3)$$

which is a measure of the accumulated deviation between recorded and simulated values.

$$R^2 = \frac{\sum_{i=1}^{n} (\overline{Q}_o - Q_{oi})^2 - \sum_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n} (\overline{Q}_o - Q_{oi})^2} \quad .... \quad (2.4)$$

where R is the linear correlation coefficient between the simulated and observed discharges. Other variables have already been defined earlier.

Some research hydrologists suggested the use of subjective judgement and operator experience within a trial and error framework for parameter estimation while the others suggested the automatic optimisation approach. With the former approach (i.e. subjective method), parameter estimation became a subjective art of which the original model developer was probably the best exponent, while the automatic optimisation approach remained somewhat of an intractable approach for complex models of the SWM type (O'Connel, 1991).

2.1.5 Kinematic Wave Models

Lighthill and Whitham (1955) laid the foundation for the kinematic wave model through their theoretical research work where the empirical storage-discharge relationship was represented by a simplified dynamic equation in which friction slope Sf is assumed to be equal to the bed slope S_o. Henderson and Wooding (1964) and Wooding (1965) formulated a kinematic wave model in which the watershed is represented as 'V-shaped' or 'open book' double plane surface in which the valley forms the channel. They obtained analytical and numerical solutions for this combination of over-land-channel system. Liggett and Woolhiser (1967) compared numerical methods for the solution of the combined overland channel flow equations. A kinematic wave solution was obtained by Woolhiser (1969) for overland flow on conic sections i.e. an assumed geometrical shape of small watersheds. Kibler and Woolhiser (1970) studied the mathematical properties of a kinematic cascade. Smith and Woolhiser (1971) coupled the kinematic cascade model to a one dimensional vertical unsaturated subsurface flow model of infiltration by matching boundary conditions at the soil surface.

Research work on kinematic wave modelling was further carried out by other researchers, notably by Brakensiek (1967), Huggins and Monke (1968), Schaake (1970) and Singh (1976).

The kinematic wave theory is based on the assumption that velocity is directly proportional to flow depth, this means that, as rainfall intensity increases, the time of response of a watershed decreases. This phenomenon is contradictory to the unit hydrograph theory. The limitation of kinematic wave modelling is the use of a unique single-valued relationship between stage and discharge. The details of kinematic wave theory are given in section 2.6. Some aspects of watershed response to rainfall are discussed as under.

2.2 WATERSHED RUNOFF MODELLING

The phenomenon of watershed runoff is complex. The knowledge of physical principles and the mathematical formulations governing it, is limited. The watershed runoff is composed of three components which occur separately (or simultaneously) with varying degree of magnitudes. These are (1) surface runoff (including channel precipitation), (2) Subsurface runoff or interflow and (3) baseflow or groundwater runoff. Surface runoff and baseflow have been studied since long and is independently understood reasonably well (Woolhiser and Brakensiek, 1982 and Hall, 1982). Interflow is not well defined and least understood. Also least understood are the dynamic interactions prevailing between these components. Further, it remains yet to establish procedures to determine these components on ungauged watersheds (Singh, 1988). The factors controlling stormflow generation are climate, geology, topography, soil characteristics, vegetation and land use. The relative significance varies in space and time.

2.2.1 Runoff Generation Mechanisms

Horton's (1933) theory assumes that surface runoff or overland flow is produced where and when rainfall intensity exceeds the infiltration rate. However in many geographic regions surface runoff is rarely observed. In most humid regions, infiltration rates are high because vegetation protects soil from rain impact and dispersal and because of the supply of humus and the activity of micro fauna create an open soil structure. Under such conditions rainfall intensities do not exceed infiltration rates and Hortonian overland flow does not occur on large areas. Some concepts of runoff generation mechanisms are given below.

2.2.2 Variable Source Area Concept

In the past, an appreciable amount of field research has been carried out mainly on hill slopes. It has shown that Hortonian overland flow rarely occurs in such catchments. Therefore, some other physical mechanisms are required to explain the runoff generation, and it has led to the emergence of another sub-discipline i.e. "hillslope hydrology."

Hursh and Barter (1944) raised doubts on the validity of the infiltration-excess runoff production mechanism, as many watersheds do yield well defined hydrographs from storms whose rainfall intensity is less than the infiltration capacity of the soil cover complex.

Betson (1964) proposed "the partial area concept", which assumes that infiltration-excess runoff occurs from a relatively small part of the watershed area. Ragan (1968) reached the same conclusion to that of Betson's after analysing a series of storms.

Rawitz et al.(1970) observed that summer storms produced practically no overland runoff in a Pennsylvanian catchment, but the hydrographs possessed all the characteristics of surface runoff.

Ragan (1968) and Dunne (1970) suggested that overland flow is generated by rain falling onto variable source areas adjacent to stream channels. Dunne and Black (1970) observed that the overland flow occurs when soil becomes saturated at the surface from below by the rising water tables. The topographic and hydrological configurations of the hillslope, control the magnitude of variable source areas. This concept explains the dynamic interactions between the three stormflow components. As the storm progresses, the saturated area expands upslope, causing more and more of the catchment to contribute the overland flow (Fig. 2.1). Thus, the saturated areas keep growing during a storm and also keep shrinking during interstorm periods (Beven and Kirkby, 1979).

2.2.3 Subsurface Stormflow Concept

Subsurface storm flow (i.e. quick response interflow) can be distinguished from the groundwater flow as it enters the stream before reaching the groundwater zone (Whipkey, 1965). Over a wide range of antecedent moisture conditions which were tested, Corbett (1979) estimated that the subsurface stormflow provided 75 to 97 per cent of the total stormflow volume.

Hewlett and his co-workers (Hewlett and Hibbert, 1967; Hewlett and Nutter, 1970) put forward the concept of "subsurface stormflow". Whipkey (1965) measured lateral inflows from subsurface sources in the field. The main requirement for subsurface stormflow is shallow surface soil horizon of high permeability, such as generally found in the forested watersheds (O'Connel, 1991).

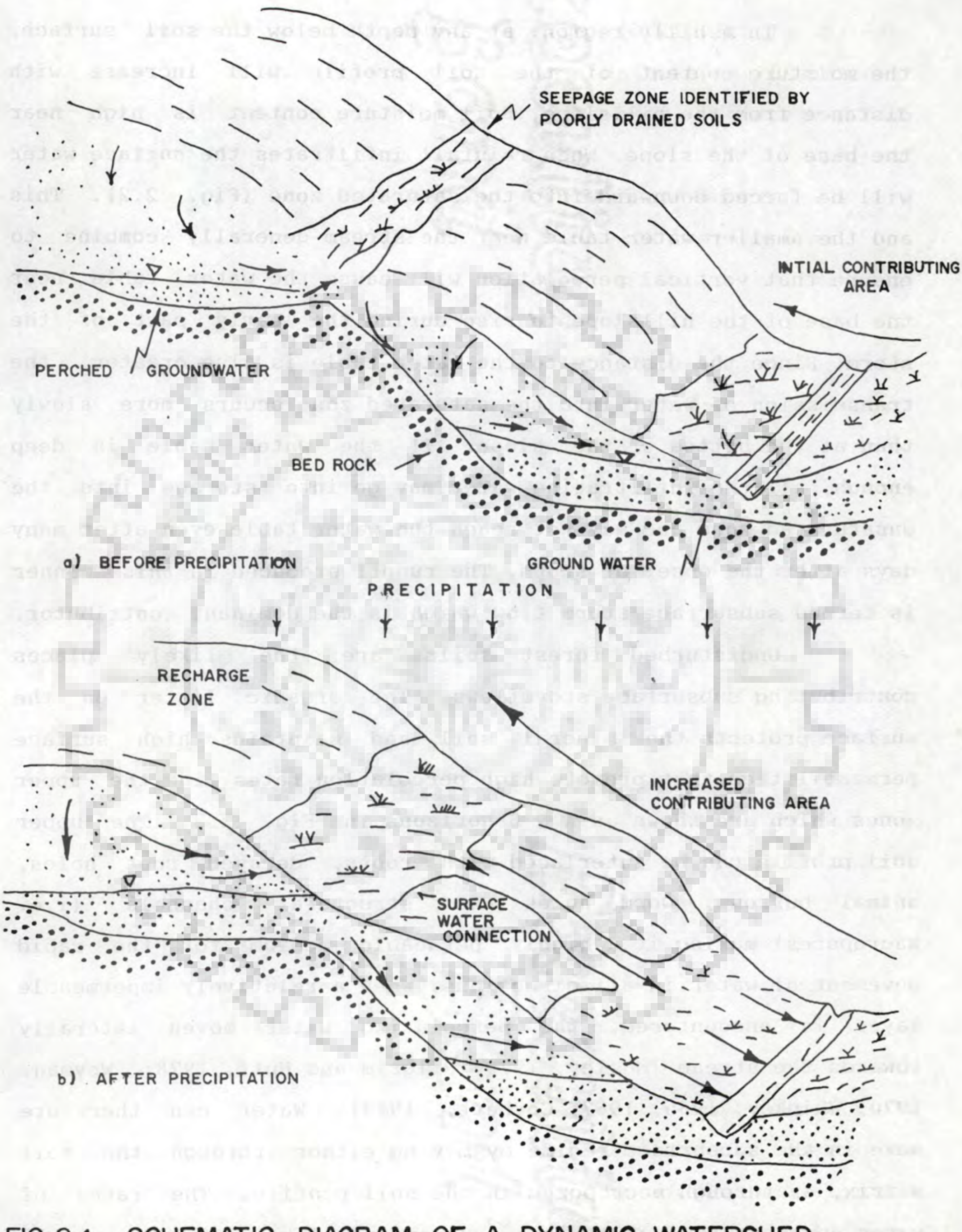

FIG. 2-1 - SCHEMATIC DIAGRAM OF A DYNAMIC WATERSHED.
(AFTER ENGMAN & ROGOWSKI, 1974)

In a hilly region, at any depth below the soil surface, the moisture content of the soil profile will increase with distance from the hillslope. Soil moisture content is high near the base of the slope. When rainfall infiltrates the surface water will be forced downward into the saturated zone (Fig. 2.2). This and the smaller water table near the stream generally combine to ensure that vertical percolation will cause the water table near the base of the hillslope to rise during the early part of the storm. Since the distance to the water table is also greater, the transmission of water into the saturated zone occurs more slowly than at the bottom of the slope. If the water table is deep enough, all the infiltrating water may go into storage into the unsaturated zone and may not reach the water table even after many days after the onset of storm. The runoff produced in this manner is termed subsurface storm flow which is the dominant contributor.

Undisturbed forest soils are the likely places contributing subsurface stormflows. The organic litter on the surface protects the mineral soil and maintains high surface permeabilities that promote high percolation rates in the upper zones which are shown as A & B horizons in Fig. 2.3. The upper soil profile can be interlaced with roots, decayed root holes, animal burrows, worm holes and structural channels (i.e. macropores) making it a highly permeable medium for the rapid movement of water in all directions. When a relatively impermeable layer is encountered, the percolating water moves laterally towards the stream (Mosley, 1979; Pilgrim and Huff, 1978; Weyman, 1970; Whipkey, 1965, 1967; Corbett, 1979). Water can therefore move in the subsurface regime by moving either through the soil matrix, or through macropores in the soil profile. The rates of water movement through these two zones are likely to be vastly different.

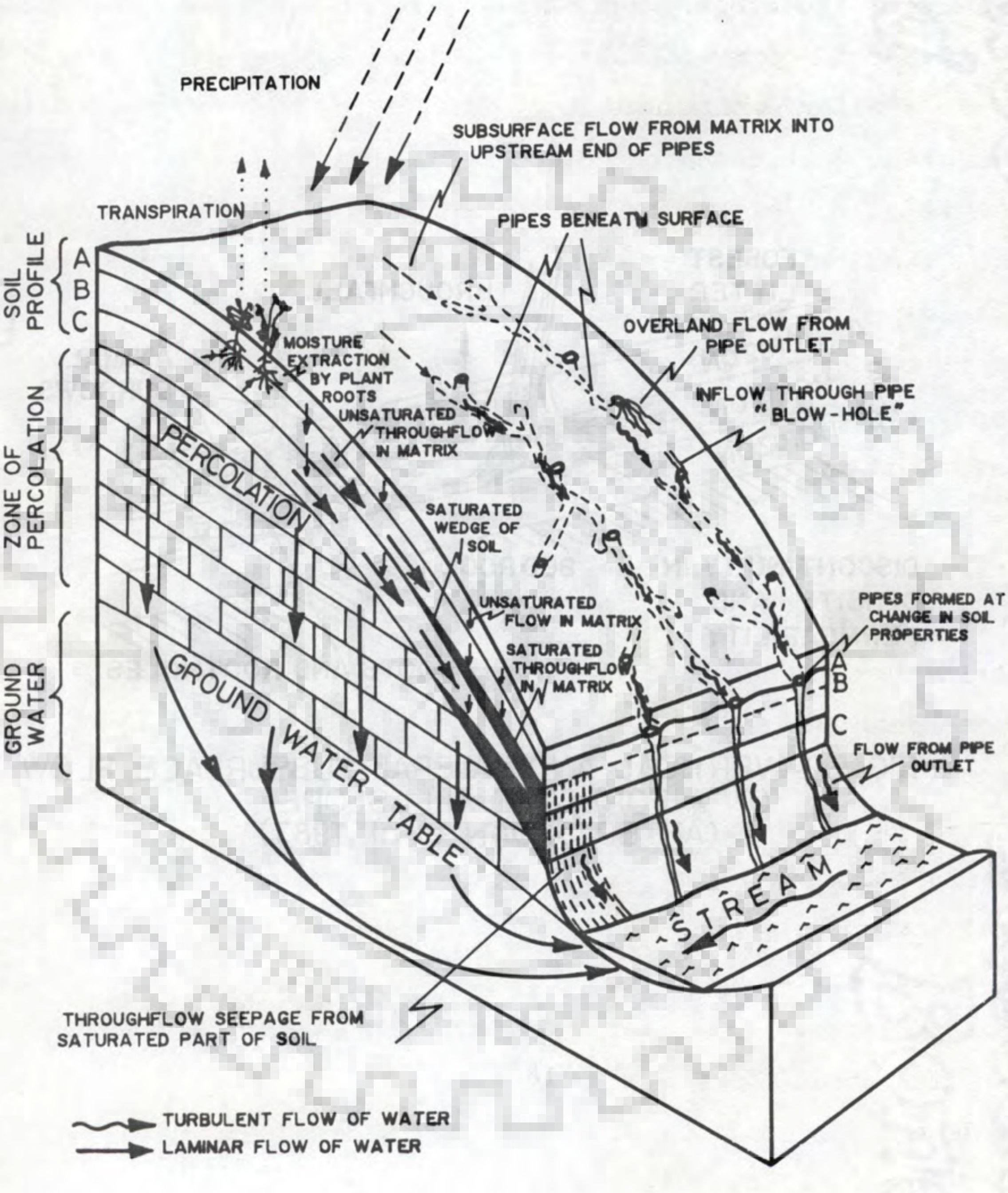

FIG. 2.2- FLOW ROUTES FOLLOWED BY SUBSURFACE RUNOFF ON HILLSLOPES (AFTER ATKINSON,1978)

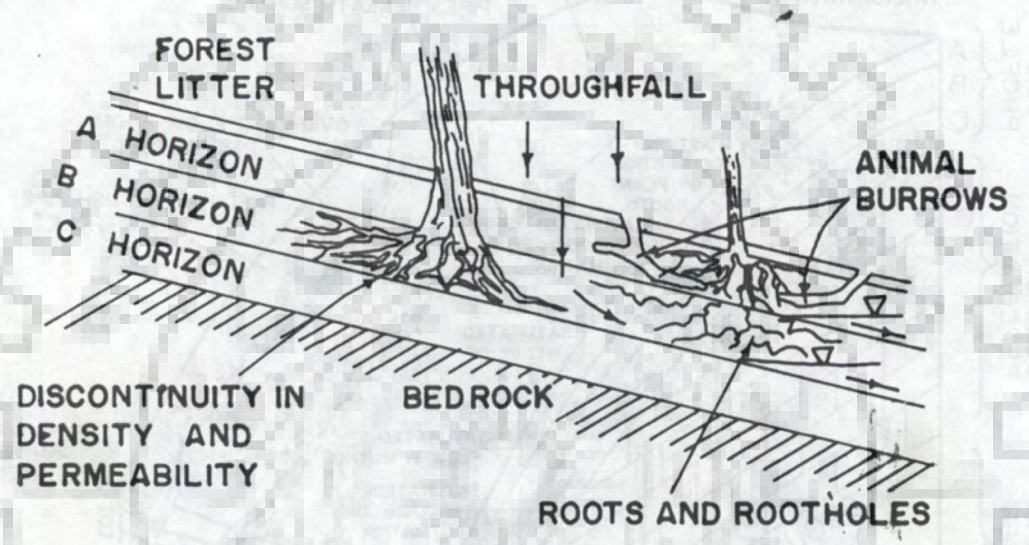

FIG. 2·3 – VERTICAL AND LATERAL SUBSURFACE FLOW ON A FORESTED HILLSLOPE. (AFTER SLOAN et al.,1983)

Barcelo and Nieber (1982) used a computer model to study the influence of soil pipe networks on watershed hydrology. They showed that a conduit system in the soil increases the overall response to rainfall (Fig. 2.4). Soil pipes also accelerate the contribution to streams by short-circuiting between productive source areas and source areas adjacent to the stream (Fig. 2.5). Such source areas were observed by Betson and Marius (1969) and Pilgrim and Huff(1978). In a study, Jones (1975) estimated that 25 per cent of stream flow was contributed by pipe flow for the watershed which he studied.

2.2.4 Topographic and Geologic Influence on Subsurface Stormflow

A watershed can be divided into valley basins and inter basins. Valley basins and inter basins can have either concave or convex slopes. However, the Valley basins will have concave contours and the interbasin the convex contours (Fig. 2.6(a)). The valley basin is water gathering (Fig. 2.6(b)) and the inter basin is water spreading.

Research by Zaslavasky and Sinai (1981) brings together the concepts of rainfall distribution, lateral subsurface and the variable source area concept with considerable insight. They found topography to be the controlling factor in the mechanisms of lateral subsurface flow and moisture distribution in a basin. In particular, they found curvature to be the most important parameter. They also found that the relative amount of moisture accumulation depended on the total rainfall, and not on the intensity.

Freeze (1972) used a three dimensional saturated, unsaturated subsurface flow model coupled with a one dimensional streamflow model to investigate the topographic and hydraulic configuration effects on mechanisms of runoff in a basin.

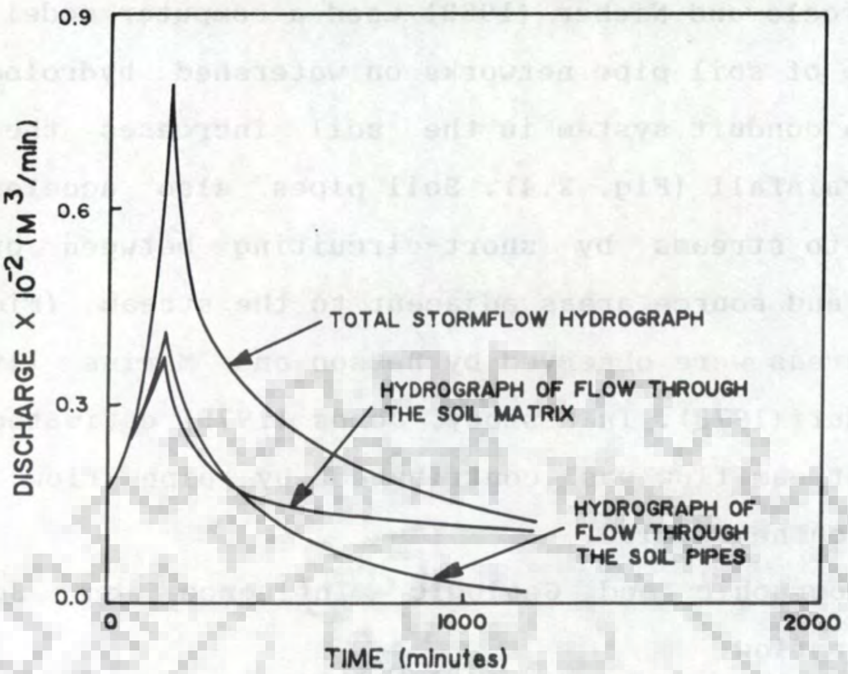

FIG. 2.4 CONTRIBUTIONS OF MATRIX FLOW AND PIPE FLOW TO THE TOTAL STORMFLOW HYDROGRAPH ON AN IDEALIZED HILLSLOPE (AFTER BARCELO AND NIEBER,1982)

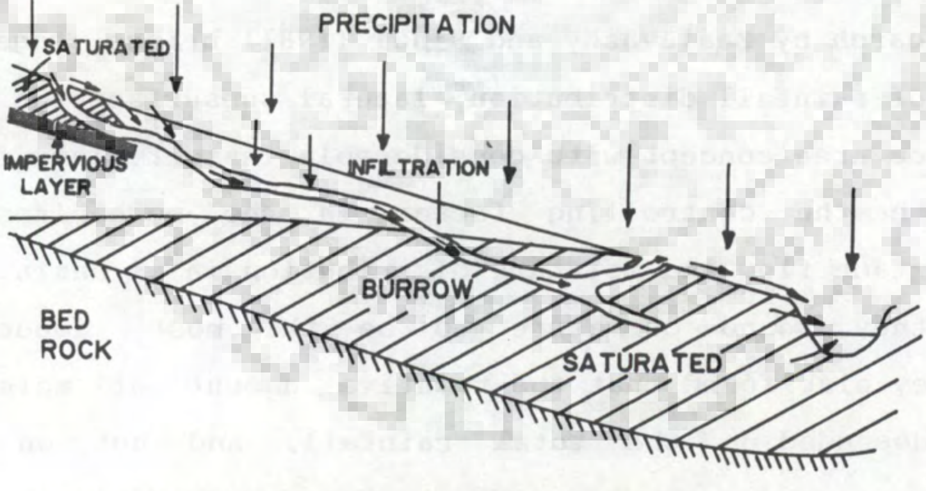

FIG. 2.5 SHORT-CIRCUITING OF SOURCE AREAS BY FLOW IN SOIL PIPES AFTER SLOAN et al., 1983)

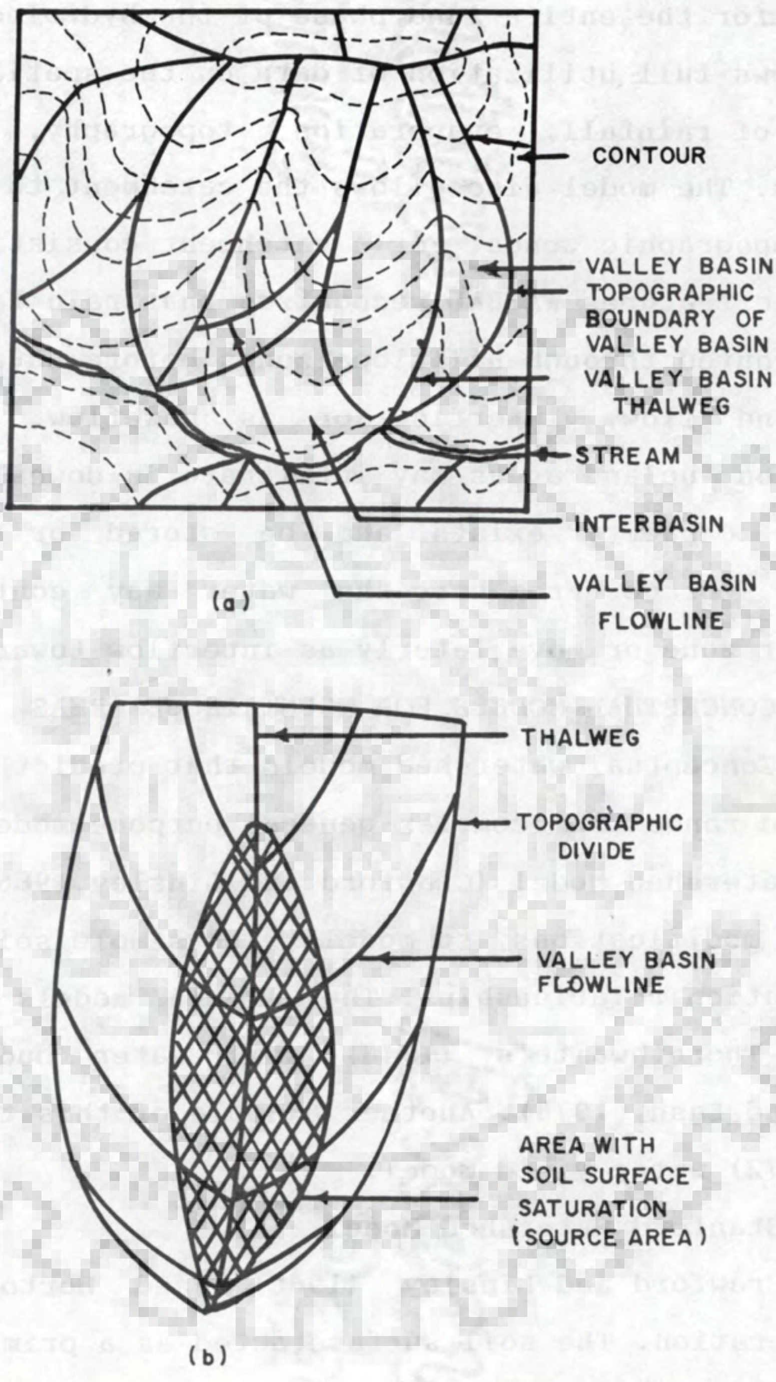

FIG. 2·6. THE EFFECT OF TOPOGRAPHY ON
a) SUBSURFACE FLOW LINES AND
b) SOURCE AREAS (AFTER NIEBER, 1979)

Knudsen et al. (1986) described a semi-distributed, physically based hydrological modelling system, WATBAL, which accounted for the entire land phase of the hydrological cycle. The model allows full utilization of data on the spatial and temporal variation of rainfall, evaporation, topography, vegetation and soil types. The model also allows the catchment to be divided into various topographic zones. For a catchment consisting of different topographic features WATBAL recognizes that rain falling on upland areas is routed through hillslope zones before entering the stream as overland flow, interflow or as baseflow. Overland flows generated on upland areas may infiltrate in downslope areas if a sufficient capacity exists and be stored or percolate to subsurface storage. From here the water may contribute to the groundwater zone or move laterly as interflow towards the stream.

2.3 CONCEPTUAL MODELS FOR MOUNTAINOUS AREAS

Conceptual watershed models that predict the response of a watershed range from complex general purpose models such as the Stanford Watershed Model (Crawford and Linsley,1966) and its many subsequent modifications, to models with simple soil water storage and evaporation relationships. The simple models are generally based on Thornthwaite's (1948) soil water budgeting concept (Federer and Lash, 1978). Another example of this type of model is Haan's (1972) water yield model.

2.3.1 Stanford Watershed Model

Crawford and Linsley (1966) used Horton's theory of runoff generation. The soil surface acted as a primary control for runoff production through the process of infiltration. This approach is not appropriate for steep sloped forested watersheds, where infiltrability is so great it is not a controlling factor. In this model, the channel hydrograph is the result of the hydrographs of the overland flow, the interflow and the groundwaterflow. Interception storage is filled before precipitation is added to any other storage. Precipitation on impervious areas is routed directly to the stream. Rainfall excess on the rest of watershed is computed with the help of cumulative infiltration function. The model uses three storages, namely, upper zone, soil zone and groundwater zone.

2.3.2 BROOK MODEL

Federer and Lash (1978) developed a daily simulation model, popularly known as BROOK model. It is a continuous lumped parameter model for watersheds less than 200 ha in area . Five storages were identified which take care of intercepted snow, snow on the ground, water in the root zone and ground. Potential evaporation is computed using Thornthwaite's (1948) empirical relationship. Leaf area and stem area indices were used to model the effect of trees on interception, evaporation, transpiration and snow melt. The following empirical function was used to simulate the contribution from variable source areas :

$$Y = m + n\, e^{r\theta} \qquad \ldots. \qquad (2.5)$$

Where,

Y = the fraction of precipitation converted to direct runoff,

m = the fraction of stream area in the watershed,

θ = the soil water content in the root zone, n and r are constants.

Darcy's equation can be written as under for homogeneous soils and ignoring hysteresis:

$$Q = K(\bar{\theta}) \qquad \ldots. \qquad (2.6)$$

where Q is the drainage rate, and $K(\bar{\theta})$ is the hydraulic conductivity at the average water content of the soil($\bar{\theta}$).

The soil moisture characteristic can be described in the form proposed by Gardner et al. (1970):

$$h = -g\theta^{b} \quad .... \quad (2.7)$$

The relationship proposed by Campbell (1974) is as under;

$$Kr = \theta^{2b+3} \quad .... \quad (2.8)$$

where h is the pressure head, θ is volumetric water content, K_r is the relative hydraulic conductivity, and g and b are constants determined from the soil water characteristic.

Federer and Lash tested the model on the Hubbard Brook watershed in New Hampshire and the Coweeta watershed in North Carolina.

2.3.3 Variable Source Area Simulator (VSAS) Model

Troendle and Hewlett (1979) developed a Variable Source Area Simulator (VSAS) model for small forested watersheds. They assumed that instantaneous streamflow is the sum of subsurface flow, precipitation on channel and saturated areas and overland flow from impervious areas.

$$q(t) = A_1(t)\ K_s \frac{dH}{dx} + A_2(t)\ P\ (t) + A_3\ P(t) \quad .... \quad (2.9)$$

Where,

q = instantaneous discharge,

A_1 = saturated area along channels where subsurface water exfiltrates to the stream,

A_2 = horizontal projected area of saturated areas,

A_3 = virtually impervious areas,

P(t) = precipitation,

K_s = saturated hydraulic conductivity,

H = hydraulic head.

Equation (2.9) is applied by dividing the watershed into segments and the segments into increments. The soil profile is divided into layers according to soil properties. A finite difference scheme with a 15 minute time interval was used to solve the subsurface equation:

Darcy's equation : $q = K(h) \nabla H$ .... (2.10)

Richards's equation $\frac{d\theta}{dt} = \nabla [K(h) \nabla H]$ .... (2.11)

where ∇ is $\frac{\partial}{\partial x} + \frac{\partial}{\partial Y} + \frac{\partial}{\partial Z}$

Green and Corey's (1971) equation of unsaturated hydraulic conductivity-water content was used which is given as under :

$$K(\theta) = a\, e^{b\theta}$$ .... (2.12)

where a and b are constants. Subsurface water is redistributed in this manner: If a lower element cannot accept the flux from an upper element because it is saturated, the water stays in the upper element and the water content of this element increases. When gravity forces flow into a saturated element, water flows into the element above or into the soil surface. At the end of each interval A_1 and A_2 are redetermined. Interception was based on the work of Helvey and Patric (1965). Since Troendle and Hewlett were only concerned with storm events, they assumed that evapotranspiration losses were negligible. The simulation analysis indicated that the greatest water movement occurs in the A and B horizons and that the storm hydrograph is largely controlled by the upper 2-4 m of soil.

2.4 PHYSICALLY BASED MODELS FOR MOUNTAINOUS AREAS

A physically based, variable area model for a basin was proposed by Beven and Kirkby (1979). The model attempts to combine the distributed effects of channel network, topology with dynamic contributing areas. It has the advantages of a simple lumped parameter model. Quick response flow is predicted from a storage/contributing area relationship derived analytically from the topographic structure of a unit within a basin. Average soil water response is represented by a constantly leaking infiltration store and an exponential subsurface water store. A simple nonlinear routing procedure related to link frequency distribution of the channel network which allows distinct basin subunits (i.e. headwater and sideslope areas) have been modeled separately.

Beven et al. (1984) tested the above mentioned model on three catchments in Central Wales (U.K.). The model has been found as a useful tool of modelling for ungauged watersheds of up to 500 sq km in humid-temperate climate. Beven (1981) also explored the possibility of using the kinematic wave equation to model subsurface storm flow. Only the simple applications were studied. Contributions from the unsaturated zone were neglected. A constant rate of input to a soil of uniform hydraulic conductivity and effective porosity throughout its depth was assumed. This case was originally studied by Henderson and Wooding (1964). Solutions obtained by using the kinematic wave equation have been compared to the more complete extended Dupit-Forchheimer equation for both steady state and transient conditions. Conditions for which kinematic wave approximations were acceptable have been specified in terms of the non-dimensionalised input parameter λ (= 4i Cosθ/(K Sin$^2\theta$)) with a critical value of the order of 0.75. Beven (1982) also gave analytical solutions for some simple cases of subsurface stormflow. The solutions are based on kinematic wave approximations for the unsaturated and saturated zones. Solutions for rising, falling and partial equilibrium hydrograph are given. The analytical model has been applied to data collected on a hillslope of the East Twin Brook catchment, Mendip, U.K. Measured and predicted hillslope hydrographs were found to be in good agreement.

Germann and Beven (1985) considered the infiltration process as a two domain flow through macropores of soil. The first domain is the soil matrix in which water is subjected to capillarity and infiltration is accounted for by Philip's sorptivity concept. The second domain is the soil macropore system in which water moves under gravity and are accounted for by kinematic wave theory. A sink function with respect to flow in the macropore system accounts for water sorption by the soil matrix. The two-domain flow model for infiltration is then applied to a block of undisturbed soil containing macropores.

Sloan and Moore (1984) compared five mathematical models for predicting subsurface flow on a uniform sloping soil trough at the Coweeta Hydrologic Laboratory. The models included one and two-dimensional finite element models based on the Richard's equation, a kinematic wave model and two simple storage-discharge models based on the kinematic wave and Boussinesq assumptions. The simple models simulated the subsurface flow and water table positions as accurately as the more complex models based on the Richard's equation, and were much more economical to use from the point of view of computational costs. Gurtz et al. (1990) used the dynamic model of the soil water balance BOWAM for the simulation of infiltration, percolation, evapotranspiration, changes in soil moisture, formation of overland flow, interflow and groundwater recharge. The BOWAM model should be applied preferably to sloping areas and higher mountain regions. It is suitable not only for the simulation of individual precipitation-runoff events, but also for the continuous soil water balance.

Moore et al. (1988) proposed a Contour-based Topographic Model for Hydrological and Ecological applications. The digital model is used for discretising three-dimensional terrain into small irregularly shaped polygons or elements based on contour lines and their orthogonals. From this subdivision the model estimates a number of topographic attributes for each element including the total upslope contributing area, element area, slope and aspect. This form of discretization of a catchment produces natural units for problem solving water flow as either a surface or subsurface flow phenomenon. The model, therefore, has wide potential application for representing the three dimensionality of natural terrain and water flow processes in the field of hydrology, sedimentology and geomorphology.

Takasao and Shiba (1988) revised the usual kinematic wave equations to consider the interaction between surface and subsurface flow in mountainous watersheds having curved surfaces, curved with A-layers of uniform thickness. A function which represents watershed surface geometry, which is called the geometric pattern function, is incorporated into the basic equations of the kinematic wave model, and the depth flow relationship for the surface-subsurface flow system is derived. When the watershed surface is linearly converging or diverging its geometric pattern function has a linear form, and numerical simulation for such cases are given. If the geometric pattern function is regarded as a new parameter of the kinematic wave model, then the kinematic wave flow model becomes very flexible. In fact, when the lateral inflow is spatially uniform, the model may be used as a simple model of a stream network system.

The System Hydrologic European (SHE) model has been developed as a joint collaboration effort of the Danish Hydraulic Institute (DHI), SOGREAH and Institute of Hydrology, Wallingford, U.K. The SHE model is a deterministically distributed physically based modelling system. Based on numerical simulation of the equations of flow and mass conservation, SHE overcomes the basic weakness of many existing catchment models and provides a reliable physical approach for predicting effect of land use changes on the hydrologic regime. The model has been developed from partial differential equations describing the process of overland and channel flow. The unsaturated subsurface flow is solved by finite difference methods. The model also consists of process of snow melt, interception and evapotranspiration. In SHE model, the one-dimensional unsaturated flow columns of variable depths, link a two dimensional groundwaterflow component. The watershed is represented in a horizontal plane by rectangular grid squares, and the river system is supposed to run along the boundaries of grid squares.

Several physically based models as described above and many more are available but their practical application is still limited, because of uncertainty of input parameters and the difference between the scale of application, a watershed, and that of model development, a plot or field (Freeze, 1978; Hadley, et al., 1985; and Wu et al., 1993).

2.5 WATERSHED MODELLING IN THE HIMALAYAN REGION

The countries of South Asia : India, Pakistan, Nepal, Bhutan and Bangladesh are dependent to varying degrees on the annual cycle of water flowing into, through and from Himalayan and trans-Himalayan mountain ranges. Though water resources of South Asia are responsible to a great extent for the development of the region, the hydrology of Himalayan watersheds has received almost no serious scientific attention (Alford, 1992).

Several research workers have emphasised that there remains a shortage of reliable scientific data on hydrology of waste land, agricultural land, urban land, forest land, as well as impact of soil conservation and degraded land reclamation in Himalayan region. In truth, the number of scientific studies remains small and the research literature is full of studies based on inference, speculation, reconnaissance or folklore (Rawat et al., 1992)

Many hydrological studies have been conducted on river basins of Himalayan rivers but a very few on small watersheds. Quick and Singh (1992) calibrated UBC watershed model to forecast flows on the upper Satluj river system considering snowmelt as source of runoff. Bhishm Kumar et al. (1992) measured discharge of Teesta river in Sikkim using tracer dilution technique. Ramasastri (1992) studied hydrometeorological aspects of September 1988 storm over Western Himalaya. Preliminary results of a hydrologic study of a small pine forest watershed has been reported in Kumaon Himalayas (Rawat et al., 1992). Rawat & Rawat (1994) determined that in the most disturbed agricultural land sixty per cent of the annual runoff occurred in July the month of heaviest rainfall, while in the undisturbed pine and oak forest it was only about twenty three per cent.

There is a complex of five instrumented watersheds established by Pakistan Forest Institute of Peshawar near Mingoro city, in the Swat valley. These watersheds lie in the range of four to twenty hectares. The studies are in calibration stage and are designed to determine the impact of different afforestation strategies on runoff and sediment yield from steep (30°) slopes on shists.

In forest, a small amount of the total rainfall regenerates surface runoff on the hillslopes after meeting the requirements of initial abstractions and infiltration. Pathak et al. (1985) observed surface runoff as 0.2 to 1.3 per cent of total rain on dense forest plots. However, these results are in variance with those reported from the Murree Hills, (Pakistan). Here a team from Pakistan Forest Institute measured runoff on a 45° slope covered by a deep soil developed under the chir and pine forest (Raeder-Roitzsch and Masrur, 1969; Choudhry and Nizami, 1985). The Pakistani team used 4m wide runoff plots. It was reported that while forested plots yielded only 4 per cent of the rainfall as runoff, the conversion of rainfall into runoff from dense grass young trees was 17 to 18 per cent, şparse grass cover 28 to 38 per cent and bare soil 47per cent. Runoff increased from 4 to 11 per cent a year after tree harvesting (Masrur and Hanif, 1972).

Seth and Khan (1960) have indicated that the moist, broad leafed forests of the Lesser Himalaya may return as much as 50 per cent of the incident rainfall back to the atmosphere through evapotranspiration. Pot studies suggest that chir (pine) has a lower transpiration rate than the local broad leaves but that it consumes more water than Sal or Oak. Consequently, chir is tending to replace other varieties on many of the hillsides of UP Himalaya (Raturi and Dabral, 1986). Mathur et al.(1976) reported 28 per cent reduction in the runoff when Eucalyptus were planted on a denuded watershed of Doon valley. Dhruva Narayana (1987) reported that on a 4.6 slope with silt clay loam soil with natural grass cover convert 21 per cent of the rainfall as runoff. On the other hand compacted, bare soils in the Shivalik foot hills, converted 71 per cent of rainfall to runoff from a 24.2 slop ing grassed watershed. This indicated that as the grass density increased from 65 to 85 q/ha, the runoff decreased from 38 to 31 per cent of the incident rainfall (Agnihotri et al., 1985).

Research Workers at Dehradun in the foot hills of UP Himalaya have reported that pine forest (1156 trees/ha) is capable of intercepting 22 per cent of incident rainfall (Dabral et al., 1968), whilst densely copiced Sal may intercept as much as 34 per cent of rainfall (Ghosh and Subba Rao, 1979).

Pathak et al. (1985) observed that stem flow accounted for less than 1 per cent of the total rainfall (0.3 to 0.9 per cent). Dabral et al. (1968) reported that stemflow in pine could reach 4 per cent of the rain fall and 6 to 9 percent in broad leafed forests (Ghosh and Subba Rao, 1979).

Pathak et al. (1985) observed that the litter layer at the ground surface, intercepted 7 to 10 per cent of the total rainfall. Ghosh and Subba Rao (1979) estimated litter interception as 5 per cent whilst Dabral et al. (1968) measured 76 per cent beneath pine (Pinus roxburghii), 9 per cent beneath Sal (Shorea robusta) and 8.9 per cent beneath teak (Tectona grandis).

Research work has also been carried out in the mountainous region of the Western Ghat (Southern India). Detailed hydrologic investigations were carried out by James and Padmini (1992) in the catchment of Pookot lake for suggesting appropriate conservation measures.

Kandasamy et al. (1992) applied four rainfall runoff models to selected river basins of Kerala (India) characterised by their mountainous features. The models considered were (i)linear (ii) linear perturbation (iii) constrained linear system and (iv) the Tank model. As a result of this investigation, the linear perturbation model was identified as the most suitable model for the steep and relatively small basins.

Putty and Rama Prasad (1992) modified a simple conceptual lumped parameter model developed in Kentucky for simulating daily streamflow. The model was modified to suit the conditions of small catchments of Westerns Ghats. The model is based on the concept of variable source area for streamflow generation. The performance of the model, which required daily rainfall and potential evapotranspiration as the inputs, was tested on two watersheds. Model parameters were optimised by trial and error for best fit. Results were found to be encouraging for runoff simulation in the mountainous region.

2.6 CONCEPT OF KINEMATIC WAVE AND ITS APPLICATIONS

In the present study, the kinematic wave theory has been used for the transformation of rainfall into runoff and also for routing of flows. Therefore, the basic concepts of this theory are being discussed in brief.

Most flood waves are generated by nonuniform lateral inflow along all the channels to the stream system. Natural flood waves are generally intermediate between pure translation and storage, which occur in a large reservoir or lake. Most flood waves move under friction control and have time bases considerably exceeding the dimensions of the stream system (Linsley et al., 1958). Description of Kinematic Wave Theory is given in the following sub-sections of this chapter.

2.6.1 Saint Venant Equations

Basic partial differential equations of wave motion capable of describing one-dimensional unsteady open channel flow were first developed by Bare de Saint Venant in 1871.

The Saint Venant equations consisting of the continuity and the momentum equations for the unsteady spatially varied non-uniform flow and are given below :

Continuity equation:

Conservation form :

$$(\partial Q/\partial x) + (\partial A/\partial t) = q \quad \text{.....} \quad (2.13)$$

Storage term	Rate of rise term	Lateral inflow rate term

Non-Conservation form :

$$V(\partial h/\partial x) + h(\partial V/\partial x) + (\partial h/\partial t) = q \quad \text{....} \quad (2.14)$$

Momentum equations:

Conservation form :

$$(1/A)(\partial Q/\partial t) + (1/A)(\partial/\partial x)(Q^2/A) + g(\partial h/\partial x) - g(S_o - S_f) = \frac{q(u-V)}{A}$$

Local Acceleration Term	Convective Acceleration Term	Pressure Force Term	Gravity Force Term	Friction Force Term	Lateral Inflow Term

..... (2.15)

Non-Conservation form :

$$(\partial V/\partial t) + V(\partial V/\partial x) + g(\partial h/\partial x) - g(S_o - S_f) = \frac{q(u-V)}{h} \quad \text{....} \quad (2.16)$$

Where,

A = cross-sectional area of flow (m^2),

Q = discharge rate of the channel (m^3/sec),

g = acceleration due to gravity (m/sec^2),

h = mean depth of flow (m),

S_o = channel bed slope (dimensionless),

S_f = friction slope defined by the Manning's equation (dimensionless),

x = Distance measured along the direction of flow (m),

t = Time (sec),

q = Net lateral inflow rate per unit length of the channel (m^2/sec),

V = X-Component of mean flow velocity (m/sec) and

u = Lateral flow velocity in x-direction (m/sec).

The terms in the momentum equation (2.16) determine the nature of flow. This can be illustrated by neglecting lateral inflow term and rearranging eq. (2.16) in the following form (Viessman et al. 1977) :

$$S_f = S_o - (\partial h/\partial x) - (V/g)(\partial V/\partial x) - (1/g)(\partial V/\partial t)$$

Friction Slope | Bed Slope | Water Surface Slope | Convection Term | Acceleration Term

Steady Uniform Flow →|

|← Kinematic Wave

|← Difusion Wave →|

|← Steady Non-uniform flow →|

|← Unsteady Non-Uniform flow →|

(Full Dynamic Wave) .... (2.17)

Saint Venant equations or the shallow water equations are well documented in standard text books (Chow, 1959; Abott, 1979; Eagleson, 1970; Stephenson & Meadows, 1986).

The idea of graphical integration using the method of characteristics was first suggested by Massau in 1889. Kuelegan (1945) applied the continuity and momentum equations simultaneously for overland flow analysis, Lighthill and Whitham (1955) analyzed St. Venant equations in detail and also studied the phenomenon of kinematic shock which can be applied to discontinuities in flow and water depth.

2.6.2 Dynamic And Kinematic Waves

Flood waves are identified either as the dynamic wave or as the kinematic wave. Although both of these kinds of waves are initially present, certain watershed characteristics can make kinematic wave the dominant characteristics of a flood event. When inertial and pressure forces are important, `Dynamic waves' govern the movement of long waves in shallow water, like a large flood wave in a wide river (Stoker, 1957). When the inertial and pressure forces are not important to the movement of wave, `Kinematic waves' govern the flow. The weight component is approximately balanced by the resistive forces due to channel bed friction under kinematic wave flow conditions. Kinematic wave flow remains approximately uniform along the channel. As the flow does not accelerate appreciably, no visible surface wave is noticeable as depicted in Fig. 2.7. A stationary observer observes apparently uniform rise and fall in the water surface elevation over a relatively long period of time. For a kinematic wave flow, the energy grade line is parallel to the channel bed and the flow is steady and uniform ($S_o = S_f$) within the differential length, while for a dynamic wave the energy grade line and water surface elevation are not parallel to the bed, even within differential element (Chow et al., 1988).

2.6.3 Applicability Of Kinematic Waves

Both kinematic and dynamic wave motions are present in natural flood waves. In many cases, the channel slope dominates in the momentum equation (2.17) hence other terms can be neglected. Therefore, most of the flood waves can be considered as formations of kinematic waves. Lighthill and Whitham (1955) proved that the velocity of main part of a natural flood wave approximates to that

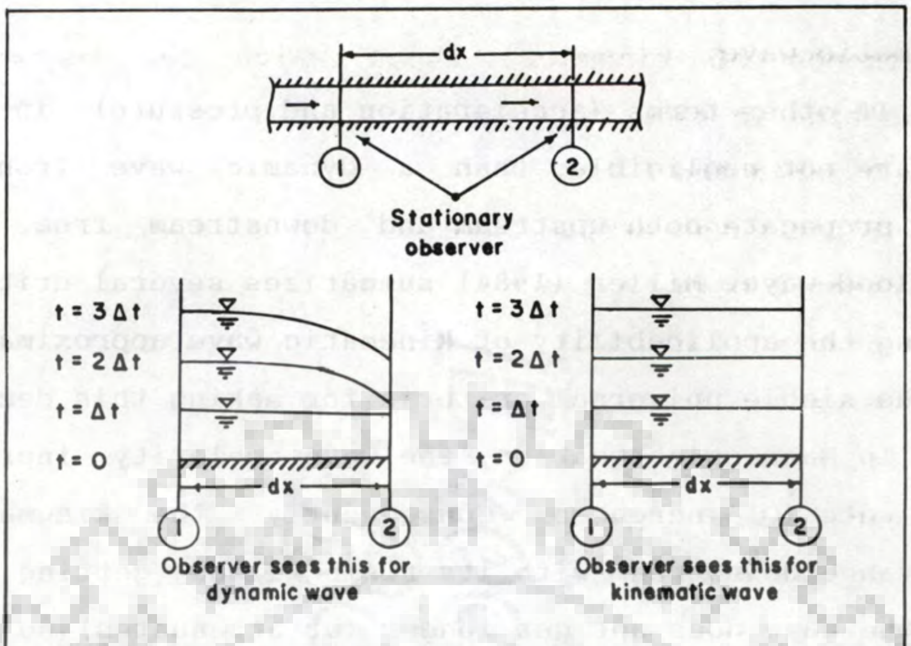

FIGURE 2.7
KINEMATIC AND DYNAMIC WAVES IN A SHORT REACH OF CHANNEL AS SEEN BY A STATIONARY OBSERVER. (AFTER *CHOW*, 1988)

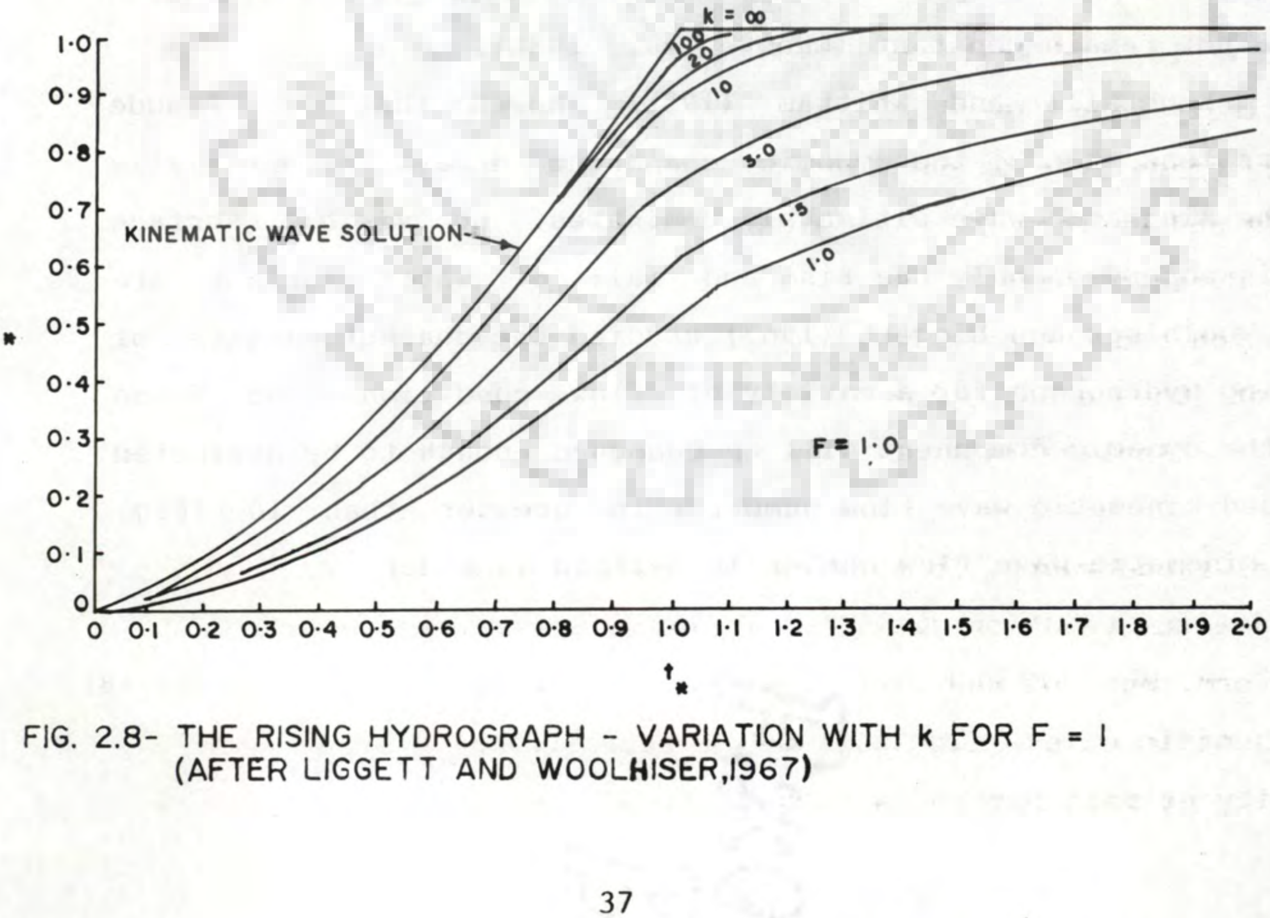

FIG. 2.8- THE RISING HYDROGRAPH - VARIATION WITH k FOR F = 1
(AFTER LIGGETT AND WOOLHISER, 1967)

of a kinematic wave.

If other terms (acceleration and pressure) in momentum equation are not negligible, than a dynamic wave front exists which can propagate both upstream and downstream from the main body of flood wave. Miller (1984) summarizes several criteria for determining the applicability of kinematic wave approximation but there is no single universal criteria for making this decision.

In Manning's equation, the wave celerity increases as discharge rate (Q) increases. Consequently, the kinematic wave should advance downstream with its rising limbs getting steeper. However, the wave does not get longer (or attenuates) so it does not subside and the flood peak stays at the maximum depth. As the wave becomes steeper, other terms of momentum equation become more important and introduce dispersion and attenuation. The celerity of flood wave at this pint is different from the kinematic wave celerity because the discharge rate is not a function of flow depth alone, and at the wave crest, flow rate (Q) and flow depth (h) do not remain constant (Chow et al., 1988).

Lighthill and Whitham (1955) showed that for Froude numbers less than 2, the dynamic component decays exponentially and the kinematic wave ultimately dominates, no visible surface wave is observed; only the rise and fall of water surface are seen. Woolhiser and Liggett (1967) studied the characteristics of a rising hydrograph for a variety of flow conditions and found that the dynamic component will be dampened enough to be neglected provided kinematic wave flow number K is greater than 10 (Fig. 2.8). Kinematic wave flow number is defined as under :

$$K = (S_o \; L)/(h \; F^2) \qquad \ldots. \qquad (2.18)$$

Where,

S_o = Channel bed slope,

L = Length of plane,

F = Froude number,

h = Flow depth,

and $F = V/(gh)^{1/2}$ .... (2.19)

A 'true kinematic' solution results as K approaches infinity, but for practical purposes kinematic wave model approximates reasonably well for the flows having K > 10. The kinematic wave model gives very good results if K > 20 and poor if K < 10. Woolhiser and Liggett (1967) also observed that the kinematic wave approximation may be used instead of the full St. Venant (Dynamic wave) equation if K > 20 and F ≥ 0.5. Overton and Meadows (1976) suggested that kinematic wave model may be used only for K > 10, regardless of the Froude number value.

Kinematic wave models have been used and assessed by various researchers like Ponce et al. (1978), Bren et al. (1978) and Hromadka et al. (1988). From these studies, one can conclude that kinematic wave approximation is now a well established method for surface runoff computation and is generally applicable where the watershed slopes are high (Shahri, 1993). These kinematic wave approximations are applied to a wide range of watersheds i.e. from mountainous to urban watersheds of small size. The characteristics of flow in mountainous watersheds on steep slopes suggest that the flow velocities may be high with high kinematic wave number (K) and Froude number greater than 1. As a result there is no backwater effect and bore formation.

2.6.4 Solution Techniques For Kinematic Wave Equations

The solution techniques for kinematic wave equations are broadly divided into two categories :

i) Analytical solution techniques

ii) Numerical solution techniques

i) **Analytical Solution Techniques**

For practical applications, in the analytical approach, the solution of St. Venant equations are limited to simplified cases with simple geometric and boundary conditions. Analytical solution is more difficult for the full dynamic equation than that of kinematic wave equation. Graphical solutions were in use for the solution of St. Venant equation for a long time in the past. The work of Chalfen et al. (1986) is an example of analytical solution to the simplified form of the St. Venant equations.

A number of researchers have developed exact as well as approximate analytical solutions for the kinematic flow approximations to compare the runoff from planes of different types and forms (Wooding 1965(a); Parlenge et al. 1981; Rose et al. 1983; Campbell et al. 1984; Moore 1985; Moore and Kinnel 1987). However, numerical techniques are more relational and easier when compared to the exact and approximate analytical solutions.

ii) Numerical Solution Techniques

Advent of digital computers, has enabled researchers to seek the solution of complicated partial differential equations for different initial and boundary conditions with the help of numerical solution techniques. Numerical solution techniques are the algorithms that use only arithmetic operations and also certain logical operations such as algebraic comparison. The numerical solution of unsteady state flow equations can be obtained by using the method of characteristics, finite difference method or the finite element techniques. Among these three, the finite difference methods are the most popular and advantageous. Researchers have proposed different computational schemes for the finite difference solutions.

2.6.5 Different Numerical Methods

There are a large number of numerical techniques for solving St. Venant and the kinematics wave equations. Each one of these has its own specific advantages in terms of convergence, stability, consistency, accuracy, and efficiency. These techniques can be classified as follows

(1) Method of characteristics

(2) Finite differences methods

(a) Explicit methods

(b) Implicit methods

(3) Finite element methods

A Brief description of implicit method has been given in the Chapter-IV under section 4.4.5, other methods are explained in many text books on flood flow routing.

2.7 THE INFILTRATION CONCEPT

For individual storms, the percentage of precipitation infiltrated varies widely, ranging from 100 per cent when all the rainfall infiltrates to perhaps 30-50 per cent for a high runoff storm. It is clear, therefore, that a watershed model must describe infiltration accurately for producing valid and useful results. Despite it's importance, the infiltration component in most of the watershed models is usually represented by an empirical relationship of one form or another. Often an equation requiring one or more fitted parameters is commonly used. Huggins and Monke (1966) observed that the choice of infiltration parameters employed in their watershed model had more influence than any other parameters on the outflow hydrographs, which again emphasizes the desirability of suitably accounting for the infiltration component.

2.7.1 Infiltration Models

Following infiltration models were used in the present study which are described below.

1) The Horton's Model

Horton suggested the following form of the infiltration equation, where rainfall intensity I > f at all times

$$f = f_c + (f_o - f_c)\, e^{-kt} \quad .... \quad (2.20)$$

where,

f = infiltration capacity (mm/hr),

f_o = initial infiltration capacity (mm/hr),

f_c = final infiltration capacity (mm/hr) and

k = empirical constant or decay constant (hr^{-1})

Rubin and Steinhardt (1964) showed that Horton curves could be theoretically predicted given the rainfall intensity, initial soil moisture conditions and a set of unsaturated characteristic curves for the soil. They showed that the final infiltration rate was numerically equivalent to the saturated hydraulic conductivity of the soil.

2) The Philip's equation

For a homogeneous soil with an uniform initial moisture content and an excess water supply at the surface, Philip has solved the partial differential equation of soil moisture flow. The solution is in the form of an infinite series, but because of rapid convergence only the first two terms need to be considered :

$$F = S_\phi\, t^{1/2} + At \quad .... \quad (2.21)$$

where F is the volume of infiltration at time t, S_ϕ and A are constants, usually named as sorptivity and continuing loss rates respectively.

On differentiating eq. (2.21) with respect to time 't' the following relationship is obtained:

$$f(t) = \frac{1}{2} \quad S_{\phi} \, t^{-1/2} \quad + \quad A \qquad .... \qquad (2.22)$$

where f(t) is infiltration rate at time t.

3) The modified Horton's model for variable rainfall

Many infiltration models utilize infiltration capacity formulae that are only valid if infiltration occurs at capacity rate from the very begining of the rain and continues at capacity rate till the very end of the storm. These two assumptions are usually not realistic. Bauer (1974) modified the Horton's relationship to account for infiltration during intermittent rainfall and accommodated a range of initial soil moisture conditions. The basic hypothesis indicates that the infiltration is a function of a soil moisture storage rate. At low soil water, the potential infiltration rate will be higher compared to a case when the soil is wet.

The Horton's model does not show dependence of its parameters on initial soil moisture content and rainfall intensity. Chu (1978) and Mls (1980) have suggested modifications which are applicable when rainfall intensity is less than the potential infiltration rate for some part of the storm. The basic assumption is that for given initial moisture the potential infiltration rate at any time is uniquely determined by the cumulative infiltration up to that time.

When surface runoff is produced by a rainfall event, the rainfall infiltration can be divided into two parts :

i) The unsaturated phase without runoff at $t < t_p$,

When the soil moisture at the surface $\theta_t < \theta_s$ (the soil moisture at saturation), the hydraulic head on the surface

$H(t) < 0$ and $f(t) = I(t)$.

Where t is time, t_p is ponding time.

ii) When $I(t)$ exceeds $f_p(t)$ and when effective rainfall starts.

For the saturated phase at $t \geq t_p$, when the surface runoff is produced and $\theta = \theta_s$ = constant, $H \geq 0$, and $f(t) \leq I(t)$ for $t \geq t_p$ while at $t = t_p$, $f(t) = I(t)$ the following relationship will hold:

$$f(t) = \min \{I(t), g(F)\} = \min \{ I(t), g [\int_0^t f(w)dw] \} \quad .... \quad (2.23)$$

Kutilek (1980) and Mls (1980) suggested that the ponding time t_p can be obtained for the unsteady rainfall $I(t)$ from the following equations:

$$\int_0^{t_p} I(w)\, dw = \int_0^{t_p} f(w)\, dw = \int_0^{t_s} f_p(w)\, dw \quad .... \quad (2.24)$$

$$I(t_p) = f(t_p) = f_p(t_s) \quad .... \quad (2.25)$$

where t_s refers to the time of infiltration and

$\int_0^{t_p} I(w)\, dw$ = the depth of water infiltrated due to $f_p(t)$

From Horton's equation, one may derive

$$f_p(t) = (f_o - f_c) - k [F(t) - f_c(t)] + f_c \quad .... \quad (2.26)$$

with $f(t) < f_p(t)$, $F(t)$ is the amount of rainfall absorbed in time t_s due to f_p. Referring to Fig. 2.9, equation (2.20) can be written for t_s

$$I(t_p) = f_c + (f_o - f_c) \exp(-kt_s) \quad .... \quad (2.27)$$

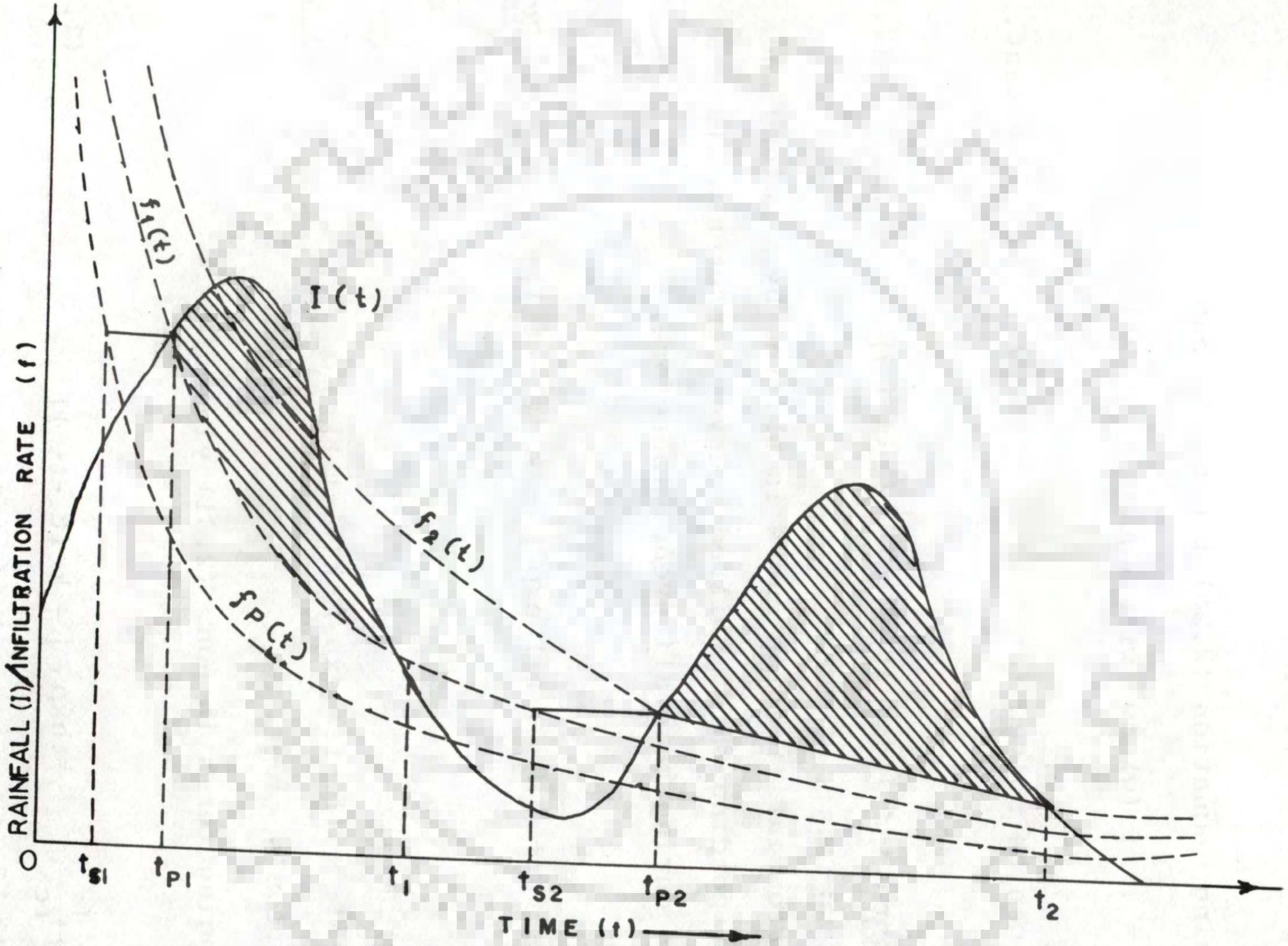

FIG. 2·9. DETERMINATION OF INFILTRATION FROM RAINFALL HAVING TWO PEAKS; HATCHED AREAS REPRESENT THE EFFECTIVE RAINFALL.

giving,

$$t_s = \frac{1}{k} \ln\left[\frac{I(t_p)-f_o}{f_o - f_c} \right] \quad .... \quad (2.28)$$

combining equation (2.26) for $t = t_s$ and

$F(t) = \int_0^{t_p} I(w)\, dw$ with equation (2.28)

which can be solved for t_p, If $I(t) = I =$ constant,

$$t_p = \frac{1}{kI} \{ f_o - I + f_c \ln (f_o - f_c) / (I - f_c) \} \quad .... \quad (2.29)$$

The Horton infiltration curve is shifted by t_s along the 't' axis. After ponding this shifted curve represents the actual infiltration during rainfall event. Therefore,

$$f(t) = f_c + (f_o - f_c) \exp[-k(t - t_s)] \quad .... \quad (2.30)$$

and

$$f(t_p) = f_c + (f_o - f_c) \exp[-k(t_p - t_s)] \quad .... \quad (2.31)$$

Rearranging terms in eqn. (2.31) yields:

$$\frac{f(t) - f_c}{f(tp) - fc} = \exp[-k(t - t_s)] \quad .... \quad (2.32)$$

Inserting $f(t_p) = I(t_p)$ from equation (2.28) and using

$Q(t) = I(t) - f(t)$ produces the following relationship:

$$Q(t) = I(t) - f_c - [\, f_o - f_c - k\int_0^{t_p} I(v)\,dv$$

$$-f_c \ln \{ \frac{[\, I(t_p) - f_c \,]}{[\, f_o - f_c \,]} \} \cdot \exp\{ -k\,(t - t_p)\}] \quad .... \quad (2.33)$$

or

$$Q(t) = f_c - [\, f_o - f_c - k \int_0^{t_p} I(v)\,dv + k\, f_c\, t_s \,]$$

$$.\exp\,[-k\,(t - t_p)] \quad .... \quad (2.34)$$

where Q (t) is the runoff rate at $t \geq t_p$, $f(t) = I(t)$ and $Q(t) = 0$. Equation (2.34) can be simplified further.

For I (t) = I,

$$Q(t) = (I - f_c)\,\{1 - \exp[\,-k\,(t - t_p)]\} \quad \text{for} \quad t \geq t_p \quad .... \quad (2.35)$$

Horton's model with more ponding times

Peschke and Kutilek (1982) developed a general procedure for determination of infiltration due to unsteady rainfall using the Green-Ampt and Kostyakov models. Singh (1989) developed a procedure for estimating infiltration based on variable rainfall intensity as a special case of above development. In this case, unsaturated and saturated phases could alternate, producing more than one ponding time. First, considering the case of rainfall having two peaks. The first ponding time, t_{p1}, is obtained from application of equation (2.23).

$$\int_0^{t_{p1}} I(t)\, dt = \int_0^{t_{s1}} f_p(t)\, dt, \qquad \text{.... (2.36)}$$

for $I(t_{p1}) = f_p(t_{s1}) = f(t_{p1})$

From Figure 2.9, it may be seen that the first unsaturated phase has the duration from t=0 to $t=t_{p1}$ and the infiltration rate f(t) equals I(t). Equation (2.38) can be used during the saturated phase with time scale shifted by Δt. The first saturated phase will be in $t_{p1} \leq t \leq t_1$.

where t_1 is the next intersection of $f_1(t)$ with I(t) after t_{p1}.

$$f_1(t) = f_c + (f_0 - f_c) \exp[-k (t - \Delta t_1)] \qquad \text{.... (2.37)}$$

The first saturated phase ends at t_1. From t_1 to t_{p2}, another unsaturated phase occurs with infiltration rate f(t)=I(t). The second ponding time, t_{p2}, is obtained from equation (2.33) as:

$$\int_{t_1}^{t_{p2}} I(t)\, dt = \int_{t_1}^{t_{s2}} f_1(t)\, dt, \text{ Since } I(t_{p2}) = f_1(t_{s2}) \qquad \text{.... (2.38)}$$

The infiltration rate $f_2(t)$ in the second saturated phase at $t_{p2} \leq t \leq t_2$ is obtained similar to equation (2.37) as:

$$f_2(t) = f_c + (f_0 - f_c) \exp[-k (t - \Delta t_1 - \Delta t_2)] \qquad \text{.... (2.39)}$$

where $\Delta t_2 = t_{p2} - t_{s2}$

Clearly $(I(t)-f_1(t))$ and $(I(t) - f_2(t))$ represent the excess rainfall.

This formulation can be generalized for more than two ponding times in a storm (Fig. 2.10). If t_{p1} is inside the i^{th} time interval of rainfall, then from equation 2.36:

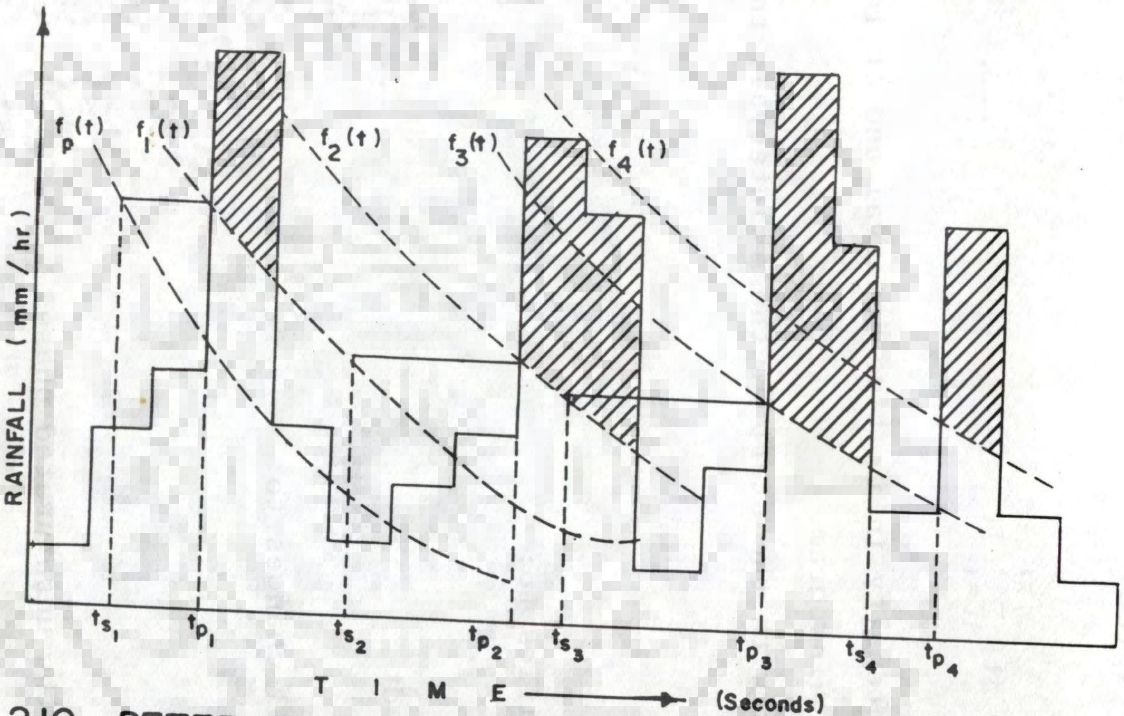

FIG. 2·10. DETERMINATION OF INFILTRATION FOR A RAINFALL HYETOGRAPH. (HATCHED AREA REPRESENTS THE EXCESS RAINFALL)

$$S_{j-1} + [\, t_{p1} - (j-1)\, \Delta t \,]\; I_j = \int_0^{t_{s1}} f_p(t)\, dt \quad .... \quad (2.40)$$

$$I(t_{p1}) = I_j \;, \quad I_j = f_p(t_{s1}) \quad .... \quad (2.41)$$

where $$S_{j-1} = \Delta t \sum_{i=1}^{j-1} I_i \quad .... \quad (2.42)$$

and I_i is the rain intensity in i^{th} time interval and Δt is the time interval of the histogram.

If t_{p1} coincides with the start of the m^{th} interval, then:

$$t_{p1} = (j-1)\Delta t \quad .... \quad (2.43)$$

Equation 2.40 simplifies to:

$$S_{j-1} = \int_0^{t_{s1}} f_p(t)\, dt \quad .... \quad (2.44)$$

and equation 2.41 changes to:

$$I_j > f_p\,(t_{s1}) \quad .... \quad (2.45)$$

consequently in the unsaturated phase,

$$S_j > \int_0^{t_{s1}} f_p\,(t)\, dt \quad .... \quad (2.46)$$

The computations proceed as follows:

The first j^{th} time interval (i.e. when the saturated phase occurs) is determined using equations 2.41 and 2.46. Function t_{p1} is evaluated by using equation 2.43 and t_{s1} using equation 2.44. If equation 2.45 is valid, t_{p1} and t_{s1} are found, if not, then t_{s1} is obtained from equation 2.40 and t_{p1} from

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equation 2.41. Then Δt_1 and $f_1(t)$ are computed by using equation 2.37. The computation of the subsequent saturated phase is carried out on similar lines.

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CHAPTER-III

DESCRIPTION OF STUDY AREA AND AVAILABILITY OF DATA

3.1 INTRODUCTION

Hydrological appraisal of the watersheds is the basic requirement for the planning, design and construction of water resource projects as well as for the soil and water conservation structures meant for restoration of disturbed watersheds. Land use planning on watershed basis requires the knowledge of hydrological behaviour of small watersheds as soil and water conservation works in India are being taken up strictly on watershed basis. Government of India has started a massive scheme on watershed management covering the whole country. The scheme is known as National Watershed Development Project for Rainfed Agriculture (NWDPRA).

For assessing the impact of watershed management in small hilly watersheds, gauging of a few selected watersheds has been proposed. Hydrological modelling of these small hilly watersheds will help in quantification of the impact of watershed management measures which need be extended to ungauged watersheds also. Hydrological investigations in small disturbed hilly watersheds are badly needed as hardly any detailed scientific study has been conducted for such watersheds of the Himalayas in Uttar Pradesh province of India.

3.1.1 THE HIMALAYAS

The Himalayan ranges constitute one of the loftiest and youngest mountain chain of the world. They have been the source of many invaluable natural resources Viz., water, forest, medicinal plants, minerals and wild life to the people of Indian subcontinent. Geologically, the Himalayas comprise a very sensitive domain due to the youthful terrain, tectonic activity and complex geologic features and varied rock types. Although the orogenic upheaval took place nearly 30 million years ago, the geologists and surveyors have established that the Himalayas are still rising albeit with a geological pace (Joshi, 1987). Morphologically the Himalayas are in a youthful stage having highly rugged topography and are extremely vulnerable to erosional processes specially through mass wasting (landslides etc.) and fluvial processes.

The Himalaya is broadly divided into three zones (or ranges), viz. the Outer or Sub-Himalaya, the Middle or Lesser Himalaya, and the Inner or Great Himalaya. However, Raina (1978) prefers to subdivide the Himalayas into four subdivisions in west to east direction and four mountain chains in south to north direction (Fig. 3.1 (a) & (b)). The sub-divisions in west to east direction are :

i) the Kashmir-Himachal Himalaya,
ii) the Himachal-Kumaon Himalaya,
iii) the Nepal-Sikkim Himalaya and
iv) the Bhutan-Arunachal Himalaya.

The ranges (i.e. mountain chains) in south to north direction are as under.

i) the Outer or Sub-Himalaya,
ii) the Lesser Himalaya,
iii) the Great Inner Himalaya and
iv) the Trans-Himalaya or Tibet Himalaya.

The U.P. Himalaya (i.e. the Himalaya of Uttar Pradesh) is a portion of the Himachal-Kumaon Himalaya. The area comprises of eight hill districts viz. Dehradun, Pauri, Tehri, Chamoli, Uttarkashi, Nainital, Almora and Pithoragarh (Fig. 3.2). The U.P.

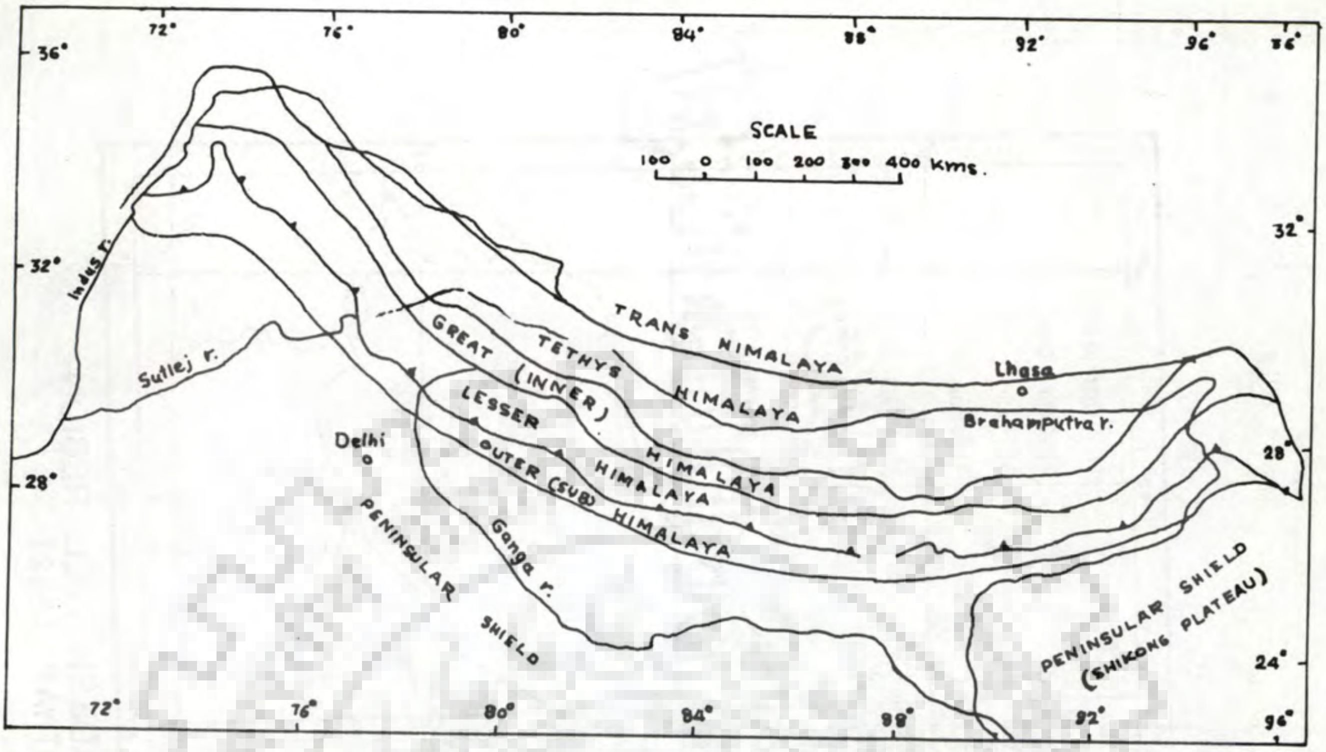


FIG. 3·1 (a) – THE FOUR FOLD LONGITUDINAL DIVISIONS OF HIMALAYA.

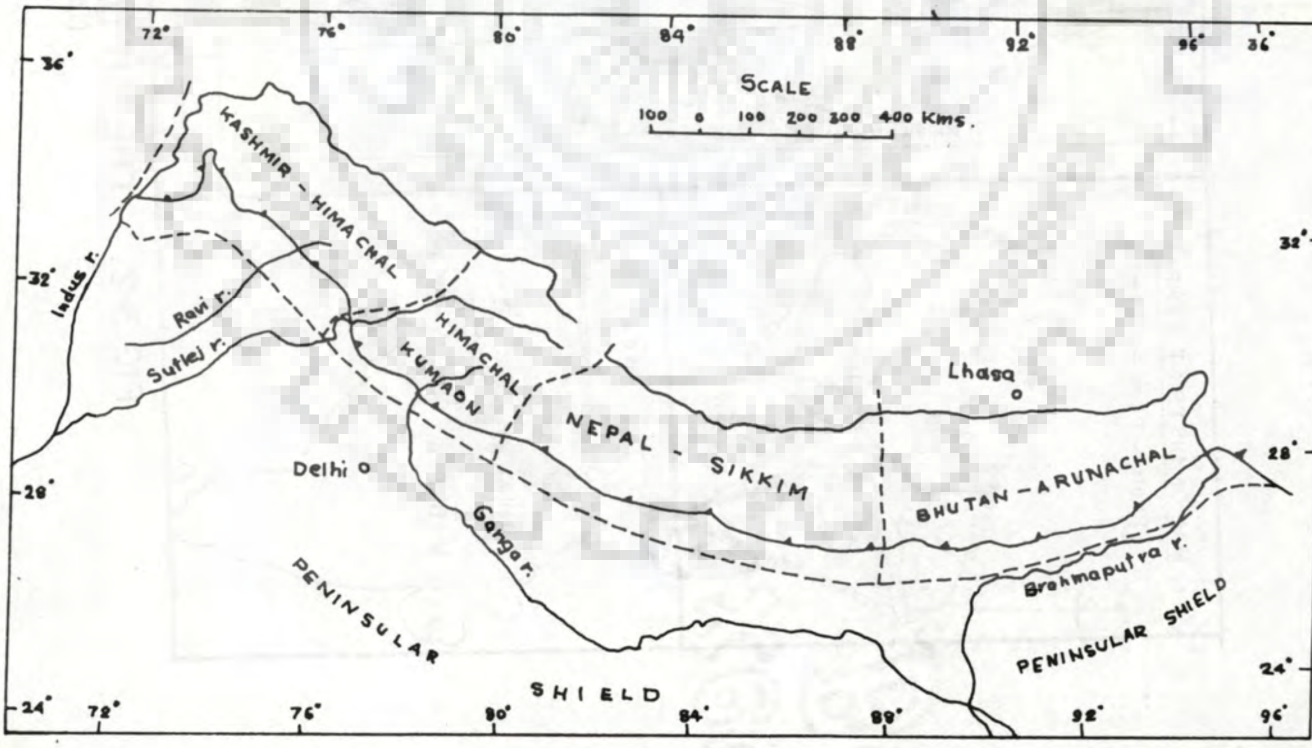


FIG. 3·1 (b) – THE REVISED FOUR TRANSVERSE SUBDIVISIONS OF HIMALAYA.
(AFTER RAINA, 1972)

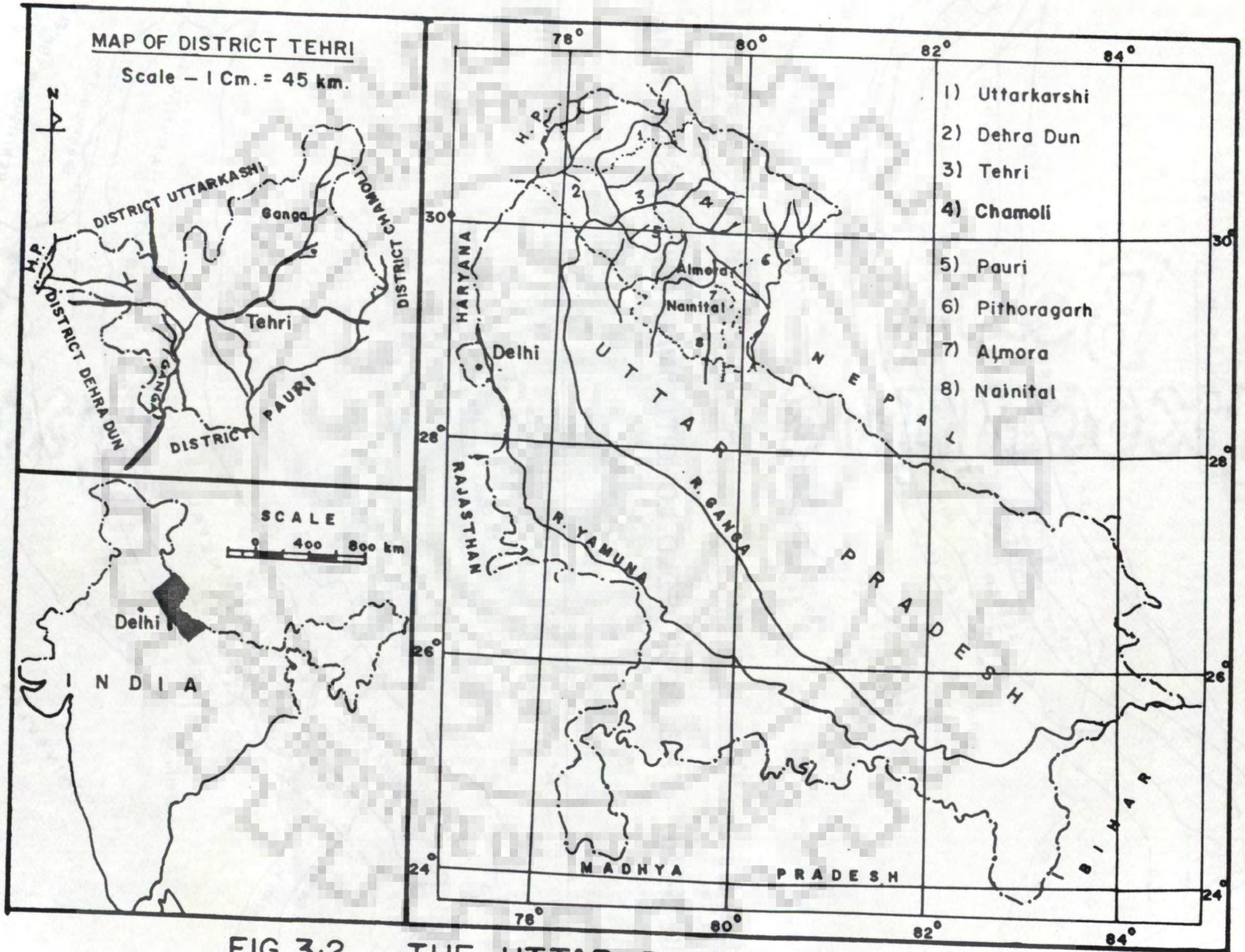


FIG. 3·2. – THE UTTAR PRADESH HILL REGION.
(AFTER KATIYAR, 1982)

Himalaya is drained by six important river systems viz. The Ganges, Yamuna, Sarda, Ramganga, Kosi and Sarju. The total area of the U.P. Himalaya within these eight districts works out to be 51,122 sq km.

3.1.2 Problems of Himalayan Region of Uttar Pradesh

Originally, the Himalaya of Uttar Pradesh had good vegetation cover. However, the explosion of population has put a lot of stress on its forest resources. Also, the developmental activities like road construction and surface mining have directly and indirectly contributed to forest destruction through clearance and landslides etc. In the present context deforestation poses serious problems in the Himalayas of Uttar Pradesh in India (Haigh et al., 1990). The population of just 4.787 million (1981) continues to expand at a rate of around 2.3 per cent per annum. This has led to encroachment of forest land by way of extension of agricultural land into forest land at a rate of about 1.5 per cent per annum and an increase in live stock at about 0.18 cattle units per annum (Shah, 1982).

Official statistics suggest that the forest cover of U.P. Himalaya is about 67 per cent. However, despite an active programme of plantation, the area under the control of U.P. Forest Department seems to have gone down by 5 per cent during the period 1965-80 (Kumar, 1981). Gupta (1979) attempted to use satellite imagery to quantify actual forest cover and suggested that just 37.5 per cent of the area is currently forested. Tiwari et al. (1986) found that about 29 per cent of U.P. Himalaya was forested but that "good forest", with a crown canopy greater than 60 per cent, accounted for only 4.4 per cent of the land cover.

The reduced vegetation cover resulted in increased surface runoff and reduced recharge to groundwater. Enhanced overland flows increased the rate of soil erosion which resulted in depleted soil depths on the hill slopes. Infiltration rates were affected adversely due to reduction in vegetation cover and soil depth. As a result, the groundwater table further lowered, springs dried up and land surface suffered desertification (Haigh, 1990).

Surface or open-cast mining and road construction have seriously disturbed the sensitive ecosystem of the U.P. Himalaya. The Mussoorie hills have been badly denuded by reckless and unscientific mining for limestone, phosphorite etc. The quarrying has resulted in the loss of vegetation and top soil, decreased groundwater storage, and accelerated soil erosion and landslides.

3.2 WATERSHEDS SELECTED FOR STUDY:

The watersheds selected for this study are Bhaintan Watershed in Tehri-Garhwal district and Jhandoo-Nala watershed (near Sahastradhara) in Dehradun district in the province of Uttar Pradesh (India). Bhaintan watershed was selected by the Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Dehradun, in collaboration with the Ford Foundation for an Operational Research Project on Watershed Management to evaluate integrated land use planning in the U.P. Himalaya. This watershed was disturbed due to mass erosion caused by road construction, landslides, and over exploitation by the inhabitants.

Jhandoo-Nala watershed was selected by the above mentioned Institute as a research project on "Mine area rehabilitation". This watershed was disturbed due to lime stone quarrying for about 30 years.

3.2.1 The Bhaintan Watershed

As mentioned above the Bhaintan watershed, happens to be a disturbed small watershed in the Outer-Middle Himalayas (U.P. Himalaya). It was selected for the hydrological investigations, the details of which are given below.

1) **Location of The Watershed**

The watershed is situated between longitudes of 78° 20′ to 78° 22′ E and latitudes of 30° 13′ to 30°15′ N. The watershed is located on the Rishikesh-Tehri State Highway in the Narendra Nagar Community Development Block of the Tehri-Garhwal District. It covers an area of about 272 ha with elevations ranging from 720 to 2013 m (Fig. 3.3). The watershed is a part of the Hyunl river catchment. Hyunl river is a tributary of the Ganges joining it at a point 9 km upstream from Rishikesh. Although, the watershed is not a part of the catchment of the proposed Tehri Dam, it may be considered as a 'representative watershed' of the Tehri Dam catchment for application of scientific results. Various extension agencies are located near the watershed, since Fakot is the head quarters of the Narendra Nagar Community Development Block. Various land use categories such as cultivated land, village common land, community forest, orchards and government reserve forest are available within the watershed for multiple land use planning. This watershed had been identified as a representative watershed for the Outer-Middle Himalayas.

2) **Physiography**

The watershed is very steep with slopes averaging 72 per cent. Seventy two percent of the watershed area has slopes greater than 50 per cent (Appendix-D3). The watershed has a drainage density of 5.2 km. per sq km and a form factor of 0.39. The compactness coefficient, circulatory ratio, and elongation ratio of the watershed are 1.28, 0.6, 0.7 respectively (Appendix-D4).

The average aspect of the watershed is in a NE direction and the shape of the watershed is elongated. The drainage pattern is dendritic. The main channel length is 2.78 km, whereas maximum

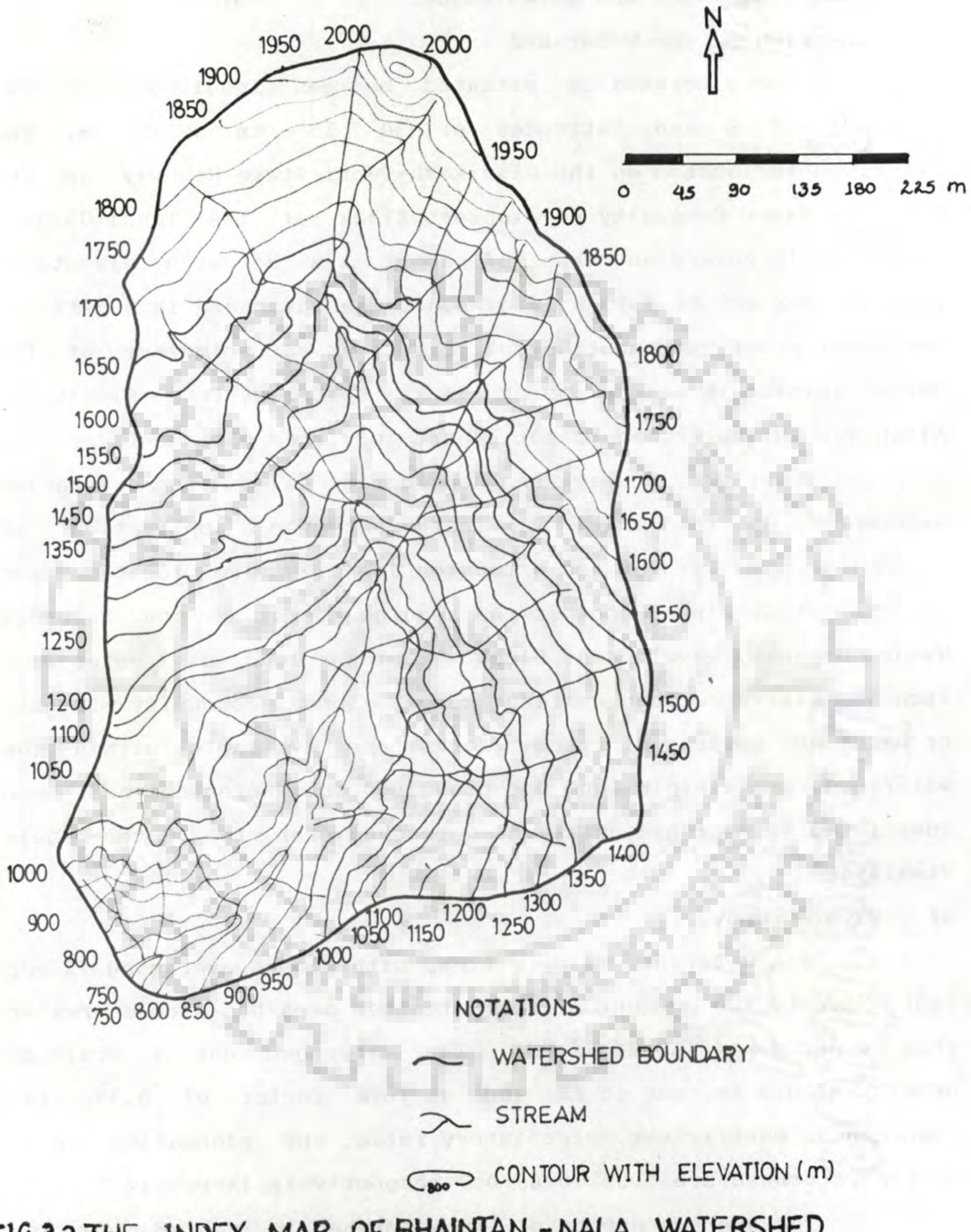


FIG.3.3-THE INDEX MAP OF BHAINTAN - NALA WATERSHED

basin length is 2.4 km. The average basin width is 1.13 km.

3) Climate:

The average rainfall of the watershed for the sixteen water years (from June 1975 to May 1991) worked out to be 1908 mm (Appendix-D5). Maximum rainfall intensities recorded for different durations, number of rainy days, and average annual rainfall are given in Appendix-D5. The maximum intensities recorded for 5, 10, 15, 30 and 60 minutes are 192, 144, 128, 110 and 100 mm per hour respectively (Appendix-D6). These intensities were recorded on September 2, 1980, during a thunder storm. Normally no precipitation is received through snowfall in the watershed, but on severely cold days some stray patches of thin snow deposition may be seen in the upper reaches of the watershed. Snowfall has got little or no impact on the hydrology of this watershed.

During the monsoon, the average daily relative humidity varies from 60 to 91 per cent while during the dry and winter period it varies from 37 to 78 percent. The highest average daily relative humidity is recorded during the month of August as it is the highest rainfall month. (Appendix-D7).

The average maximum temperature varies from 19°C in December and January to 34°C in May, while the average minimum temperature varies from 6°C in January to 25°C in May (Appendix-D8).

The average daily pan evaporation ranges from 1.7 to 2.1 mm in January when mean daily temperatures are low and from 6.2 to 9.9 mm in May and June (Appendix-D9).

4) Soils and Geology

Description of soils and geology of the area are given below.

a) Soils:

Bharadwaj, Gupta and Nayal (1974) surveyed the Bhaintan watershed up to Bhagori and classified the soils into five soil series and two miscellaneous land types based on origin and genesis of soil and landscapes (Fig. 3.4). For the present study the Bhaintan watershed has been taken up to Ghursera.

The soils are moderately gravelly, non-calcareous, medium textured and very deep, derived from colluvium of Katkore and Pata series. These are well drained with moderate permeability. Organic matter is distributed throughout the profile, hence soils are quite fertile and productive. Soils are neutral having pH around 7.7 in all soil horizons. Clay is elluviated in the range of 50 to 100 cm depth. The soils are silty loam and moderately gravelly. Following two landscapes have also been identified in addition to five soil series.

i) Rocky and Precipitous Land

Rock outcrops are of sandstones, quartzite, and hard shale and occur on steep slopes. These are generally barren having few trees, shrubs, or bushes that too occurring in cracks. Towards the top portion of the watershed rocks are weathered and large stones and rock masses occur. This type of land occupies about 12 per cent of watershed area.

ii) Land Slide and Road-cut Debris

A large amount of debris has accumulated by the side of the road due to natural landslides and road-cut failures. The debris contains 30 to 50 per cent gravels and 20 to 50 per cent stones. The slope of the land is very very steep and severely eroded. The per cent of total area, bulk density, water holding capacity and available water holding capacity of the different soil series are given in Appendix-D10. About one per cent watershed area is under land slides and road-cut debris.

(b) Geology:

On the northern flank of Pharat window, black-grey,

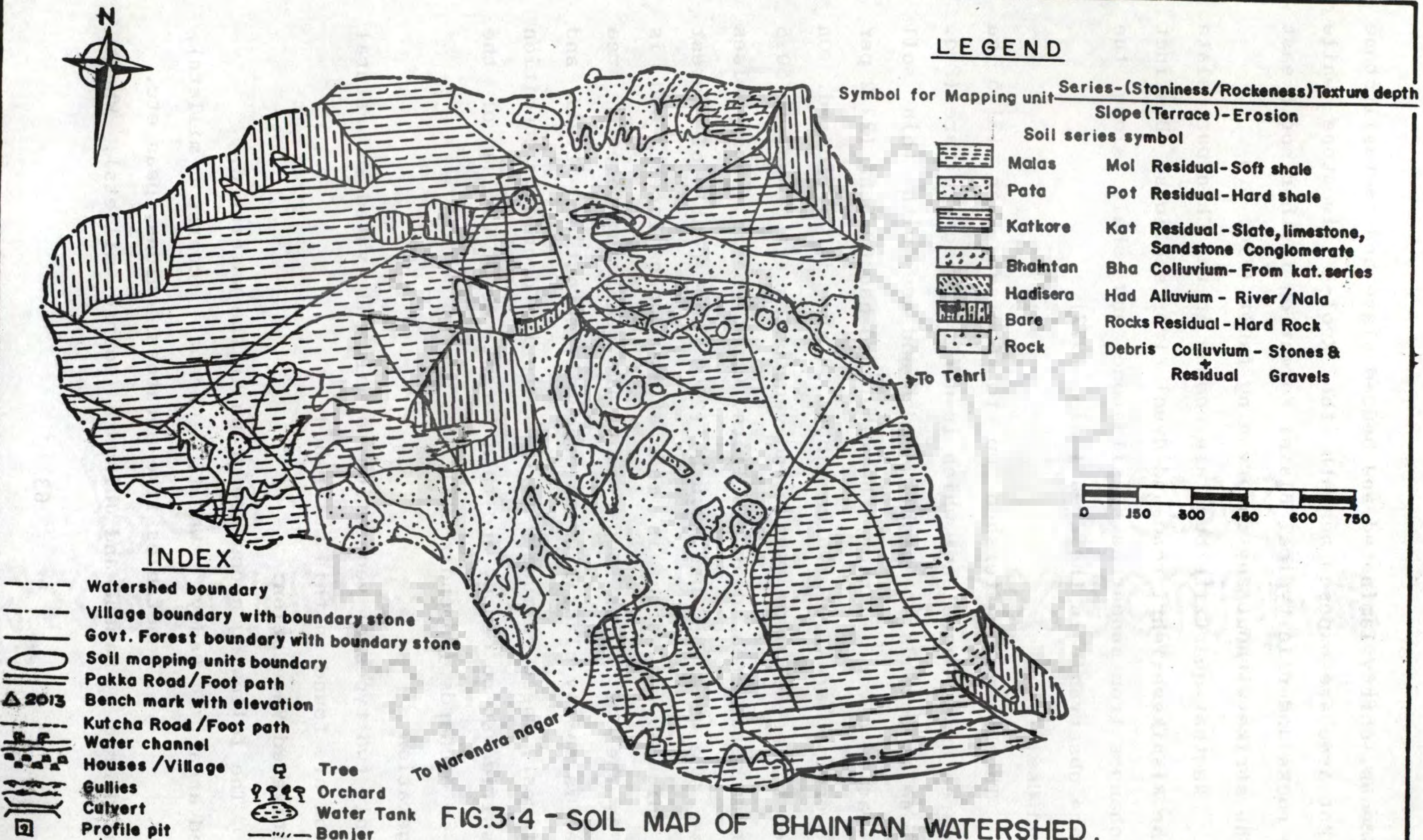


FIG.3·4 - SOIL MAP OF BHAINTAN WATERSHED.
(AFTER CSWCRTI, 1979)

carbonaceous, chirty laminated and bedded slate and metasiltstone near Fakot area are exposed beneath the Krol-A limestone while similar rocks underlie typical Blaini Formation further north east along the strike without any intervening fault (Fig. 3.5).

Nagthat quartzite beds are common in the Chandpur slate along the Rishikesh-Tehri road and Hyunl river sections. Distinct facies changes from sandstone to siltstone and shale along the strike are observable in the area (Jain, 1972).

5) Land Use

The Bhaintan watershed up to Ghursera has 131.5 ha (48.5%) area under wasteland, which is unfit for agriculture (Fig. 3.6). These wastelands are highly eroded and are with thin soil and vegetation cover. Further, the watershed has 60.5 ha (22.2 per cent) in cropped area of which about 5 ha is irrigated. On irrigated terraces, paddy, wheat and vegetables are grown. In 50.5 ha of unirrigated area, coarse millets, wheat, maize, and pulses are grown. The watershed has 79.6 ha (29.2 per cent) of forest area of which 38.5 ha area is moderately dense forest and is managed by the U.P. Forest Department. The remaining forest area (41.1 ha) is mostly classified as community forest or "Civil and Soyam" forest. These community forests are in degraded condition and classified as no çanopy and thin forest. About 0.4 ha of the area is in orchards (Appendix-D11).

6) Vegetation

Mainly two types of vegetation, namely cultivated and natural vegetation are found in this watershed.

i) **Cultivated Vegetation:**

The following crops are grown in the watershed;

Irrigated area : Paddy, Wheat, Cheena (coarse millets), Vegetables like potatoes, onions, peas etc.

Unirrigated area : Mandua and Jhingora (coarse millets), Wheat,

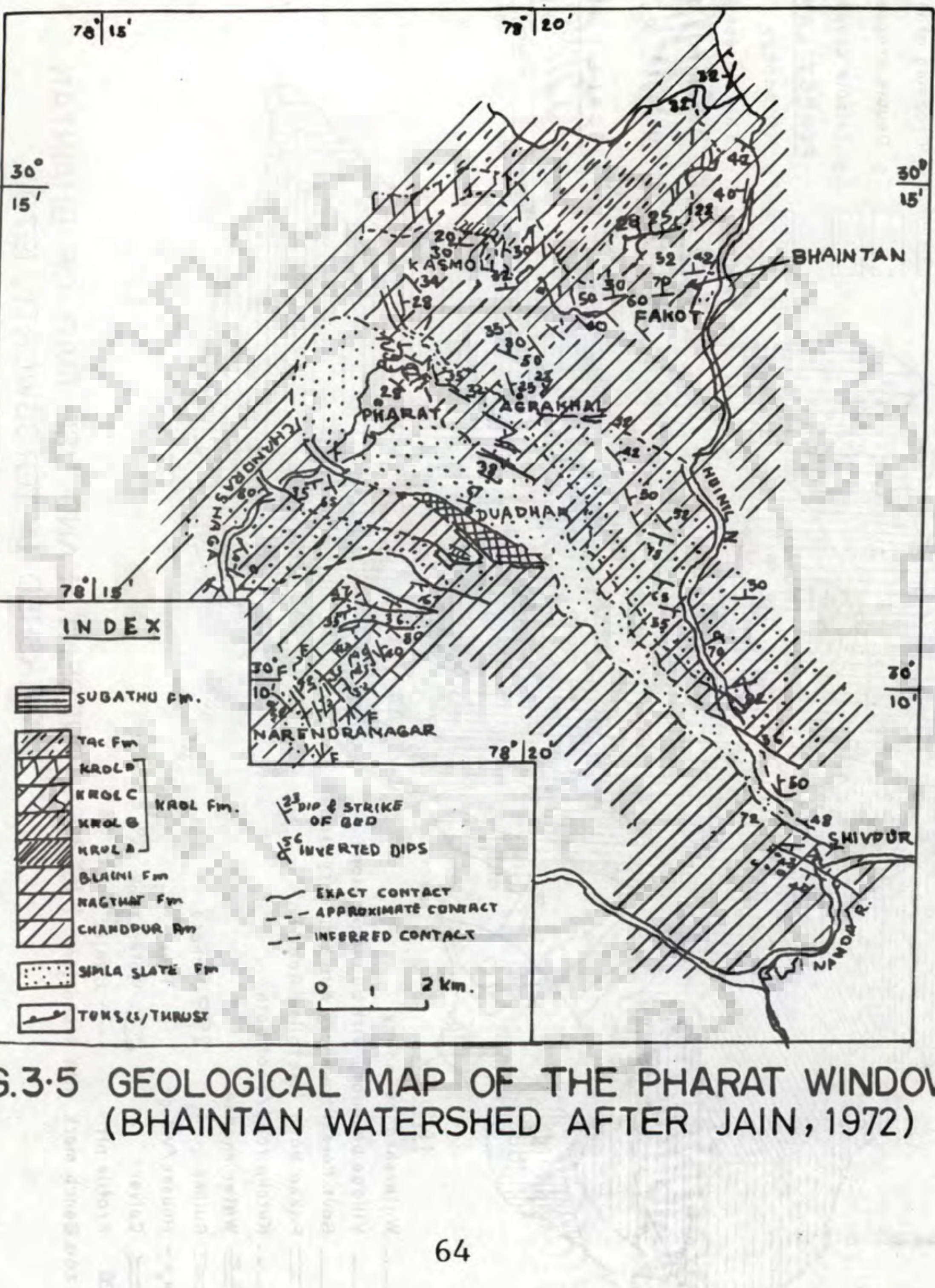


FIG.3·5 GEOLOGICAL MAP OF THE PHARAT WINDOW. (BHAINTAN WATERSHED AFTER JAIN, 1972)

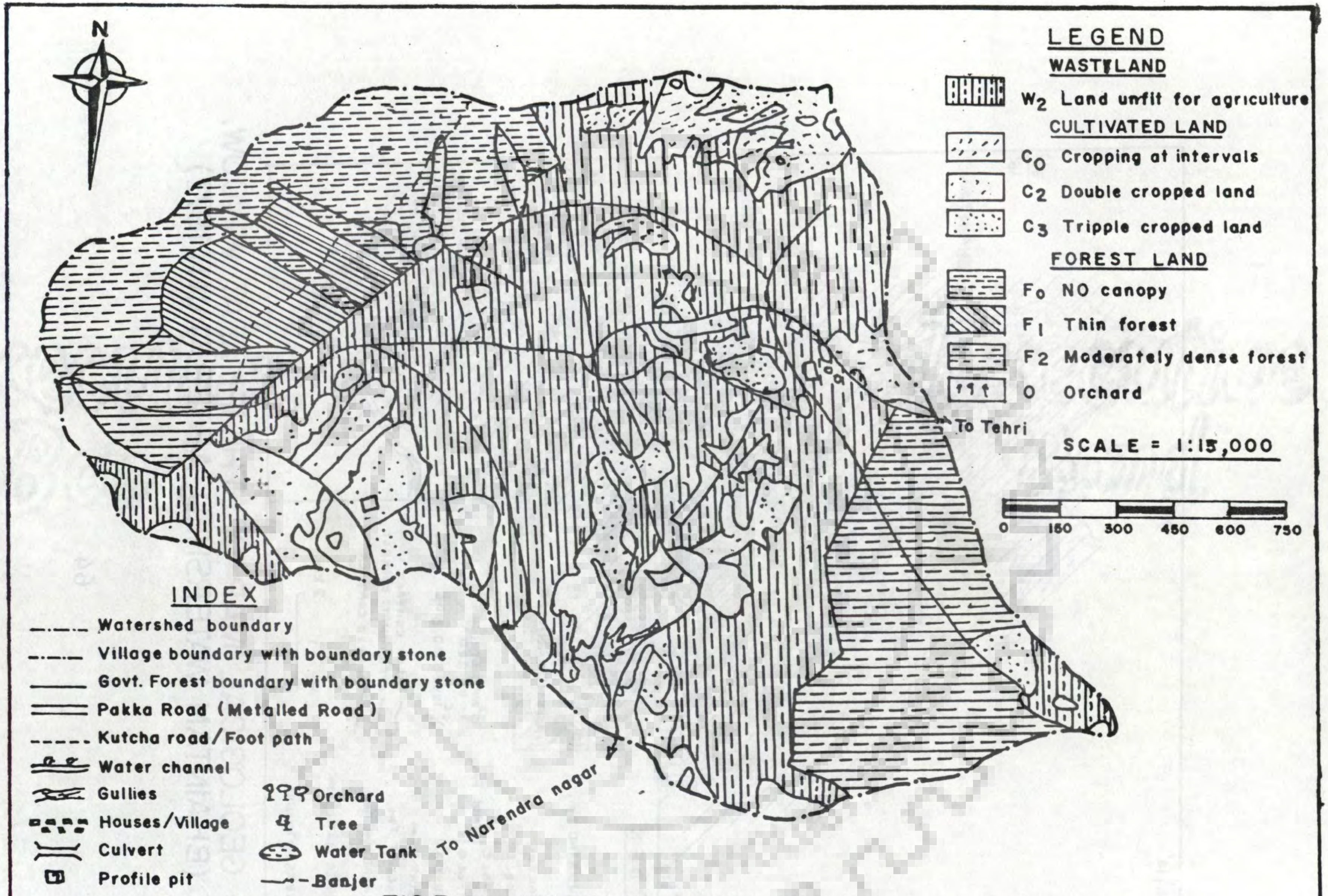


FIG.3·6 PRESENT LAND USE MAP OF BHAINTAN WATERSHED (AFTER CSWCRTI, 1979).

Barley, Maize, pulses etc.

Orchards: There are four small orchards in the watershed having approximately 15 to 30 plants each of Mango, citrus, peach, pomegranate, Walnuts, etc.

ii) Natural Vegetation:

The natural vegetation has been divided into three categories: 1) Trees, 2) shrubs and 3) Grasses including legumes. Good natural vegetation exists primarily in the Government reserve forest managed by the U.P. Forest Department. The vegetation on community lands, managed by the local population, is sparse, and is in poor condition because of mismanagement.

The main vegetation found in the forest area of Bhaintan watershed are listed in Appendix-D16(a).

7) Hydrology

Practically no information on the hydrological behaviour of small hilly watersheds in the U.P. Himalayan region is available. As such it was considered worthwhile to collect information on rainfall and water yield from this watershed.

a) Rainfall Measurement

The distribution of rainfall in the U.P. Himalaya with respect to time and space is highly variable. In general, more than 80 per cent of the annual precipitation occurs during the monsoon period of three months i.e. from the middle of June to the middle of September. Most of the rainfall in the region is caused by the southwest monsoon. In general, the volume of rainfall gradually decreases as one moves from the southwest to the northeast.

To obtain satisfactory information on rainfall distribution within the study watershed, a network of nine standard and one recording raingauges was established at Fakot near the Bhaintan watershed (Fig. 3.7). The raingauges were

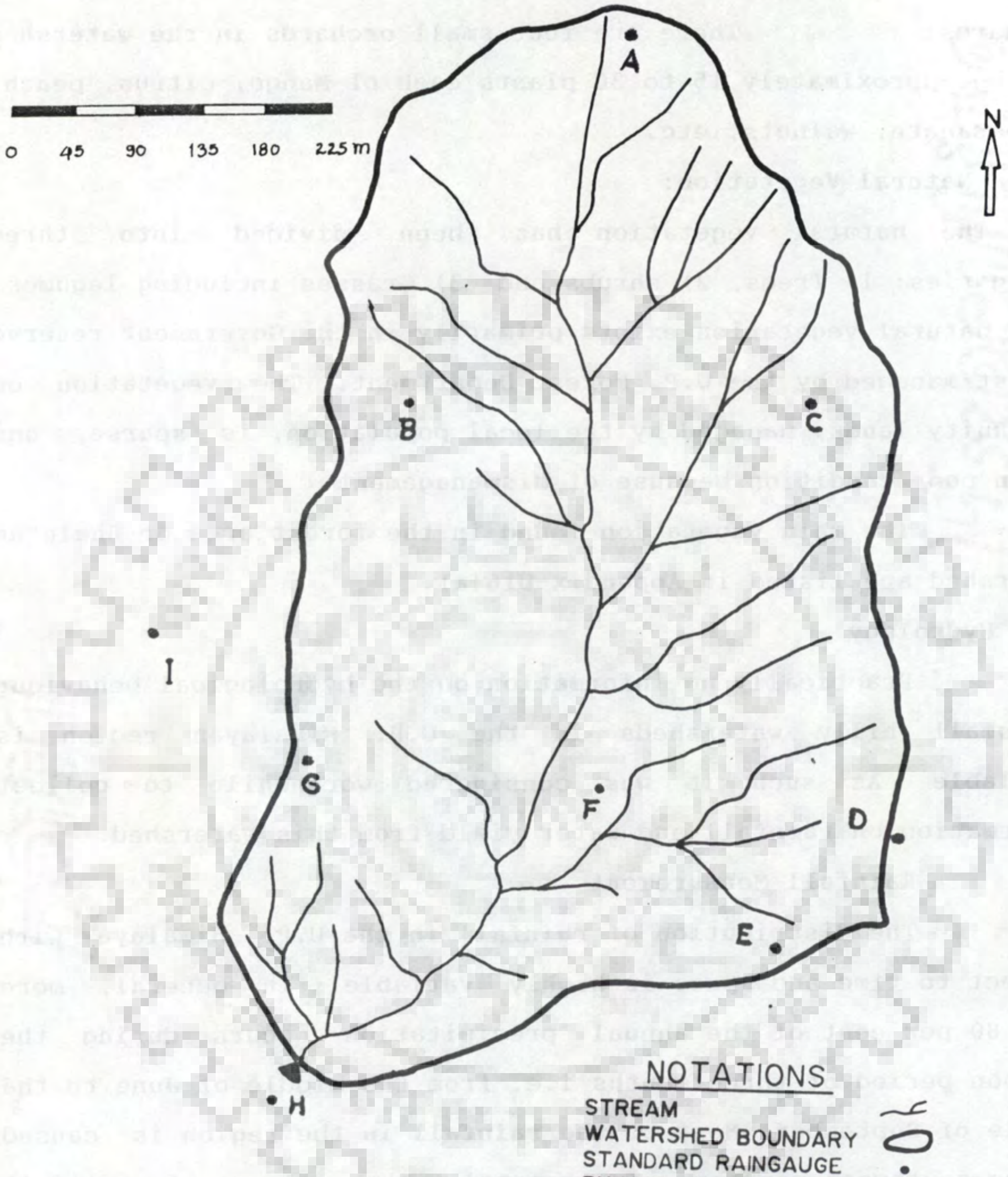


FIG.3.7-THE DRAINAGE MAP SHOWING LOCATIONS OF RAIN GAUGE SITES (BHAINTAN WATERSHED).

located to get a uniform distribution with respect to elevation, distance from valleys and ridges, operational efficiency, and safety of the gauges.

Average rainfall for the watershed was calculated by arithmetic average in addition to Thiessen polygon and Isohyetal methods for four water years. The difference between Arithmetic and Thiessen polygon method averages, was found to be in a range of $\pm$ 1.5 percent while difference between Arithmetic averages and Isohyetal method averages varied between $\pm$ 3.0 percent. Therefore, it was considered practical to use the Arithmetic average method for obtaining average rainfall of the watershed.

Katiyar (1982) analysed the rainfall data of 9 raingauges in the watershed through stepwise multiple regression and proposed the equations for the calculation of average annual monsoon season rainfall of the area.

b) Runoff Measurement

During the summer of 1979 a trapezoidal flume (Fig. 3.8) was constructed at Ghursera about 500 m upstream of Bhagori to gauge three subwatersheds totaling an area of 272 ha. The flume has a span of 6.4 m, length of 3.3 m and bottom width 0.4 m. The side slopes are 1:2.14 on either side of the central portion. The slope of the flume is kept at 4 per cent to avoid deposition of bed load which may adversely affect the stage-discharge relationship of the gauging structure.

8) Soil and Water Conservation Works Carried Out in the Watershed

The water has been diverted from the main drainage channel (or springs) to irrigate the fields. Old channels were repaired for about 1500m length and 573 m long new channels have been added. Where discharges of irrigation channels are lower, the water is stored in tanks before irrigating the fields. Two tanks

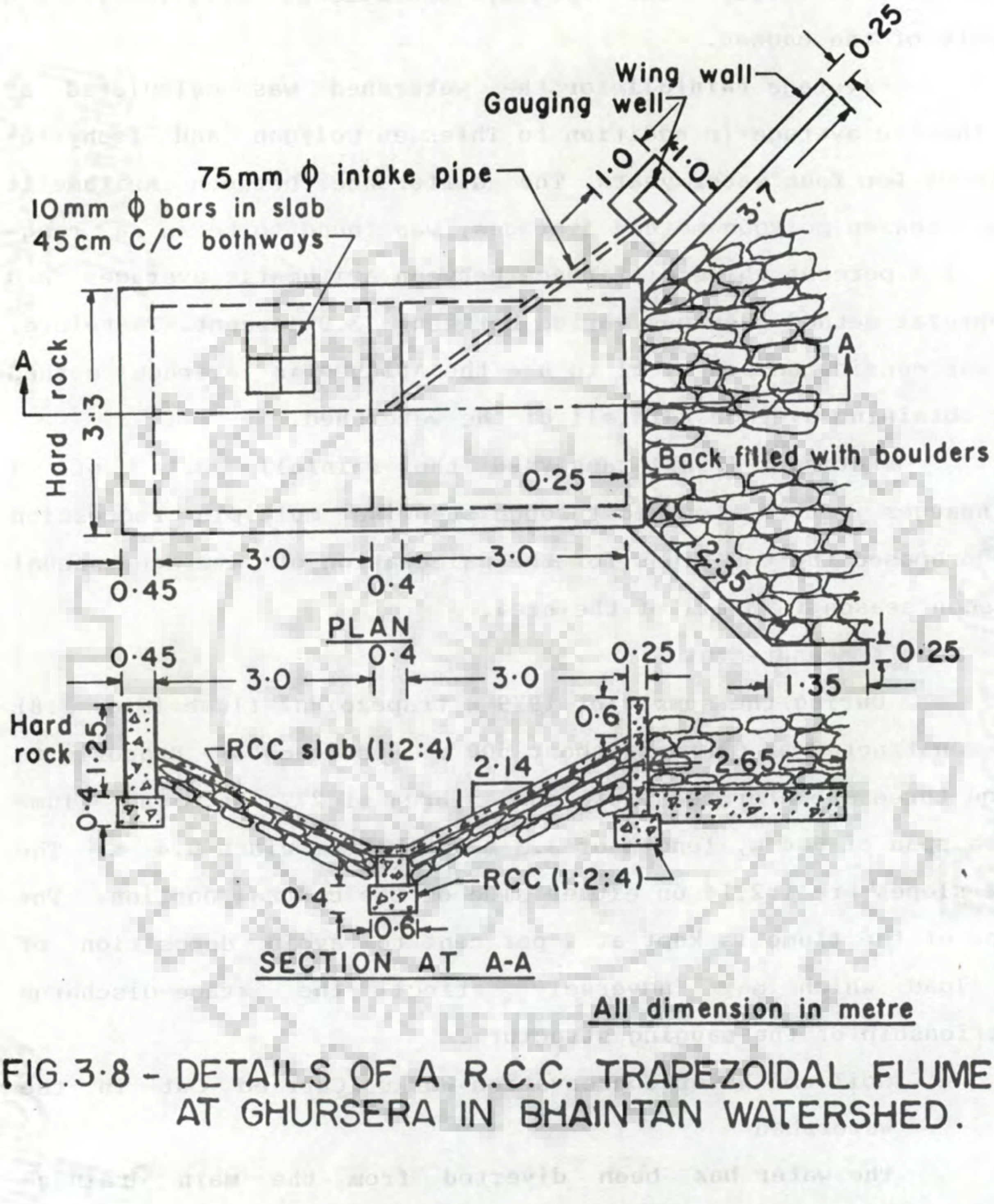


FIG.3·8 - DETAILS OF A R.C.C. TRAPEZOIDAL FLUME AT GHURSERA IN BHAINTAN WATERSHED.

were repaired and five new tanks of different sizes have been constructed for water storage.

Wherever water resources were developed terrace improvement and leveling became necessary. Stone risers with a top width of 40 cm and batter slope of 4:1 to 5:1 (V:H) were provided to the requisite height. The height of riser varied from 0.3 m to 2m.

Some landslides and landslips have been stabilised with the locally available material. Since the village trails cause extensive damage (i.e. due to concentration of runoff), these were treated for about 4.6 km of length with stone water diverters. Few gullies have been treated with loose boulder check dams, gabion check dams and vegetative checks.

For the improvement of community lands, and also to meet the demands of fuel and fodder, plantations on about 12 ha of community land was resorted to. About 6.0 ha area could be brought under tropical fruits like citrus (Galgal, Kagzi etc.), and mango (Dasehri, Langada etc.) and about 3.5 ha under temperate species (Viz apples, walnuts, plums and apricots).

3.2.2 Jhandoo-nala Watershed

The lime stone quarries at Mussoorie hills in Dehradun district are located on very steep hilly terrain. The open cast method of mining is resorted to quarry high grade limestone, having purity from 90 to 99 per cent. These mined areas (Photograph 3.1) are producing huge amount of debris including big sized boulders, chemical affluents and flash flows during monsoon season. No scientific study, worth to mention, has been carried out on the hydrological behavior of small mined steep hilly watershed. For the purpose of hydrological investigations in disturbed steep hilly watersheds, the Jhandoo-Nala watershed was selected. The abandoned mined watershed was producing sediment at the rate of 550 tonnes per hectare per year before treatment and was devoid of vegetation (Katiyar et al. 1987) as shown in Photograph 3.2.

1) Location

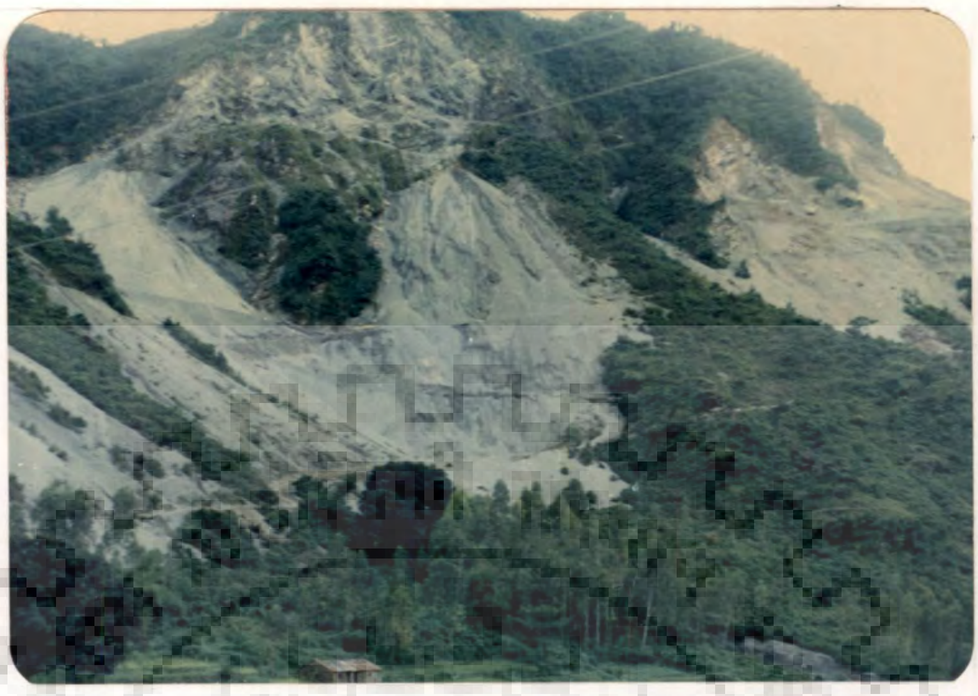
Jhandoo-Nala watershed is a subwatershed of Kharawan-Dhandaula mined watershed located near Sahastradhara, a tourist place in Dehradun district. Kharawan-Dhandaula watershed is 46 ha in area and has four subwatersheds. This watershed is located in between 32^{o} 23' to 32^{o} 23 1/2' N latitude and between 78^{o} 7 1/2' to 78^{o} 8' E longitude and at a distance of 14 km from Dehradun on Dehradun-Sahastradhara mettled road (Fig. 3.9). It is on the southern aspect of Outer/Lesser Himalaya. This watershed is surrounded by lime stone mines in the north, Baldi river in the south, sulphur spring in the east and U.P. Forest Department Outpost in the west.

2) Physiography

The Jhandoo-Nala watershed has an area of 17.7 hectares and ranges in elevation from 870 m to 1310 m with a relief of 440 m. Jhandoo-Nala runs from north to south giving the watershed an almost due north-south axis. Slopes average about 60 per cent for east aspects and 45 per cent for west aspects. There are no lakes or reservoirs located within the watershed. The watershed has an oblong shape (Fig. 3.10). The slopes are steep with an average slope of about 50 per cent. The area comprises of exposed cut rock surfaces, mine spoil deposits, landslide and gullies. The mine spoil/debris flows directly into Baldi river, which is a tributary of the river Ganges.

3) Climate

The watershed lies in subtropical zone (sub-tropical broad leafed hill forest).



PHOTOGRAPH 3.1- A view of ugly scars and debris on the steep hill slopes due to unscientific lime stone quarrying in Mussoorie hills.

PHOTOGRAPH 3.2- Jhandoo-Nala mined watershed devoid of vegetation before soil conservation treatment.

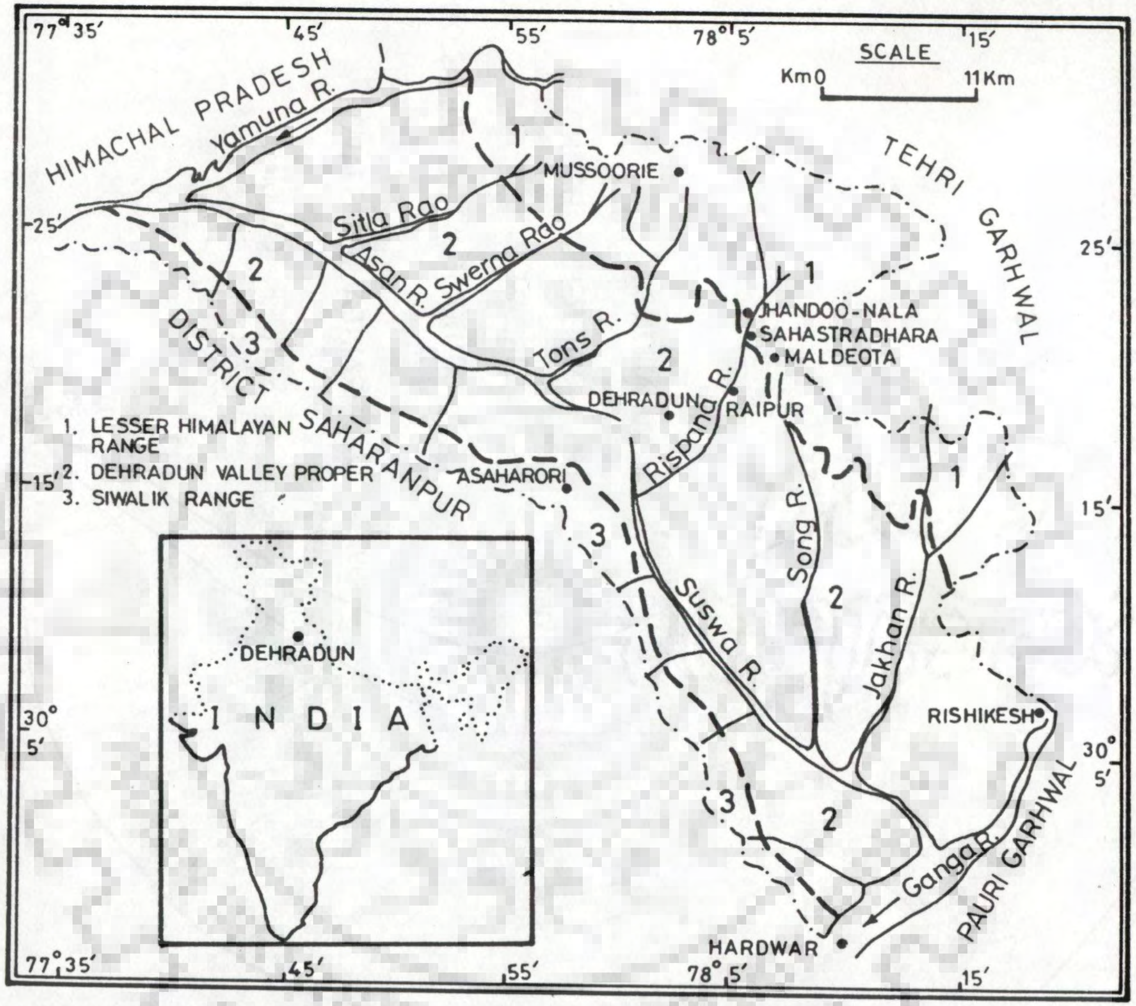


FIG. 3·9 – LOCATION MAP OF JHANDOO-NALA WATERSHED (AFTER JUYAL et al., 1995).

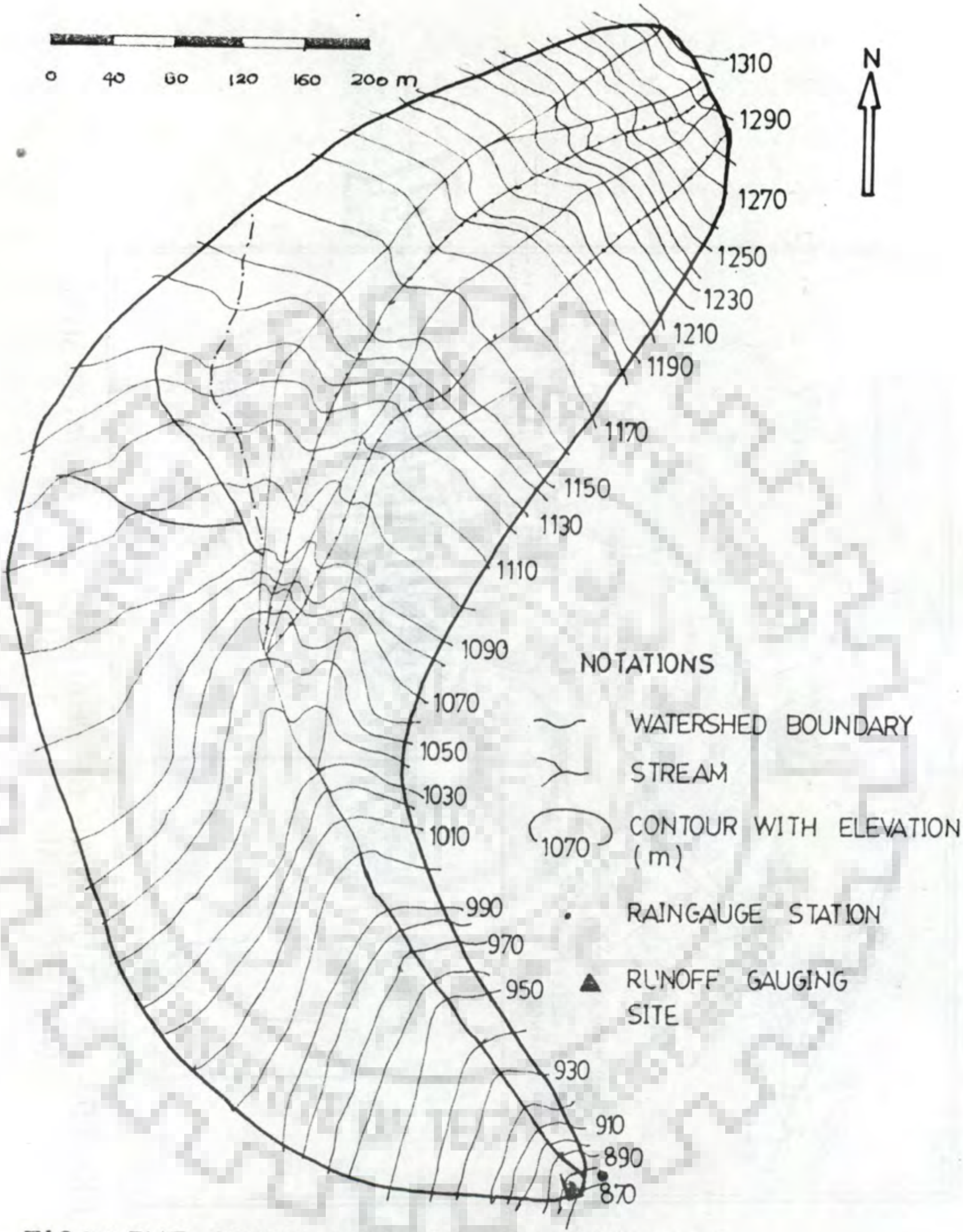


FIG.3.10-THE INDEX MAP OF JHANDOO NALA WATERSHED

a) Rainfall

Average rainfall recorded within the watershed from 1984-85 to 1993-94 (i.e. for 10 water years) works out to be 2624 mm. The monthly, annual and average rainfall for this period at Jhandoo-Nala watershed are given in Appendix-D13. Maximum rainfall intensities recorded for 5, 10, 15, 20, 30, 60, and 120 minutes were computed as 240, 180, 150, 132, 120, 110 and 80 mm/hr respectively (Appendix-D14). Average rainfall (50 years) of Rajpur meteorological observatory, which is 5 km away from Jhandoo-Nala watershed is 2968 mm with 97 rainy days (Appendix-D15).

About 88 per cent of rainfall is recorded during monsoon season. As per the meteorological data collected at Rajpur (Dehradun district) meteorological observatory, the month of May is the hottest month with average maximum temperature of 38.2°C. The months of December and January happen to be the coldest months with average monthly minimum temperature of 3.6°C.

The area is not windy as it is surrounded by high hills. The average wind velocity for different months ranges from 1.1 to 3.4 km/hr (Appendix-D15). Maximum average daily evaporation has been recorded during the months of May as 9.1 mm/day. Average daily sunshine hours have been recorded lowest in the month of July (3.4 hrs/day) and maximum in May (10.2 hrs/day). During the months of February and March occasional hail storms occur and cause extensive damage to vegetation. Mild frost occurs during the period December end to January end.

Normally no precipitation is received through snowfall in this watershed, but during severely cold days some stray patches of thin snow deposition are seen in the upper reaches of the watershed. Snowfall has got little or no impact on the hydrology of this watershed. Daily (24 hour) maximum rainfall was recorded as 369 mm on 12-13th August, 1986, which surpassed the past record of maximum daily rainfall recorded at Rajpur during the past 85 years (Katiyar et al., 1987).

4) Geology and Soils

The Krol formation from which lime stone is quarried, is the main rock formation of the watershed. It has been divided into five units, viz. A, B, C, D and E, where B and E units consist of red shales and A, C and D units comprise of limestone-dolomite-marble, clayey limestone sequences. The A unit is intercalated with chert. The C unit comprises of huge thick deposits of pure limestone mixed with dolomite and grading into marble at some places. Jhandoo-Nala watershed lies in C unit of Krol formation. The Chandpur phyllite/slate mainly consisting of grey, green, purple, maroon red and black coloured phyllites/slates present at the bottom of the rock sequence in the area(Fig. 3.11). Pink white to cream coloured, gritty quartzites overlie the Chandpur phyllites/slates in the rock sequence there. A horizon consisting mainly of boulders embedded in a thick matrix (i.e. Blaini boulder bed) overlies the Nagthat quartzite. In this boulder bed, unsorted and rounded fragments of limestone, quartzite and shale are embedded in clayey or sandy matrix. This boulder bed marks the Permo carboniferous glaciation (Negi, 1982).

The Main Boundary Thrust (M.B.T.) which separates the rocks of the pre-tertiary age from the tertiary age, is the major tectonic feature of the area. In this area, the Krol thrust coincides with M.B.T. The Mussoorie syncline is sandwiched between the M.B.T. in the south and Aglar fault in the north. The Mussoorie syncline has considerably weakened the country rocks.

Soils of the watershed vary from sandy loam to silty clay loam and are very gravelly (i.e. the gravel percentage varied from 30 to 90). Soils are very loose (porous) due to the use of dynamite explosions for mining of limestone. Some areas below the

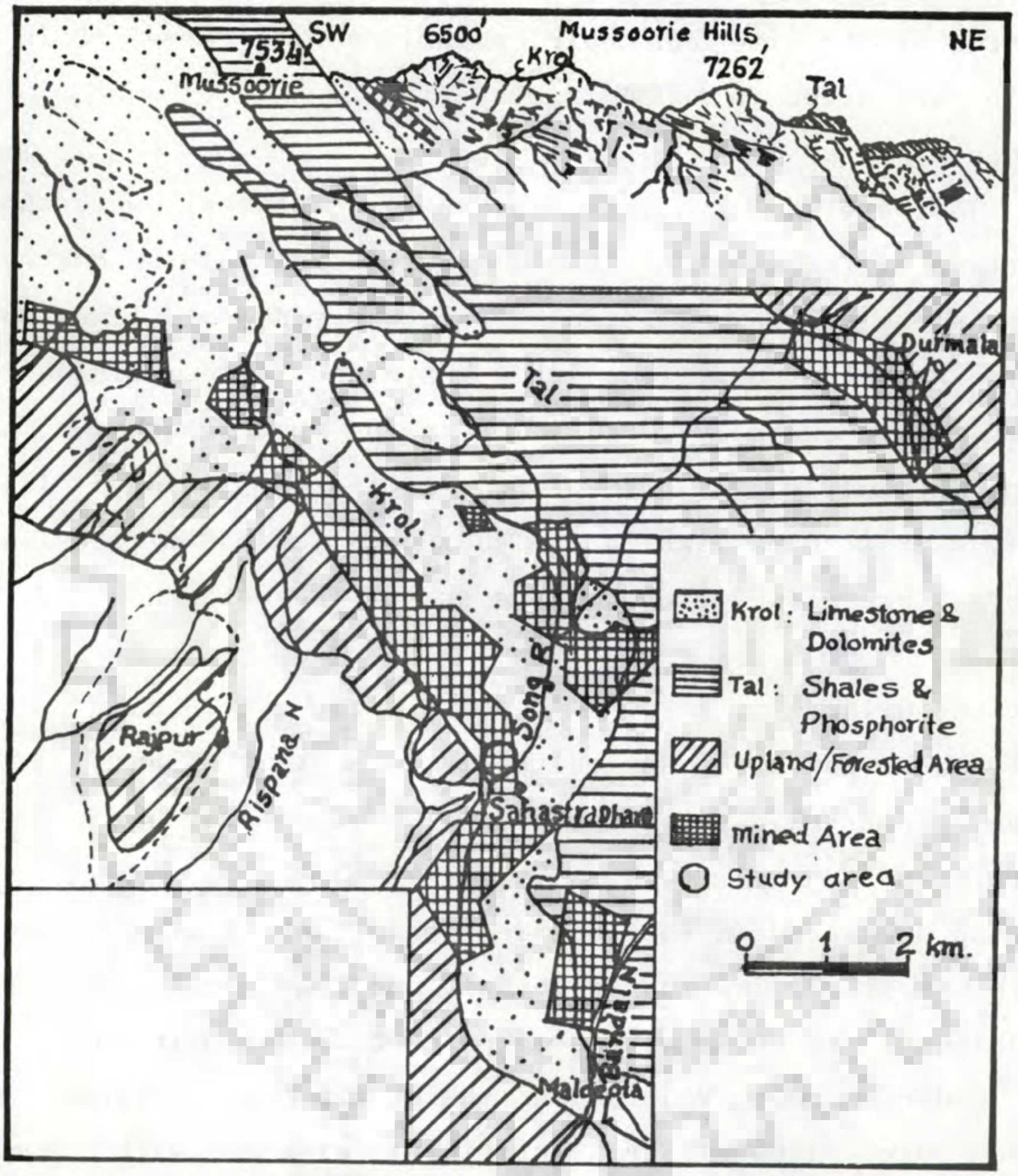


FIG. 3-11 GEOLOGY OF MINING AREAS IN MUSSOORIE HILLS SHOWING SAHASTRADHARA BLOCK WHICH COMPRISES JHANDOO-NALA WATERSHED. (AFTER ROY & ANANTHARAMAN, 1980)

mines, overlain by debris dumps and consisting of smaller size particles are also porous. Due to high infiltration rates, surface runoff is very little in the upper reaches which is affected by mining activity, but channels have flashy flows during intense rain events. The physico-chemical properties of the mine spoil/debris at the site and their comparison with normal soils in Doon Valley are given in Appendix-D12.

5) Land use

The watershed was predominantly a forest watershed. Major portion of the watershed was given on lease to M/s Northern India Lime stone company, Dehradun for quarrying of limestone. Forest area has been converted into wasteland after mining of limestone. Only one family is residing in the upper reaches of the watershed. The family owns 0.76 ha of cultivated, rainfed land, where only Kharif crops like Mandua, Jhingora (coarse millets) and Maize (corn) are grown. Present land use of the watershed is as follows :

i)	Cultivated land	0.76 ha
ii)	Waste land (unfit for agriculture)	8.35 ha
iii)	Scrub forest (thin to medium canopy)	8.60 ha

6) Vegetation :

As discussed in the earlier paragraph there is very little area under cultivation (0.76 ha), where coarse millets like Mandua, Jhingora are grown with some patches of Maize (corn).

Under forest vegetation there are two types of vegetation, viz. natural and artificial planted with human efforts. The details of vegetation found in Jhandoo-Nala watershed is given in Appendix-D16(b).

7) Hydrology

The Jhandoo-Nala watershed drains directly into the Baldi river. A trapezoidal flume has been constructed during

1986-87 with a span of 5.3 m and length of 4 m (Fig. 3.12). The width of central flat portion is 0.5 m and a bed slope of 3 per cent has been provided to make the flume self cleaning. Side slopes of flume, have been given as 1:5 (V:H) up to 1 m on either side of central flat portion. Beyond this sloping central portion, side slopes have been provided as 1:10 (Vertical:horizontal). The flume has been constructed with 1:2:4 RCC. The flume is connected to a stone masonry gauging well (Photograph 3.3), over which a stage level recorder is fitted to record the fluctuations in the channel stages.

A standard raingauge and a siphon type recording raingauge were installed near the outlet of the watershed. Since the area of the watershed is very small (17.71 ha), one recording and one non-recording raingauge were considered to be sufficient to gauge rainfall of the watershed. Reliable runoff data could not be obtained from 1986-87 to 1989-90 because the watershed was highly disturbed and debris flow used to choke the pipe-inlet to gauging well. After 1989-90 this disturbance was reduced to minimum because of soil conservation treatment.

8) Soil conservation treatment

The main drainage channel of the Jhandoo-Nala watershed was treated with grade stabilisation structures like gabion cross barriers (Photograph 3.4), silt detention basins, check dams etc. Attracting, repelling and sedimenting type of gabion spurs were also constructed to channelise the flow in desired direction and reach. Gabion toe walls were provided to prevent bank cutting where channel side slopes were steep and unstable (Katiyar et al. 1993).

Check dams and cross barriers were also combined with retaining walls on channel banks parallel to the water flow in order to prevent the scouring and undermining of the channel

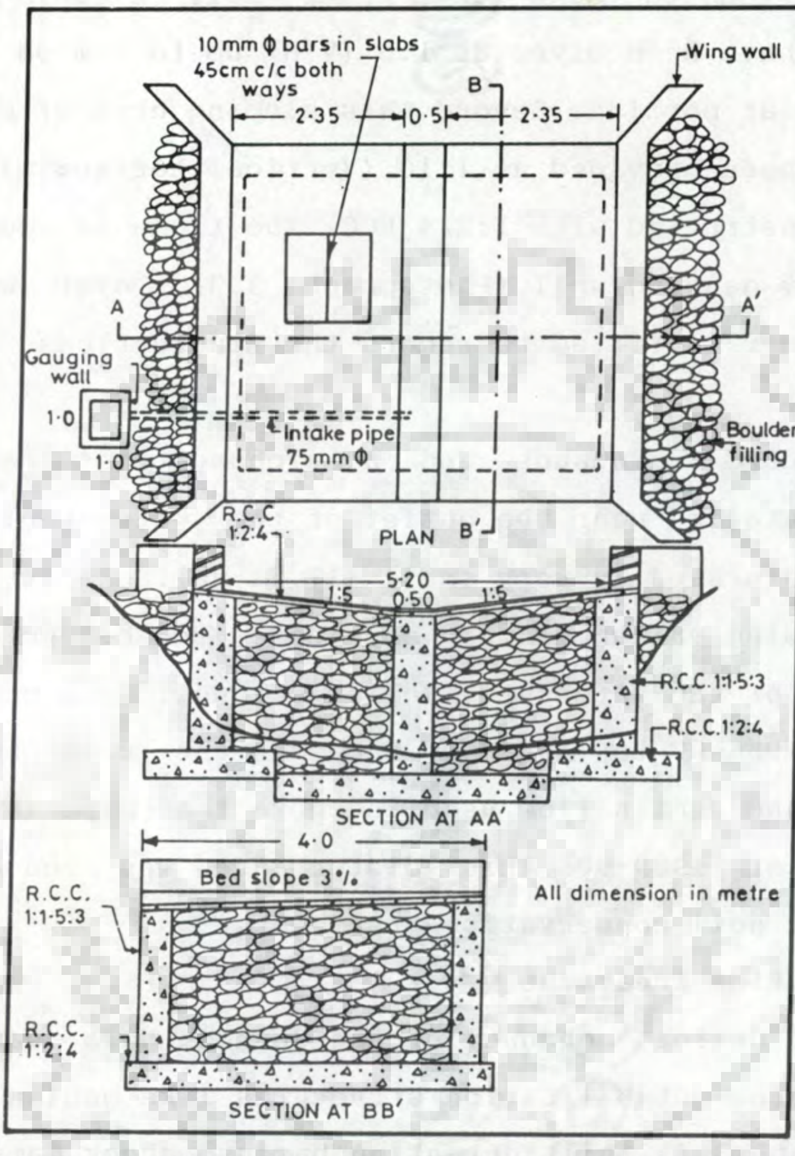


FIG.3·12- R.C.C. TRAPEZOIDAL FLUME CONSTRUCTED AT JHANDOO-NALA (NEAR DEHRADUN) (AFTER JUYAL et al.,1995)

PHOTOGRAPH 3.3- A view of the trapezoidal flume constructed at Jhandoo-Nala.

PHOTOGRAPH 3.4- Gabion structures in main drainage channel of Jhandoo-Nala watershed.

PHOTOGRAPH 3.5- A view of vegetation planted on the banks and bed of main drainage channel.

PHOTOGRAPH 3.6- Grass clumps planted between the loose rock filled check dams.

PHOTOGRAPH 3.7- Logwood crib structures filled with stones in the landslide area of Jhandoo-Nala watershed.

PHOTOGRAPH 3.8- Crib structures filled with brushwood on moderate slopes.

banks.

The drainage channel banks and beds were planted with the cuttings/root stock of Salix tetrasperma, Arundo donax, Ficus infectoria etc.(Photograph 3.5), and steeply sloping banks with Hybrid napier, Impomoea carnea, Eulaliopsis binata, Saccharum spontaneum etc.

The slope of the debris dumps has been eased out and benches have been formed at vertical interval of 10 m to 20 m according to the site condition. Continuous contour trenches have been dug on the benches. These trenches have been sown with seeds of Acacia catechu (Khair) and planted with Saccharum spontaneum, Arundo donax etc. Loose rock filled check dams have been constructed to plug the rills and small gullies on the mine haul roads and areas where water flow rarely occurs. Stumps of Lannea grandis, Erythrina suberosa, Ficus infectoria and grass clumps of Bhabhar (Eulaliopsis binata) have been planted near the loose rock filled check dams (Photograph 3.6). Water diversion structures in the form of low level stone cross barriers have been provided on the bends of mine haul roads so that water is diverted into natural drainage channel at different places along the road length and it does not concentrate on the road to cause soil erosion.

In the landslide affected areas, the average land slope is 70 per cent. To stabilize these areas, benches have been formed with the help of logwood crib structures filled with stones (Photograph 3.7). Benches formed with the help of these crib structures have been planted with different tree, shrub and grass species which were suitable for the area. Crib structures filled with brushwood were provided in the areas with lesser magnitude of slope and discharge (Photograph 3.8).

Geojute was tried to stabilise debris dumps/mine spoils in the abandoned lime stone quarry at five locations in four different slope groups (30-70 per cent) covering an area of 0.86 ha in the year 1988-89 (Juyal et al., 1991).

These soil conservation treatments have stabilised drainage channels and flows during summer months. Surface flows have been converted into subsurface flows to a great extent which resulted in lesser soil erosion. Debris dumps are almost stabilised and no more debris flow takes place from these dumps. Jhandoo-nala's main drainage channel, which used to go dry by November end is now a perennial stream. Peak discharges are much lower and better quality water flows during monsoon months (Photograph 3.9) as compared to before soil conservation treatment. Vegetative cover has improved from barely 10 per cent in 1984-85 to about 70 per cent (Photograph 3.10) in 1994-95 (Juyal et al., 1995).

3.3 AVAILABILITY OF DATA

In order to carry out the hydrological studies in steep hilly watersheds on proposed lines, one would require detailed data pertaining to rainfall, stream flows and watershed physiography.

For each of these factors, the requirement of data is given as under.

A. Morphometric, soils and vegetation data

i) Channel bed slopes at shorter space intervals i.e. each contour strip or grid or sub catchments etc.,

ii) overland slopes at shorter intervals,

iii) roughness of the main channel as well as of tributaries and overland planes,

iv) physical properties of soil e.g. initial and final infiltration rates, infiltration decay constant, water holding capacity, field capacity, saturated hydraulic conductivity, sorptivity etc. at different places in the

PHOTOGRAPH 3.9- Clear water flowing during monsoon after soil conservation treatment.

PHOTOGRAPH 3.10- Jhandoo-Nala watershed with good vegetation after soil conservation treatment.

watershed,

v) land use and type of vegetation at different places,

vi) water diversion for irrigation, drinking and other purposes,

vii) details of cross sections and gauging structure, alongwith the details of longitudinal sections of the main channel and tributaries, and

viii) details of urbanization and its development (if any), etc.

B. Meteorological and Hydrological Data Required

The following hydro-meteorological data is required for developing and testing of hydrological models on small mountainous watersheds.

i) Data of self recording raingauges at shorter time intervals for the storms under study, preferably at more than one station on the watershed,

ii) data of non-recording raingauges at different aspects and elevations of the watershed,

iii) stream stages at different sections of the main channel and tributaries,

iv) measured flow rates at shorter time intervals,

v) stage-discharge relationships at different stream gauging locations,

vi) inflow hydrograph data of tributaries at shorter time intervals,

vii) backwater data upstream of hydraulic structure (if any), and

viii) baseflow observations.

Mostly due to budgetary constraints, such elaborate data base as stated above remains non-existing in most of the developing countries. For that matter India is not an exception. However to some extent such detailed data of the type stated above and needed for development of event based models were available on two mountainous watersheds under discussion. Both the watersheds have been described in detail in previous section of this chapter.

3.3.1 Availability of data at Bhaintan Watershed for the present study

Bhaintan watershed is located in Tehri-Garhwal district on Rishikesh-Tehri State Highway. Following data were made available for the study.

i) The storm Rainfall Data

One recording raingauge is located at Fakot about 500 m away from Bhaintan watershed. Data for the five storm events could be obtained for the study. The rainfall data have been read from the available charts at 10 minutes time interval which has been reported in column (2) of Appendix-Cl. There are nine non-recording raingauges in the watershed. Monthly data of these gauges was available.

ii) Run Off Data

There are two runoff gauging station in Bhaintan watershed. The data of gauging station at Bhagori could not be used for modelling purpose as quantity of water diversion for irrigation upstream of it were not available. The runoff data of gauging station at Ghursera was considered for the modelling purpose. The charts of water stages for the storm events under consideration have been procured for the analysis. The runoff data recorded at the site were in the form of water stages at 10 minute interval which were converted into flow rates at outlet by using the stage-discharge table. The obsrved discharge rates of these five storm events are given in column (4) of Appendix-Cl.

3.3.2 Availability of Data at Jhandoo-Nala watershed for the present study.

As stated earlier the Jhandoo-Nala watershed is located in Dehradun district 14 km away from Dehradun on Dehradun-Sahastradhara road.

i) The Storm Rainfall Data

One recording raingauge and one non-recording raingauge are located near the outlet of the watershed. Data for 25 storm events could be obtained (i.e. from 1990 to 1993) for the study. The rainfall data have been read from the available charts at 10 minutes time intervals. Rainfall intensities have been calculated and are given in column (2) of Appendix-C2.

ii) The Runoff Data

There is only one runoff gauging site at the outlet of the watershed. The charts of runoff data for 25 storm events under consideration have been procured for the analysis. The runoff data recorded were in the form of stages charts which were read at 10 minutes interval and were converted into flow rates at the outlet by using state-discharge table. The observed runoff rates for the storm events under consideration are given in column (4) of Appendix-C2.

CHAPTER-IV

DESCRIPTION OF HYDROLOGIC MODELS FOR MOUNTAINOUS WATERSHEDS

4.1 INTRODUCTION

In mountainous regions, infiltration capacities are high because vegetation protects the soil from rain packing and dispersal. Also, because of supply of humus and the activity of micro fauna, an open soil structure is created. As described in Chapter-I, the soils of Himalayan watersheds are generally gravelly containing 20 upto 50 per cent gravels by volume. This is also responsible for high infiltration rates. Surface runoff is comparatively small as compared to subsurface runoff which consists of interflow and baseflow. Subsurface runoff has been found to continue for a pretty long time even after the rainstorms. In such cases, the models which transform the rainfall excess function into direct runoff serve limited purpose only. Also, since the separation of baseflow continues to be empirical, many times such models have been found to give approximate results on such watersheds.

In order to reach logical conclusions and to evolve suitable methodologies for runoff computations from mountainous watersheds, detailed studies have been carried out to verify the applicability of different models. Thus, the main objectives of the present study are to develop suitable rainfall-runoff simulation models using simpler approaches for surface hydrologic computations for small and steep hilly watersheds of Outer Himalayas. The following approaches have been tried on two such watersheds discussed in the earlier chapter. In order to suit the prevailing conditions, modifications to these approaches have been discussed and applied. The basis for such modifications are discussed in details. In general, these approaches may be classified as lumped and distributed in nature.

4.2 THE APPROACHES

Under lumped approach, the following two types of hydrologic models were tried.

i) Time-Area based models (i.e. temporally variable models) and

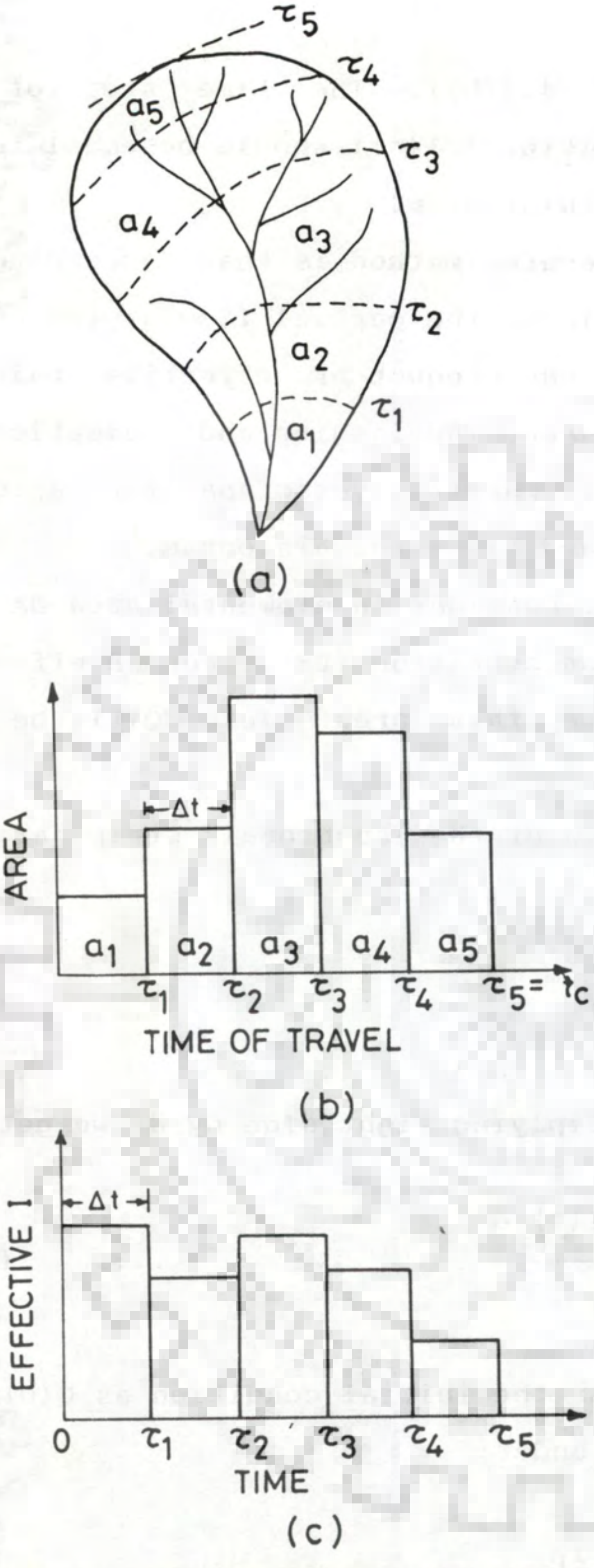
ii) Variable Source Area based models (i.e. spatially variable models)

Under distributed approach, Distributed Physiographic model was tried.

A brief description of these models alongwith the proposed modifications suited for Indian conditions of small Himalayan watersheds are discussed below.

4.2.1 Time-Area Based Model

Generally, the Time-Area concept is used for spatially lumped but temporally variable models. The time-area method of hydrologic routing transforms an effective rainfall hyetograph into a direct runoff hydrograph. Unlike the rational method, the time-area method can account for the temporal variation of rainfall intensities. The time-area methodology is based on the concept of time-area histogram (i.e. a histogram of contributing catchment subareas). To develop a time-area histogram the time of concentration of the catchment is divided into a number of equal time intervals. Cumulative time at the end of each time interval is used to divide the catchment into zones delineated by isochrones. Isochrones are the loci of points of equal travel time to the catchment outlet. The catchment subareas delineated by isochrones (Fig. 4.1(a)) are measured and plotted in the form of a



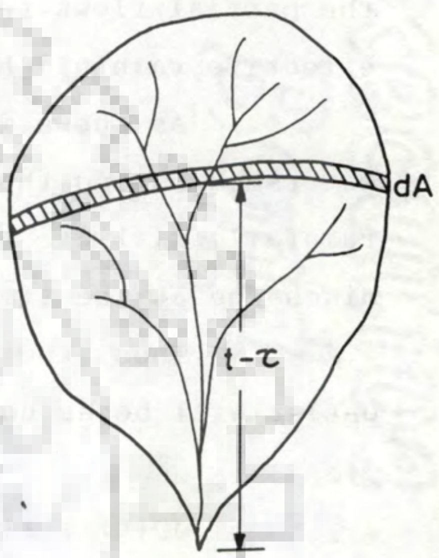


FIG.4·2- A TYPICAL WATERSHED

FIG. 4·1 - TIME AREA METHOD. (a) WATERSHED DECOMPOSITION BY ISOCHRONES, (b) TA HISTOGRAM AND (c) EFFECTIVE RAINFALL HYETOGRAPH histogram as shown in (Fig. 4.1(b)). The time step of the effective rainfall hyetograph (Fig. 4.1(c)) should be equal to the time interval of the time-area histogram.

The basis of the time-area method is that according to the runoff concentration principle, the partial flow at the end of each time interval is equal to the product of effective rainfall intensity and contributing subarea. The lagging and summation of the partial flows result in a runoff hydrograph for a given effective rainfall hyetograph and time-area histogram.

As shown in Fig. 4.2, consider an elemental area dA of a watershed having the time of concentration $(t-\tau)$. For an effective rainfall, $I(\tau)$ at time τ over this area, let $dQ(t)$ be the discharge at the time t.

Thus, the contribution of the isochronal strip at the outlet will be as under:

$$dQ(t) = I(\tau)\ dA\ (t-\tau) \qquad \ldots. \quad (4.1)$$

Now dividing and multiplying right side by $d\tau$ we get

$$dQ(t) = \frac{dA(t-\tau)\ I(\tau)\ d\tau}{d\tau} \qquad \ldots. \quad (4.2)$$

On integration and for the initial condition as $Q(0)=0$; the discharge $Q(t)$ is given as under:

$$Q(t) = \int_0^t \frac{dA\ (t-\tau)}{d\tau}\ I(\tau)\ d(\tau) \qquad \ldots. \quad (4.3)$$

Thus, discretised runoff hydrograph ordinates can also be expressed as under:

$$Q(j) = \sum_{i=1}^{nar} A(i)\ I(j-i+1) \qquad \ldots (4.4)$$

Where A(i) is the area enclosed within the i^{th} and $(i+1)^{th}$ isochrones,

nar represents number of time areas in a catchment,

$I_{(j)}$ is the intensity of rainfall excess during the j^{th} time step, and Q(j) is the discharge rate during the j^{th} time step.

Equation (4.4) is a discrete convolution of I and A.

4.2.2 Rainfall Excess Computations

The time distribution of rainfall excess was computed using the following two methods:

i) The conventional approach of ϕ-index method, and

ii) the infiltration approach based on modified Horton's model, using the variable rainfall infiltration approach (discussed in detail in Chapter-II under section 2.7.1).

The former is simpler in application. It suffers from the limitation that for high intensity rainfalls under dry conditions of the watershed, the model over estimates the rainfall excess in the earlier part whereas it under estimates in the same during the later part of the storm.

4.2.3 Merits

While the time-area method accounts for runoff concentration only, it has the advantage that the catchment shape is reflected in the time-area histogram, and thereby in the runoff hydrograph as well. This method is very simple and convenient as it requires rainfall intensity hyetograph and time-area histogram and does not require parameter optimization or sensitivity analysis.

4.2.4 Assumption and Limitations

The fundamental assumption in the time-area method is one of translation. It allows for the delay experienced by water in reaching the catchment outlet. In the conventional time-area method, only the translation effects are taken into account. Therefore, hydrographs calculated with this method often show lack of diffusion, resulting in higher peaks than the observed (Mathur, 1972). These methods may yield acceptable results for small watersheds where storage effects are minimal (Singh, 1988).

As discussed in section 5.1, the usefulness of this approach will depend on correct estimation of the time of concentration of the watershed.

In small watersheds rainfall distribution is generally assumed uniform. But in small disturbed watersheds the generation of excess rainfall, within the isochronal strip, is not uniform for the same gross rainfall. Hence, in the disturbed watershed, the Time-Area based models may not yield excellent simulation results.

4.2.5 Computer programmes

The computer programme for Time-Area based model has been developed in FORTRAN-4 and is given in Appendix-A1. The computer programme also includes three subroutines viz. EXR, OBJECT and INFILT. Its input data file is given in Appendix-B1.

4.3 VARIABLE SOURCE AREA MODEL (Variable Space Model)

As discussed in Chapter-I, the soils of hilly watersheds are open structured (gravelly), and have high humus content. In such watersheds natural soil pipes formed due to animal burrows, root holes etc. can significantly change the response as compared to what would have been expected from an uniform watershed in the lowland plains. It has also been observed that as a result of this the duration of recession limbs of hydrographs is much more for most of the storm events.

Many researchers in the field of hillslope hydrology like Betson and Marius (1969), Dunne and Black (1970) and Corbett (1979) etc. have observed in their field investigations that overland flow does not occur uniformly over a watershed as originally thought. This brought about the development of the concept of partial 'source area', or that of the 'variable source' area. A 'source area' is that part of the watershed where precipitation is converted to runoff (Sloan et al., 1983). These source areas are often near the drainage channels and quickly become 'saturated' during rainfall events. Physiographically these may be saturated areas (wet lands) with shallow water tables that rise after they are fed through infiltration and subsurface flows. As the water table rises, the zone of saturation moves upward i.e. towards the loose and permeable surface layers. Thus, the contributing area keeps expanding. This concept is named as the 'variable source area' concept. The field studies conducted by Dunne and Black (1970) provided sufficient evidence in favour of the variable source area concept.

It has been reported that in mountainous river reaches where subsurface flows form the major part of the total volume, the peak discharge receive the major contributions through the precipitation which falls in the immediate vicinity of the two banks (Hewlett and Nutter, 1970).

Sloan et al. (1983) developed a daily model for predicting the runoff from small Appalachian watersheds using the concept of Variable Source Area. Such a conceptual lumped parameter model is schematically illustrated in Fig. 4.3. A watershed is assumed to have a series of interconnected water storages with inflow and outflow representing the actual physical processes. These processes are described in the following section

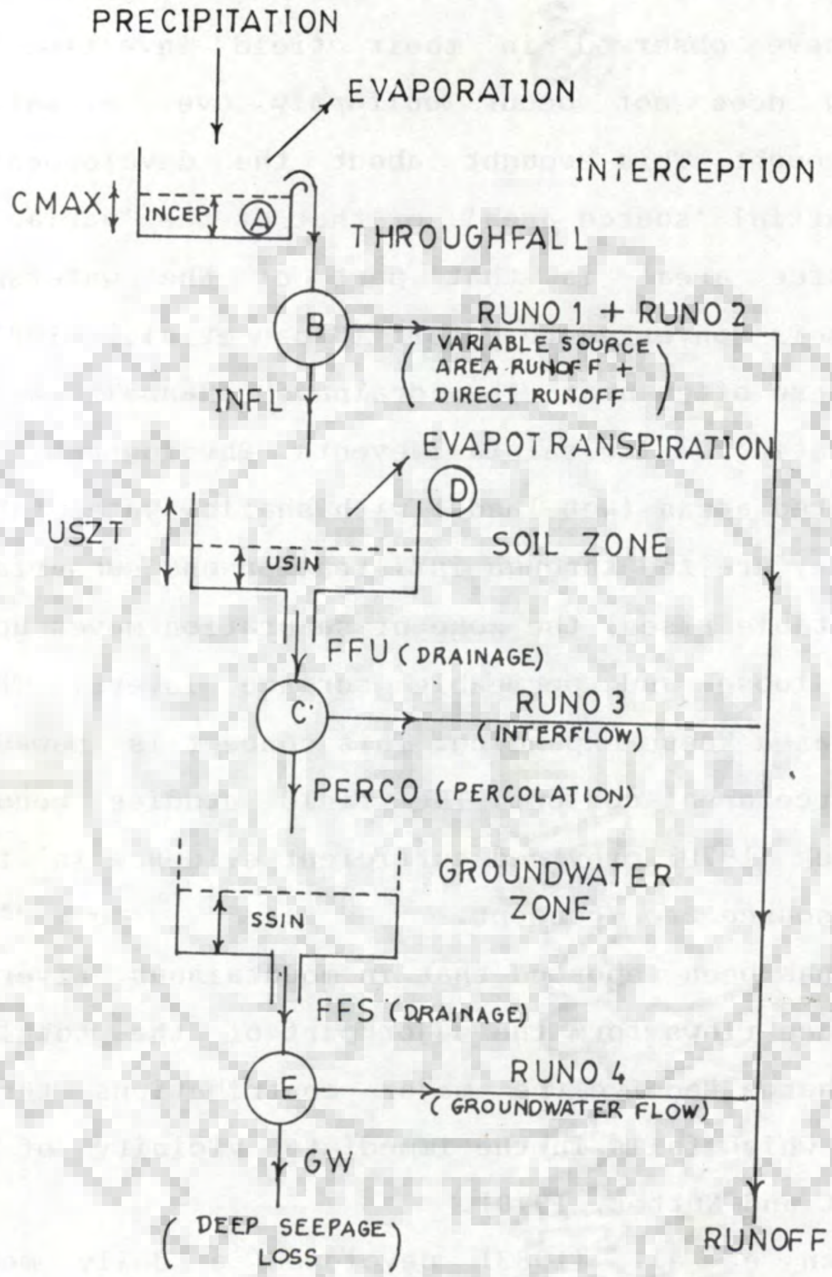


FIG. 4.3 - SCHEMATIC FLOW DIAGRAM OF THE DAILY WATERSHED MODEL
(After Sloan et al., 1983)

(4.3.1) using both physically and empirically based equations. This daily watershed model is developed utilizing the concepts of three models viz. the model proposed by Boughton (Boughton, 1966), the MONASH model (Porter and McMahon, 1971, 1976) and the BROOK model (Federer and Lash, 1978, Federer, 1982). The model is based on the Variable Source Area concept as proposed by Hewlett and Nutter (1970) and further extended by Jones (1979). According to this approach the quick flows to a drainage channel are contributed mainly by a fraction of the watershed area which gets saturated due to continuous rainfall. This contributing area keeps expanding or contracting, depending upon the soil moisture conditions of the watershed.

The model consists of three water storage zones, namely the Interception Zone, the Soil Zone, and the Groundwater Zone. The model has thirteen parameters and one 'Function' (FCAN). The model is suitable for non-snow fed catchments as it does not account for the snow melt runoff.

4.3.1 Mathematical Formulation

The various hydrological processes involved in different zones referred to above have been simulated through mathematical equations as discussed underneath.

a) Interception

At any time the actual capacity of the interception storage (CMAX) is a function of the maximum interception storage (CEPMAX) and the degree of canopy development (FCAN). The parameter CEPMAX depends on the type of vegetation. It is taken care of by the maximum leaf-area indices as well as by the stem-area indices. The function FCAN depends on the annual canopy growth characteristics and on the stem-area index. Evaporation from the interception storage is assumed to occur at the potential rate. Thus, the following three relationships take care of the interception process.

$$CMAX = CEPMAX * FCAN \quad .... \quad (4.5)$$

$$INCEP = PPT \quad (\text{ if } PPT < CMAX) \quad .... \quad (4.6)$$

$$INCEP = CMAX \quad (\text{if } PPT > CMAX) \quad .... \quad (4.7)$$

where, the notations as given below refer to daily values.

CMAX = actual interception capacity (mm)

CEPMAX = maximum interception capacity (mm)

INCEP = actual interception (mm)

PPT = precipitation (mm)

FCAN = canopy development function which modifies CEPMAX for time of year

b) Through fall

It is that part of precipitation which contributes towards infiltration and runoff from the saturated source areas. It is equal to precipitation minus actual interception and is expressed as under.

$$RFALL1 = PPT - INCEP \quad .... \quad (4.8)$$

Where, RFALL1 is throughfall or precipitation minus interception (mm)

c) **Source Area (or Saturated Area) Runoff**

The size of the saturated source area expands exponentially as the water content increases in the soil zone (i.e. as USIN increases). This source area includes the stream area (PCAR) and the saturated zones in the vicinity of stream. It may expand (or contract) depending on precipitation. The extent of variable source area (or saturated area) is computed by the empirical equation proposed by Federer and Lash (1978) and is expressed as under.

$$PA = SC * e^{SAC\ (USIN/USZT)} \quad \ldots\ldots \quad (4.9)$$

$$RUNO1 = PA * RFALL1 \quad \ldots\ldots \quad (4.10)$$

Where,

SAC	=	source area exponent,
SC	=	source area coefficient,
USZT	=	maximum amount of water that can be stored in soil profile (mm),
PA	=	extent of saturated area as fraction of watershed area excluding PCAR,
PCAR	=	fraction of area always contributing to direct runoff,
USIN	=	actual water volume in upper soil zone (mm), and
SSIN	=	actual water volume in groundwater storage (mm).
RUNO1	=	source area (or saturated area) runoff.

Thus, the source area runoff is part of surface runoff (i.e. the overland flow on saturated areas).

d) Channel Precipitation It is the precipitation falling directly over the water surface of drainage channels. Thus the magnitude of this portion of surface runoff is given as under:

$$RUNO2 = PCAR * RFALL1 \quad \ldots\ldots \quad (4.11)$$

Where RUNO2 =amount of precipitation falling directly over the water surface of drainage channels.

e) Infiltration

If overland flow from saturated source area (RUNO1) and channel precipitation (RUNO2) are subtracted from the throughfall (RFALL1), the remainder represents the infiltration into the soil zone. Infiltration rates in steep sloped forested mountainous watersheds are generally very high. These rates have been assumed to be infinite as traditional Hortonian (Horton, 1933) infiltration rarely occurs (Sloan et al. 1983). Infiltration is computed by using the relationships given below.

$$PB = PA + PCAR \quad .... \quad (4.12)$$

$$INFL = (1-PB) * RFALL1 \quad .... \quad (4.13)$$

Where,

PB = fraction of watershed area contributing surface runoff in the form of RUNO1 and RUNO2 and

INFL = infiltration (mm) into the ground.

f) Drainage From the Soil Zone

Drainage from the soil depends on its moisture content (USIN). It is assumed to increase exponentially as the moisture content increases. The relationship for the drainage from the soil zone is thus defined as under.

$$FFU = FU * (USIN/USZT)^{KU} \quad .... \quad (4.14)$$

where,

FFU = drainage from upper soil zone (mm),

FU	=	soil water conductivity coefficient and
KU	=	soil water conductivity exponent.

g) **Interflow (Lateral through flow) and Percolation**

The water draining from the soil zone gets divided into two components i.e. the interflow (or lateral through flow) and percolation to the groundwater. Interflow is computed by the following relationship.

$$RUNO3 = FFU * K1 \quad .... \quad (4.15)$$

Where,

K1 is fraction of soil zone drainage becoming interflow and

RUNO3 is interflow (mm).

Percolation (PERCO)

Percolation is the vertical drainage to groundwater from the soil zone. It is taken care of by the following relationship.

$$PERCO = FFU * (1-K1) \quad .... \quad (4.16)$$

h) Evapotranspiration

Actual evapotranspiration from the Soil Zone can have a maximum value equal to the potential evapotranspiration. Otherwise it will be a function of the available water (USIN-USWP). The following four relationships take care of the evapotranspiration function.

$$AEVAP1 = INCEP \quad .... \quad (4.17)$$

$$AEVAP2 = EVAP* (USIN - USWP)/(USZT-USWP) \quad .... \quad (4.18)$$

$$EVPT = INCEP + AEVAP2, \quad \text{if } EVPT < EVAP \quad .... \quad (4.19)$$

$$EVPT = EVAP, \quad \text{if } EVPT > EVAP \quad .... \quad (4.20)$$

Where,

EVAP = potential evapotranspiration,

EVPT = actual evapotranspiration,

AEVAP1 = evaporation from the canopy and

AEVAP2 = evaporation from the soil.

i) Groundwater Storage

The groundwater storage receives water through percolation from the Soil Zone.

$$FFS = FS * (SSIN)^{KS} \quad .... \quad (4.21)$$

Where,

FFS = drainage to groundwater,

FS = groundwater recession coefficient and

KS = groundwater recession exponent.

j) Groundwater Contribution to runoff and deep seepage losses

Drainage to groundwater is divided into baseflow and deep seepage losses. The relationships are given as under.

$$RUNO4 = FFS * K2 \quad .... \quad (4.22)$$

Where

K2 = fraction of groundwater drainage becoming baseflow and

RUNO4 = groundwater flow

k) Deep Seepage loss

$$GW = (1-K2) * FFS \quad .... \quad (4.23)$$

Where

GW = Deep seepage loss or groundwater recharge

l) Surface runoff = RUNO1 + RUNO2 .... (4.24)

m) Subsurface runoff = RUNO3 + RUNO4 .... (4.25)

n) Total runoff = RUNO1 + RUNO2 + RUNO3 + RUNO4 .... (4.26)

4.3.2 Proposed modifications

The daily model developed by Sloan et al. (1983) has been modified in the following ways.

(i) The daily simulation model has been converted into an event based simulation model.

(ii) The interception and evapotranspiration losses have not been taken into consideration.

(iii) The depletion of soil zone and groundwater zone have been limited to field capacity only.

This is to mention that Putty and Rama Prasad (1992) modified the equation 4.9 to express the extent of variable source area as a function of actual water content in soil zone as well as the ground water storage. This was invariance to the model proposed by Sloan et al. 1983; in which the actual water content was considered in the upper soil zone only. Thus the equation as modified by Putty and Rama Prasad (1992) is given as under.

$$PA = SC\, e^{SAC\,(K3*USIN+K4*SSIN)/CSMAX} \quad .... \quad (4.27)$$

This equation was further modified in this study. The parameter CSMAX is replaced by USZT. Thus the modified relationship is given as under.

$$PA = SC\, e^{SAC\ (K3*USIN+K4*SSIN)/USZT} \quad .... \quad (4.28)$$

The above relationship reduces one parameter. As mentioned above, the depletion of soil moisture in soil zone and the groundwater zone is limited to field capacity only. Thus drainage from upper soil zone (FFU) and drainage to groundwater (FFS) are computed by the following modified equations.

$$FFU = FU * (USIN-USFC)/USZT^{KU} \quad .... \quad (4.29)$$

$$FFS = FS * (SSIN-USFC)/USZT)^{KS} \quad .... \quad (4.30)$$

Accordingly, the modified conceptual parameter model so proposed is schematically illustrated in Fig.4.4.

Because of the proposed modifications, the modified model has the capability of its application to actual time steps which may be much smaller in duration. The application of proposed model onto the two small Himalayan watersheds, namely Bhaintan and Jhandoo-Nala watersheds is given in the next chapter.

In the above mentioned relationship the following notations have been used.

CSMAX = sum of maximum soil zone and groundwater storages

K3 = fraction of upper zone storage contribution to expansion of source area

K4 = fraction of ground zone storage contributing to expansion of source area

Other parameters have been defined earlier in section 4.3.1.

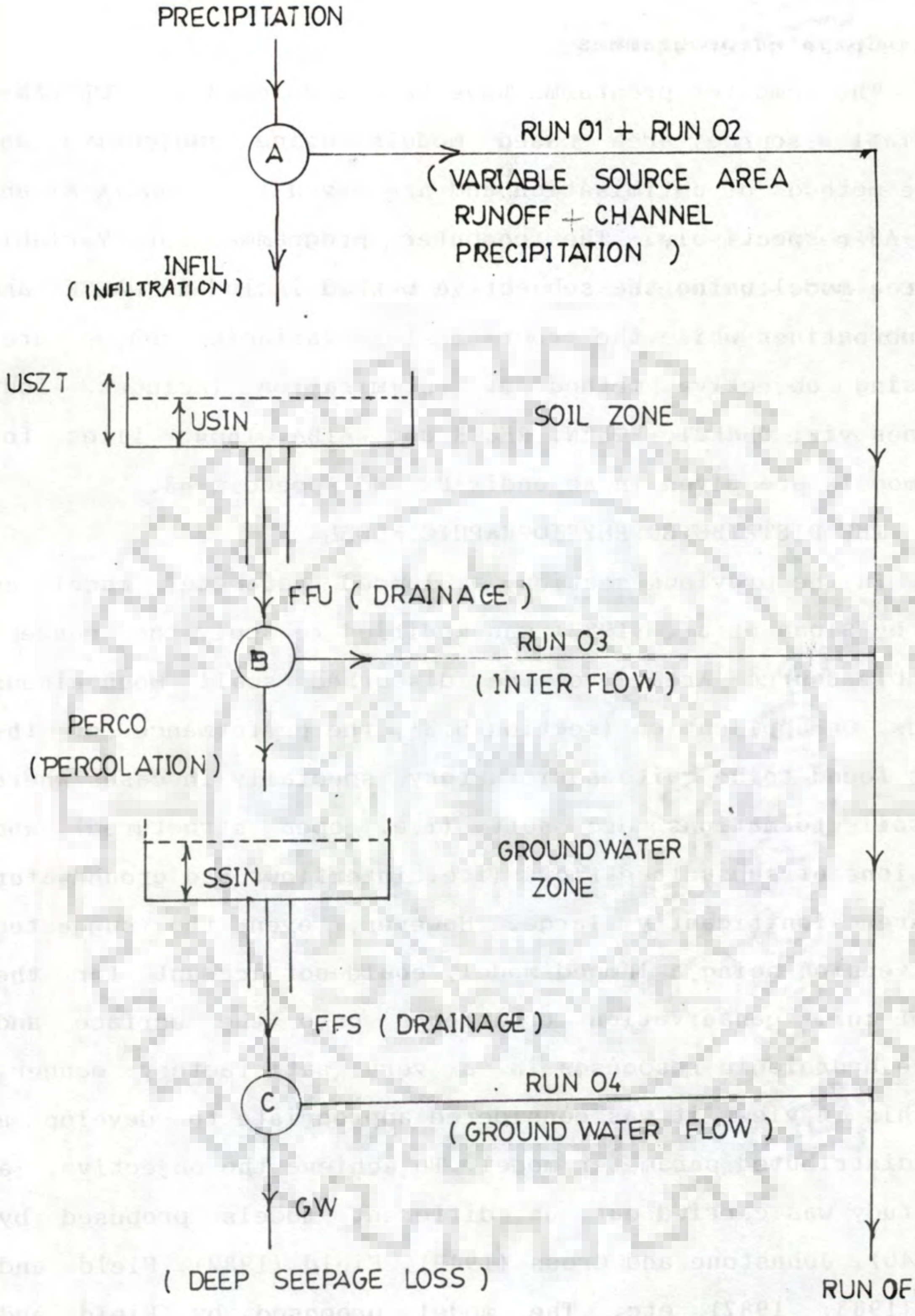


FIG. 4.4 - SCHEMATIC FLOW DIAGRAM OF THE EVENT BASED VARIABLE SOURCE AREA MODEL.

4.3.3 Computer programmes

The computer programme have been developed in FORTRAN-4 for Variable source area based models using subjective and objective methods of optimisation and are given in Appendix-A2 and Appendix-A3 respectively. The computer programme for Variable source area model using the subjective method includes WATER and OBJECT subroutines while the programme for Variable source area model using objective method of optimisation includes four subroutines viz. OBJECT, ROSEN, RESTR and WATBA. Input files for the two models are given in Appendix-B2 and Appendix-B3.

4.4 THE DISTRIBUTED PHYSIOGRAPHIC MODEL

In the previous section, a lumped parameter model as proposed by Sloan et al. (1983) was modified to apply the concept of `Variable Source Area' to the disturbed small mountainous watersheds. On application (section 5.3), the performance of the model was found to be quite satisfactory, specially in cases where the top soil formations are soft (i.e. open structured) and contributions of subsurface flows (i.e. interflows and groundwater flows) are significantly large. However, even the suggested modified version being a lumped model, could not account for the effects of soil conservation treatments onto the surface and subsurface hydrologic responses in a very satisfactory manner. Keeping this in view, it was considered appropriate to develop a suitable distributed parameter model. To achieve the objective, a careful study was carried out on different models proposed by Clark (1945), Johnstone and Cross (1949), Field (1982), Field and Williams (1983, 1987) etc. The model proposed by Field and Williams (1987) was considered most appropriate because the same had been applied by them with success onto the high sloped watershed also. In the forthcoming sections, a modified version of this model is being proposed.

4.4.1 Proposed Distributed Parameter Physiographic Model Configuration Consisting of Tributary And Main Channel Subwatersheds

Field and Williams (1987) divided the watershed into different subwatersheds keeping in view the surface drainage characteristics. The same concept has been used by a number of other researchers as well (Laurenson, 1964; Chander, 1970; Mathur, 1974; Shahri, 1993 etc.). However, it was realised that a micro level detailing is needed for the watershed management practices which are essentially needed for controlling the stream behaviour in disturbed watersheds.

In the present study, as shown in Fig. 4.5(a) the watershed is divided into subwatersheds of various tributaries (viz., TSWi where, i = 1, 2, 3, ... n). However, a considerable watershed area all along the main channel is left out and this remains to be accounted for. These (main channel subwatersheds) are represented by MCSWi, (where i = 1, 2, 3.... n). It was found that the hydrologic characteristics of the main channel subwatersheds are different from the tributary subwatersheds. The runoff mechanics for the watershed of Fig. 4.5(a) is shown in Fig. 4.5(b).

4.4.2 Design of the Tributary and the Main Channel Subwatershed Elements

Each tributary and main channel subwatershed is conceptually represented with the help of two nonlinear reservoirs. The 'upper' nonlinear reservoir represents the surface storages and surface flows whereas the lower one accounts for the subsurface runoff. This is in contrary to the model of Field and Williams (1987) where a linear reservoir was used for subsurface flow computations. Thus, in Fig. 4.6 the conceptual representations for the main channel subwatersheds MCSW1 and

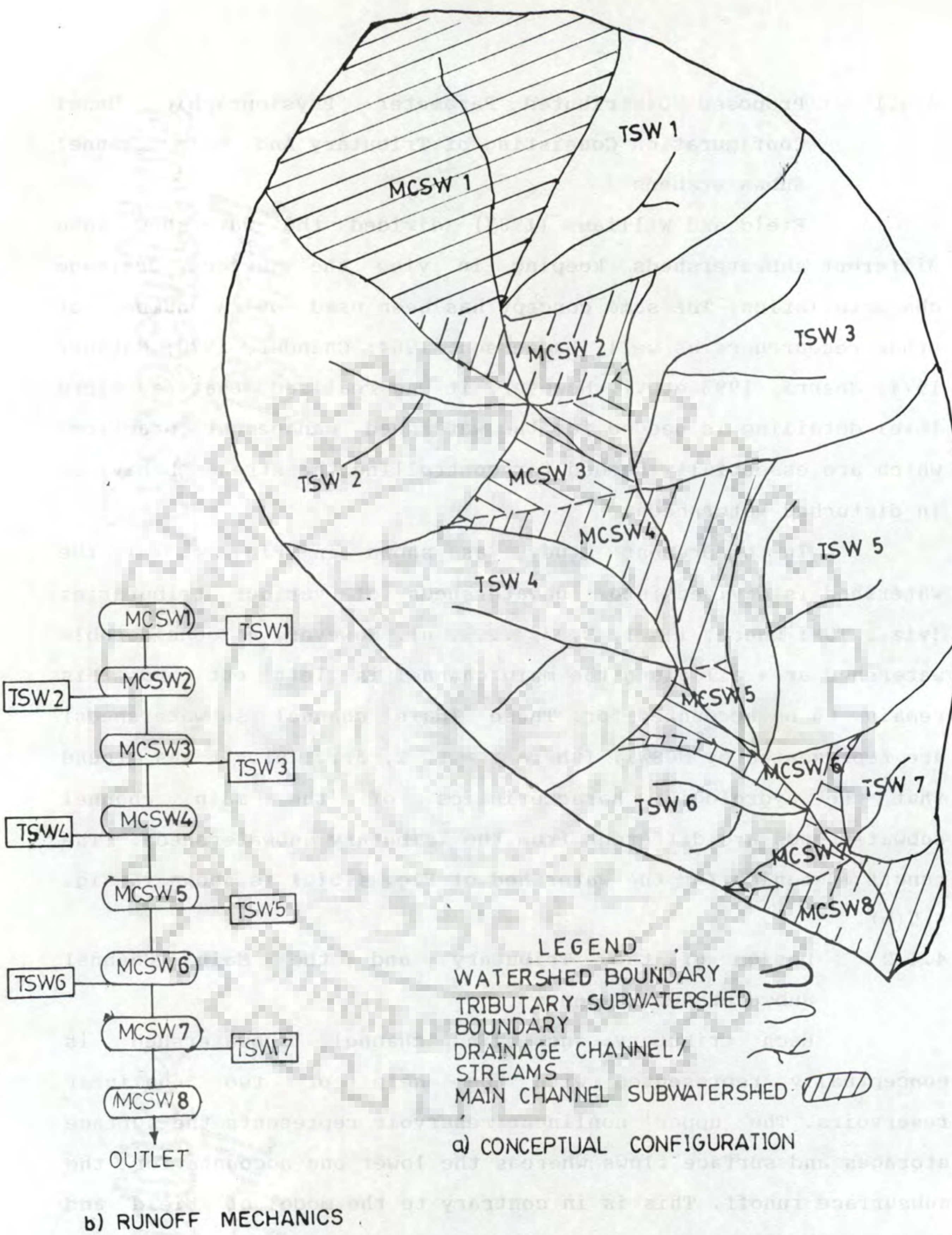
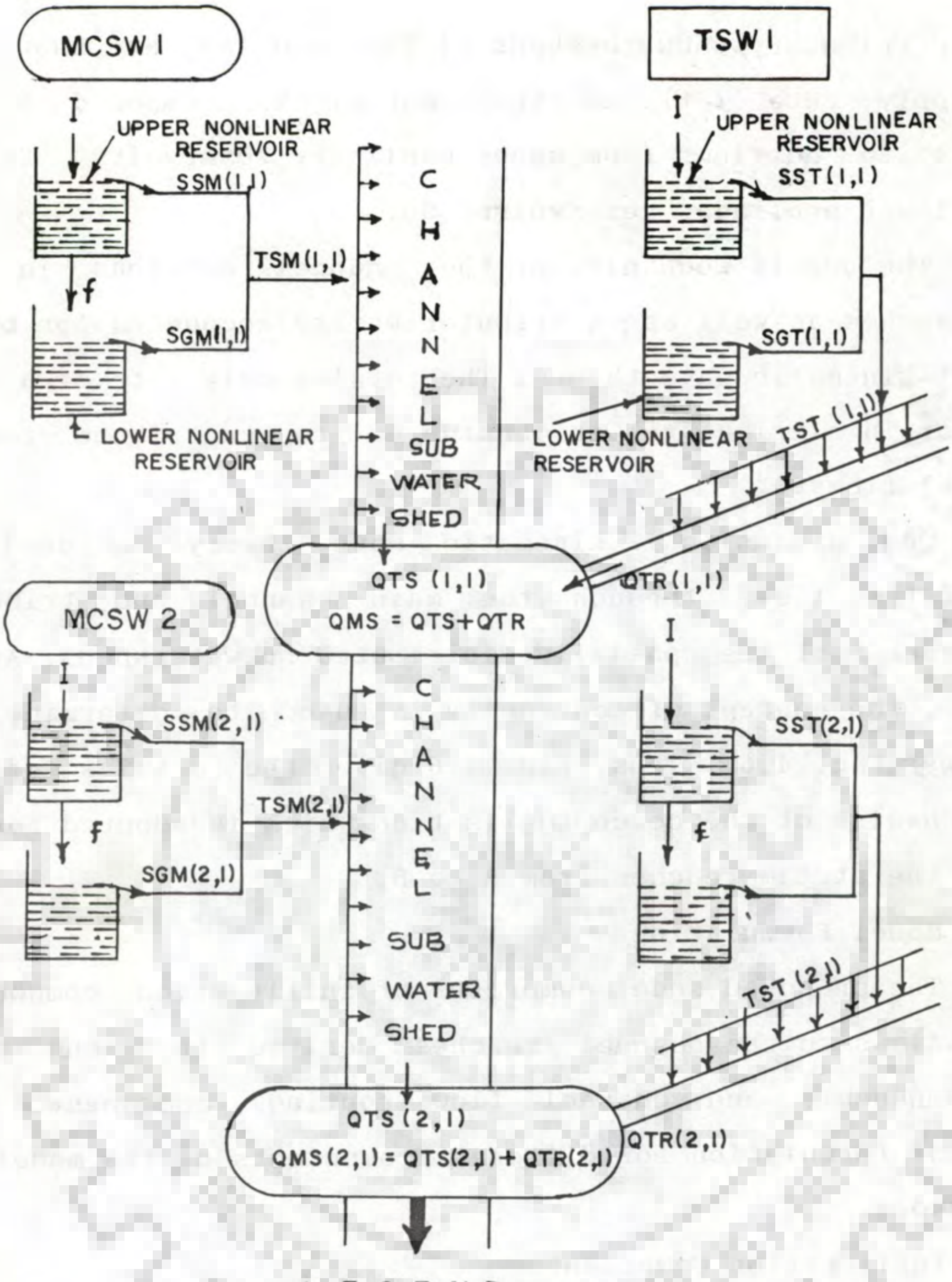


FIG. 4.5 - DISTRIBUTED PHYSIOGRAPHIC MODEL



LEGEND

MCSW =	Main channel Subwatershed.	TSW =	Tributary Subwatershed
QTS =	Discharge Contributed by main channel Subwatersheds.	QTR =	Discharge rate at the outlet of tributary Subwatersheds
QMS =	Discharge at the outlet of main channel Subwatershed.	I =	Rainfall intensity (mm/hr)
		f =	Infiltration rate (mm/hr)

SSM, SGM = Contribution from upper and lower nonlinear reservoirs of main channel Subwatershed

SST, SGT = Contribution from upper and lower nonlinear reservoirs of Tributary Subwatersheds.

TSM = Total contribution of upper and lower nonlinear reservoirs of main channel Subwatersheds.

FIG. 4·6 - CONCEPTUAL ELEMENTS FOR RUNOFF ROUTING.

MCSW2, and tributary subwatersheds of TSW1 and TSW2 are shown. The total supply rate (St) to the channel is composed of two components i.e. outflows from upper nonlinear reservoirs, Ss and from the lower nonlinear reservoirs, Sg.

The runoff mechanics of the channel sections in main channel reaches as well as in tributaries are accounted for by the concept of kinematic wave theory. The total supply rate of a main channel (or in a tributary) is considered to contribute towards the lateral flows.

One dimensional kinematic wave theory is used for routing of the flow, through the main channel and tributary channel reaches of the spatially distributed subwatersheds. At the confluence, the concept of continuity is used to determine the total flows (Fig. 4.6). Thus, Fig. 4.6 gives the details of the runoff mechanism of the conceptualisation which is adopted for the study for the stream reaches from A to B.

4.4.3 Model Formulation

The proposed model comprises of infiltration component, lateral inflows to the channel reaches derived from the total supply component, and channel flow routing component. The mathematical formulation for different components of the model is given as under.

1) Infiltration Component

To determine the surface supply rate (Ss) infiltration component is required in the proposed model. The following three models were used for computing infiltration capacities.

i) **Philip's model**

The Philip's equation (1969) for infiltration is given below.

$$f = \frac{1}{2} S_{\Phi} (tr)^{-1/2} + \phi \quad .... \quad (4.31)$$

Where,

f = infiltration capacity (mm /hr),

S_ϕ = sorptivity (mm $h^{-0.5}$),

t_r = time since start of storm rainfall (hr) and

ϕ = continuing loss rate (mm).

This relationship has been used by Field and Williams (1987).

ii) Horton's model

Horton (1933) proposed the following equation for the determination of infiltration rates during a storm. Horton assumed that the water supply for infiltration is not restrictive and the decay takes place at exponential rate from the beginning of storm. The equation has been extensively used by hydrologists and given as under.

$$f = fc + (fo - fc)e^{-kt_r} \quad .... \quad (4.32)$$

where,

f = infiltration rate at time t_r (mm/hr),

fo = initial infiltration rate (mm/hr),

fc = final infiltration rate (mm/hr) and

t_r = time since commencement of rainfall (hr).

iii) Variable Rainfall Infiltration Model (VRIM)

Horton 's model does not account for infiltration during intermittent rainfall. Singh (1989) presented a special case of the general procedure developed by Peschke and Kutilek (1982) for determination of infiltration during an unsteady rainfall. The Variable Rainfall Infiltration Model (VRIM) has been described in detail in Chapter-II under section 2.7.1.

As discussed in the forthcoming section on application, the variable rainfall infiltration method has been found to be very satisfactory for the typical rainfall-infiltration relationships which prevail in the watersheds of tropical countries.

2) Lateral Flow Rate Components
(supply rates from surface and subsurface storages)

As shown in Fig. 4.7(a), a tributary or a main channel subwatershed having the drainage area Ai with the main channel length in it as Li is conceptually represented by two nonlinear reservoirs as shown in Fig. 4.7(b). As discussed earlier the upper nonlinear reservoir account for the surface water component and the lower one represents the groundwater contributions. The average width of subwatershed will thus works out as given below:

$$Bi = Ai / Li \quad .... \quad (4.33)$$

The storage-discharge relationship of the upper nonlinear reservoir for surface storages is given by :

$$A\,Ss \;\alpha\; L\,(hs)^{1/\gamma_s} \quad .... \quad (4.34)$$

where,

A = area of surface reservoir (m^2),

hs = average depth in surface storage (m),

Ss = volumetric rate of surface supply per unit area (m/s) and

γ_s = exponent of surface supply rate.

Rearranging and substituting the value of L from equation 4.33

$$hs = Cs\,B^{\gamma_s}\,Ss^{\gamma_s} \quad .... \quad (4.35)$$

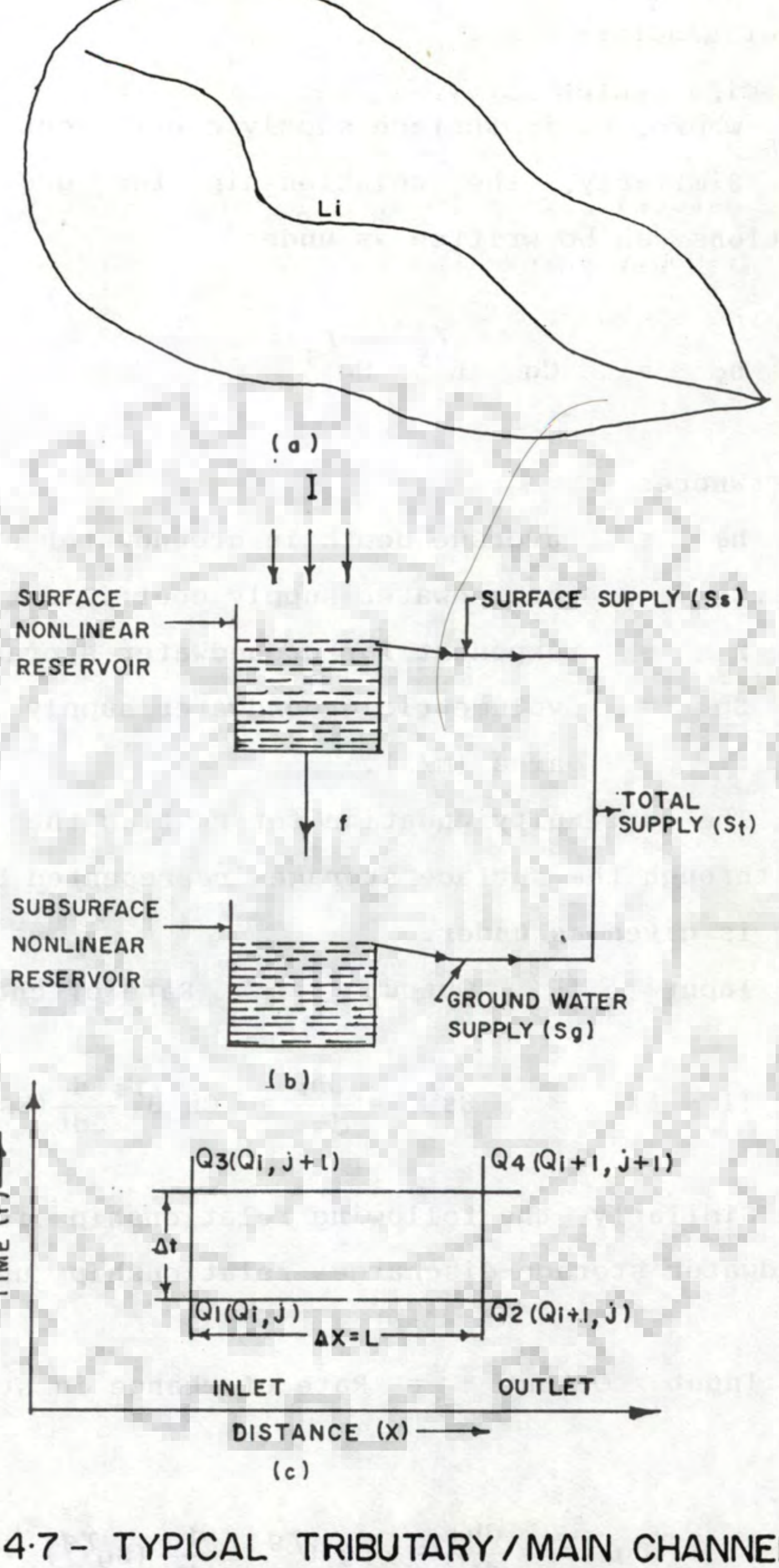


FIG. 4·7 - TYPICAL TRIBUTARY/MAIN CHANNEL SUBWATERSHED: (a) PLAN VIEW, (b) CONCEPTUAL REPRESENTATION THROUGH NONLINEAR RESERVOIRS, AND (c) SPACETIME MODULE.

where, Cs is surface supply coefficient ($m^{(1-2\gamma s)}$ $s^{\gamma s}$).

Similarly, the relationship for groundwater storage contributions can be written as under.

$$h_g = C_g \; B^{\gamma_g} \; S_g^{\gamma_g} \qquad \ldots. \qquad (4.36)$$

Where,

h_g = average depth in groundwater storage (m),

C_g = groundwater supply coefficient ($m^{(1-2\gamma s)}$ $s^{\gamma s}$),

γ_g = exponent for groundwater storage,

S_g = volumetric groundwater supply rate per unit area (m/s).

The continuity equation for routing the input rainfall function through the surface storages represented by the nonlinear reservoir is given as under.

Input - Output = Rate of change in storage

$$(I - f) - S_s = \frac{dh_s}{dt} = C_s \; B^{\gamma_s} \frac{d}{dt}(S_s^{\gamma_s}) \ldots. \qquad (4.37)$$

Similarly, the following relationship is obtained for the groundwater storage-discharge relationship using continuity equation.

Input − Output = Rate of change in storage

$$f - S_g = \frac{dh_g}{dt} = C_g \; B^{\gamma_g} \; \frac{d}{dt}(S_g^{\gamma_g}) \quad \ldots. \qquad (4.38)$$

where

I = rainfall intensity (m/s),

f = infiltration rate (m/s),

dhs = change in depth of surface storage reservoir (m),

dhg = change in depth of groundwater storage reservoir (m),

dt = change in time (time step) (s) and other parameters have been defined previously.

Equation 4.37 and 4.38 can be written in finite difference form (after rearrangement) as under;

a) For Surface storage reservoir :

$$(2Cs\ B^{\gamma_s}/\Delta t)\ Ss_2^{\gamma_s} + Ss_2 = (2Cs\ B^{\gamma_s}/\Delta t)\ Ss_1^{\gamma_s} - Ss_1$$

$$+ (I_2 + I_1) - (f_2 + f_1) \quad .... \quad (4.39)$$

b) For Groundwater storage reservoir :

$$(2Cg\ B^{\gamma_g}/\Delta t)\ Sg_2^{\gamma_g} + Sg_2 = (2Cg\ B^{\gamma_g}/\Delta t)\ Sg_1^{\gamma_g}$$

$$- Sg_1 + (f_2 + f_1) \quad .... \quad (4.40)$$

Where the subscripts 1 and 2 represent conditions at time t and t+Δt, respectively. Eqs. 4.39 and 4.40 are solved for Ss_2 and Sg_2 respectively using the Newton's technique. Thus, with the known initial values of surface (Ss) and groundwater supply (Sg) rates for an elemental subwatershed values at subsequent times are obtained incrementally for a available temporal distribution of rainfall intensity (I) and infiltration rate (f).

3) Channel Flow Routing

Lateral flows (q) are received through the total supply rate (S) from the element (subwatershed) and are routed using kinematic wave equations. The Saint Venant's equation of continuity for one-dimensional flow in a channel is as under.

$$\frac{\partial Q}{\partial x} + \frac{\partial Ac}{\partial t} = q \quad .... \quad (4.41)$$

Where,

Q = channel discharge rate (cumec) at time t,

x = distance measured in the direction of flow(m),

Ac = the channel cross-sectional area of flow (m^2),

t = time (s) and

q = the lateral inflow per unit length of channel (m^2/s).

In the kinematic wave theory as described in Chapter-II under section 2.6.2 that the Saint Venant equation for momentum reduces to $Sf = So$

$$Sf = So \text{ or } Sc \quad .... \quad (4.42)$$

Where,

Sf = friction slope of overland or channel,

So = bed slope of overland and

Sc = bed slope of channel.

This suggests that an unique relationship of stage-discharge can be obtained from Manning's equation which is given as under:

$$Q = \frac{1}{nm} Ac \cdot \frac{Ac^{2/3}}{p^{2/3}} \cdot Sc^{1/2} \quad .... \quad (4.43)$$

Or

$$Q = [Ac^{5/3} / (nm\ p^{2/3})]\ Sc^{1/2} \quad .... \quad (4.44)$$

Which can be written as

$$Q = K_c \; S_c^{1/2} \quad .... \quad (4.45)$$

Where

$$K_c = \text{channel conveyance} = A_c^{5/3} / (n_m \, p^{2/3}) .... \quad (4.46)$$

p =wetted perimeter of channel (m), and

n_m =Manning's roughness coefficient for channel,

A power relationship is assumed between channel conveyance (Kc) and cross-sectional area of channel (Ac) which is given below.

$$K_c = C_r \, A_c^{m} \quad .... \quad (4.47)$$

Where,

Cr is the channel conveyance coefficient and

m is the channel conveyance exponent.

On comparing equations 4.45, 4.46 and 4.47, the channel conveyance can be written as:

$$C_r = A_c^{(5/3-m)} \; / \; (n_m \, p^{2/3}) \quad .... \quad (4.48)$$

Substituting the value of Kc from eq 4.47 into equation 4.45, the following equation is arrived at :

$$A_c = \alpha \; Q^{1/m} \quad .... \quad (4.49)$$

Where,

$$\alpha = 1 / (Cr\ Sc^{1/2})^{1/m} \quad .... \quad (4.50)$$

It is known that, total supply comprises of surface water supply (Ss) and groundwater supply rate (Sg) i.e.

$$St = Ss + Sg \quad .... \quad (4.51)$$

The total supply rate (St) forms the lateral flow to the channel of subwatershed having width B. Therefore, it can be written as:

$$q = A\ St / L = B\ St \quad .... \quad (4.52)$$

Substituting the values of q (i.e. from equation 4.52) and Ac (i.e. from equation 4.49) into the equation 4.41, the following relationship is arrived at:

$$\frac{\partial Q}{\partial x} + \alpha \frac{\partial (Q^{1/m})}{\partial t} = B\ St \quad .... \quad (4.53)$$

The equation 4.53 can be written as under in the finite difference form using implicit scheme of Smith (1980) as shown in Fig. 4.7(c).

$$\alpha(Q_4^{1/m} - Q_2^{1/m})/\Delta t + (Q_4 - Q_3)/\Delta x = B\ (S_1 + S_2)/ 2 \quad .... \quad (4.54)$$

Where S_1 and S_2 are the total supply rates at the beginning and end of the time interval Δt, respectively. Rearranging the terms equation 4.54 can be written as below:

$$(\alpha \Delta x/\Delta t)\,(Q_{i+1}^{j+1})^{1/m} + Q_{i+1}^{j+1} = (\alpha \Delta x/\Delta t)\,(Q_{i+1}^{j})^{1/m} + Q_{i}^{j+1} + A\,(S_1 + S_2)/\,2 \quad \ldots\ldots \quad (4.55)$$

4.4.4 Numerical Scheme for the Solution of Nonlinear Kinematic Wave Equation

The nonlinear kinematic wave equation 4.53 was solved by Smith (1980) through implicit scheme for the form given in equation 4.55. However, the results were not very encouraging. Therefore, Nonlinear Numerical Scheme for solution of kinematic wave as proposed by Chow et al. (1988) was adopted and the same is given below :

Numerical Scheme :

$$\frac{\partial Q}{\partial x} + \alpha \beta Q^{\beta-1} \frac{\partial Q}{\partial t} = q \quad \ldots\ldots \quad (4.56)$$

Where $\beta = 1/m$

Finite difference form of equation 4.41 can be expressed as:

$$\frac{Q_{i+1}^{j+1} - Q_{i}^{j+1}}{\Delta x} + \frac{Ac_{i+1}^{j+1} - Ac_{i+1}^{j}}{\Delta t} = \frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \quad \ldots\ldots \quad (4.57)$$

Q is taken as independent variable using equation 4.49.

$$Ac_{i+1}^{j+1} = \alpha\,(Q_{i+1}^{j+1})^{\beta} \quad \ldots\ldots \quad (4.58)$$

$$Ac_{i+1}^{j} = \alpha\,(Q_{i+1}^{j})^{\beta} \quad \ldots\ldots \quad (4.59)$$

Following relationship is obtained after substituting equations 4.58 and 4.59 in equation 4.57.

$$\frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha \left(Q_{i+1}^{j+1} \right)^{\beta} = \frac{\Delta t}{\Delta x} Q_{i}^{j+1} + \alpha \left(Q_{i+1}^{j} \right)^{\beta}$$

$$+ \Delta t \left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \right) \quad \ldots (4.60)$$

All the terms in this equation on the right hand side are known while the discharge rate Q_{i+1}^{j+1} is only unknown on the left hand side. This equation is nonlinear in Q_{i+1}^{j+1} so it was solved using Newton's method (a numerical solution scheme). The known right-hand side at each finite-difference grid point is:

$$D = \frac{\Delta t}{\Delta x} Q_{i}^{j+1} + \alpha \left(Q_{i+1}^{j} \right)^{\beta} + \Delta t \left(\frac{q_{i+1}^{j+1} + q_{i+1}^{j}}{2} \right) \quad \ldots \quad (4.61)$$

A residual error can be defined as:

$$f\left(Q_{i+1}^{j+1} \right) = \frac{\Delta t}{\Delta x} Q_{i+1}^{j+1} + \alpha \left(Q_{i+1}^{j+1} \right)^{\beta} - D \quad \ldots \quad (4.62)$$

The first derivative of $f(Q_{i+1}^{j+1})$ is:

$$f'\left(Q_{i+1}^{j+1} \right) = \frac{\Delta t}{\Delta x} + \alpha \beta \left(Q_{i+1}^{j+1} \right)^{\beta - 1} \quad \ldots \quad (4.63)$$

The objective is to find the value of Q_{i+1}^{j+1} which makes $f(Q_{i+1}^{j+1})$ equal to zero.

Using Newton's method with iterations k = 1, 2,....

$$(Q_{i+1}^{j+1})_{k+1} = (Q_{i+1}^{j+1})_k - \frac{f(Q_{i+1}^{j+1})_k}{f'(Q_{i+1}^{j+1})_k} \quad .... \quad (4.64)$$

The convergence will take place when

$$f (Q_{i+1}^{j+1})_{k+1} \leq \varepsilon \quad .... \quad (4.65)$$

Where ε is an error criterion, decided by the user.

The initial estimate for Q_{i+1}^{j+1} is important for the convergence of this non linear scheme. The solution from the linear scheme is used as the first approximation to the nonlinear scheme which is obtained using the following relationship:

$$Q_{i+1}^{j+1} = \frac{\frac{\Delta t}{\Delta x} Q_i^{j+1} + \alpha\beta Q_{i+1}^{j} \left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2} \right)^{\beta-1} + \Delta t \frac{(q_{i+1}^{j+1} + q_{i+1}^{j})}{2}}{\left[\frac{\Delta t}{\Delta x} + \alpha \beta \left(\frac{Q_{i+1}^{j} + Q_i^{j+1}}{2} \right)^{\beta-1} \right]} \quad .... \quad (4.66)$$

Li et al. (1975) performed a stability analysis with this scheme and concluded that this nonlinear scheme is unconditionally stable. It was also found that a wide range of values of $\Delta t/\Delta x$ could be used without introducing large errors in the shape of the discharge hydrograph.

Initial and boundary conditions are to be provided for the solution of nonlinear kinematic wave equations which are discussed in following sections.

4.4.5 Initial conditions

Since normally the runoff gauging is done only at the outlet therefore initial discharges (baseflow rates) are not available at other points (i.e. at the confluences of tributaries and main drainage channel). Initial conditions are established on the assumption that the baseflow at the confluence is in proportion of the area drained (sum of areas of tributary and main channel subwatersheds) up to that point to total watershed area which is expressed by the following relationship.

$$QMS(N+1,1)=QMS(N,1)+\left[\frac{ARTR(N)+ARMS(N)}{ARWS}\right]QBF \quad .... \quad (4.67)$$

Further, main channel subwatersheds which are nearer to main drainage channel, are assumed to contribute more compared to the tributary subwatersheds, a weight factor THETA has been introduced as expressed by the equation given below.

$$QTR(N,\ 1)=\frac{ARTR(N)\ x\ QBF\ x\ THETA}{ARWS} \quad .... \quad (4.68)$$

$$QTS(N,\ 1)=QMS(N)-QMS(N-1)-QTR(N,1) \quad .... \quad (4.69)$$

Where,

QMS(N, 1) = Discharge rate at the N^{th} confluence (i.e. at the outlet of N^{th} main channel subwatershed) at the first time step,

QTR(N, 1) = Discharge rate at the outlet of N^{th} tributary subwatershed at the first time step,

QTS(N, 1) = Discharge rate contributed by the nonlinear reservoirs (surface and subsurface) of the N^{th} main channel subwatershed at the first time step,

ARWS = Total area of the watershed,

ARMS(N) = Area of N^{th} main channel subwatershed,

ARTR(N) = Area of N^{th} tributary subwatershed,

QBF = Discharge rate at the outlet of the watershed at the first time step and

THETA = Weight factor.

4.4.6 Boundary Conditions

The watershed is divided into Tributary subwatershed and main channel subwatersheds as mentioned earlier. At the ridge line inflows to the tributary subwatersheds remain zero for all the time i.e.

$$Q(0, t) = 0.0 \qquad \ldots. \qquad (4.70)$$

The proposed model has been applied onto the two watersheds (described in Chapter-III) and the details are given under section 5.4.

4.4.7 Computer Programmes and Applications

The computer programme developed for the proposed model has been given in Appendix-A4. The computer programme, written in FORTRAN-4 includes three subroutines namely SOLUSN, OBJECT and INFILT. The applications of the model onto the two test watersheds are described in section 5.4.

Input and output file for simulation of one storm event is given in Appendix-B4 and Appendix-B5 respectively.

CHAPTER-V

APPLICATION OF MODELS

5.1 INTRODUCTION

As discussed in Chapter-IV, the following three models, two lumped and one distributed, were developed for assessing their applicability onto the hilly watersheds. These are summarised as under.

(a) Lumped Models: These consisted of the following two models:

(i) Time-Area Based Model: The methodology is based on division of watershed through isochrones to obtain the time-area histogram. The rainfall excess function was computed using the ϕ-index method as well as the variable rainfall infiltration approach. The time distribution of direct runoff is obtained by applying the rainfall excess onto the time-area histogram.

(ii) Variable Source Area Model: This model consists of three storages, viz. surface storage, subsurface storage and the groundwater storage. The total runoff is obtained from the contribution of the three storages which are conceptually represented through nonlinear reservoirs.

(b) Distributed Physiographic Models Using Kinematic Wave Routing

A Physiographically distributed model was developed, as given below.

Distributed Physiographic Model: The watershed was split up into tributary subwatersheds and the main channel subwatersheds. The surface and subsurface runoff contributions to the channel were computed using nonlinear reservoirs, The channel routing was performed by using the kinematic wave theory.

In this chapter, the details of application of the three models mentioned above onto the two watersheds of Bhaintan and Jhandoo-Nala are explained. The availability of data on these two watersheds has been discussed in Chapter-III. Sensitivity analysis of all these models, with an exception of the Time-Area Based Model, has been carried out with the data registered at Jhandoo-Nala watershed.

5.2 APPLICATION OF TIME-AREA BASED MODEL ONTO BHAINTAN AND JHANDOO-NALA WATERSHEDS

The physiographic characteristics of the two watershed were described in section 3.2.1(2) and 3.2.2(2). For application of the proposed model following procedure is adopted.

5.2.1 Construction of Time-Area Histogram

As a first attempt, the time of concentration for the watersheds was computed using Kirpich formula (Kirpich, 1940) which is given below:

$$Tc = \frac{0.0197\ (L)^{0.77}}{Se^{0.385}} \quad \ldots. \quad (5.1)$$

Where,

Tc = time of concentration for the watershed (min),

L = watershed length measured along the channel (m),

Se = the weighted uniform or average slope of the channel (m/m).

As mentioned in section 3.2.1(2) & 3.2.2(2), the weighted overland slopes of Bhaintan & Jhandoo-Nala watersheds are 72 and 50.5 per cent respectively. Also the total main channel lengths of Bhaintan and Jhandoo-Nala are 2780 and 848 m respectively.

Thus, the time of concentration for Bhaintan watershed was found to be 14 minutes. An inter-isochronal interval of one minute was selected to give 14 blocks on the time-area histogram.

In order to draw the isochronal pattern, the profile of main channel of Bhaintan watershed was drawn as shown in Fig. 5.1. It was segmented into 14 equal parts corresponding to the adopted time step of one minute. By superimposing the time scale over the channel distance scale i.e. the abscissa of Fig. 5.1, the elevations of the intersections of the isochrones with the main channel were determined. Next, the isochrones were drawn by joining the points of same time of travel (Fig. 5.2). Areas between the isochrones were measured by planimetering. These areas are denoted by A_i, i = 1, 2, 3, ...14 as shown in Fig. 5.2. Subsequently in order to arrive at the time area histogram these areas were plotted against time of travel for different time intervals τ_i, i = 1, 2, 3,.....14 (Fig. 5.3).

A similar procedure was adopted for Jhandoo-Nala watershed. Using equation 5.1, the time of concentration of Jhandoo-Nala watershed was found out to be five minutes. A time interval of 30 seconds was selected to give 10 isochronal strips on the watershed. The profile of main channel is drawn as shown in Fig. 5.4. The isochronal pattern for this watershed is shown in Fig. 5.5. The time-area-histogram so arrived is given in Fig. 5.6. Time of travel and area of isochronal strips are given in Table 5.1.

5.2.2 Computation of Rainfall Excess Function

As mentioned, in section 5.1, the rainfall excess function was computed using the ϕ-index method as well as the variable rainfall infiltration approach. In Chapter-III, data availability of twenty five storm events for the Jhandoo-Nala watershed and five storm events for Bhaintan watershed were discussed.

As discussed in Chapter-II, conventionally ϕ-index

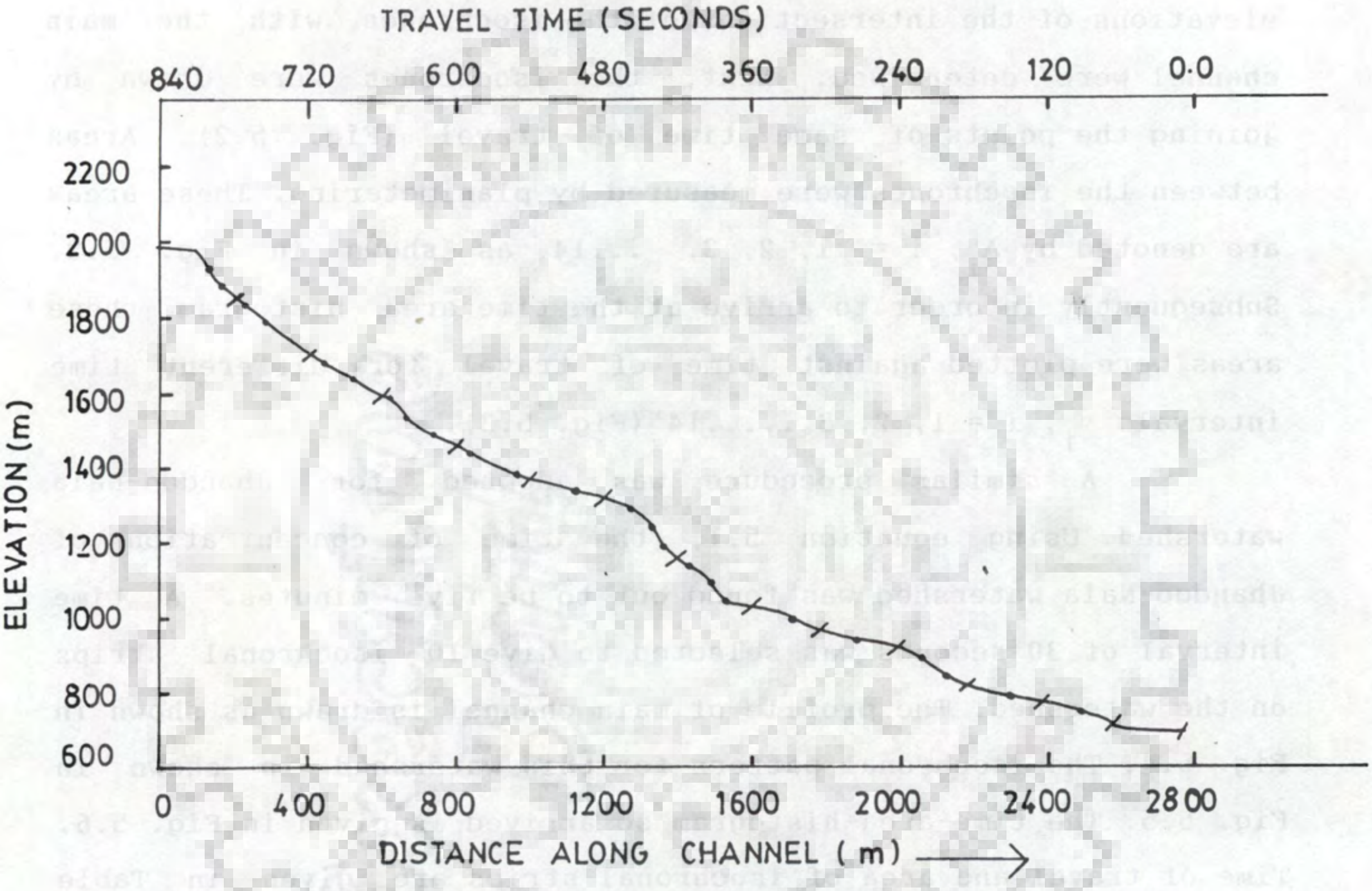


FIG 5·1–PROFILE OF MAIN CHANNEL AND TRAVEL TIME OF BHAINTAN WATERSHED

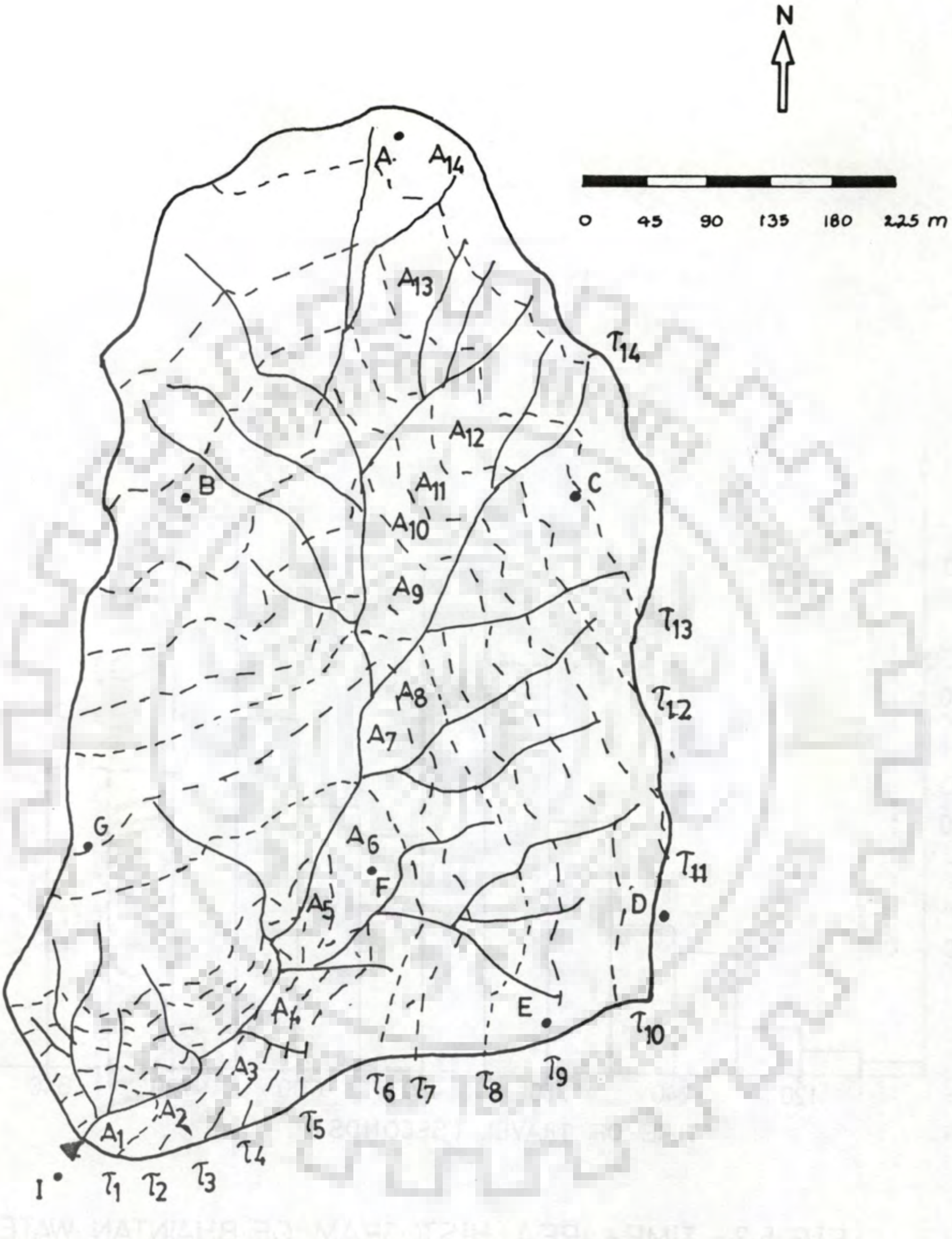


FIG 5.2 - WATERSHED DECOMPOSITION BY ISOCHRONES
(BHAINTAN WATERSHED)

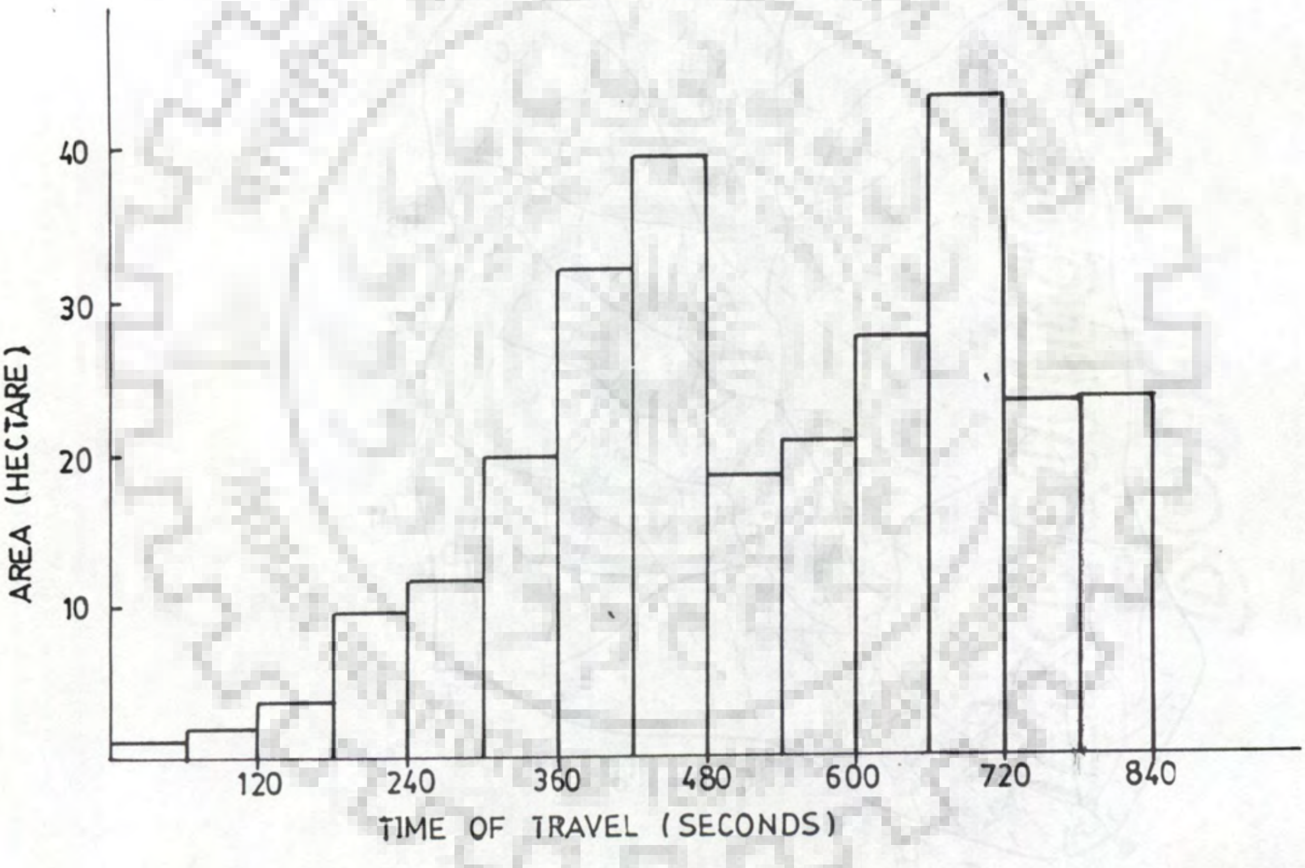


FIG 5.3 - TIME-AREA HISTOGRAM OF BHAINTAN WATERSHED

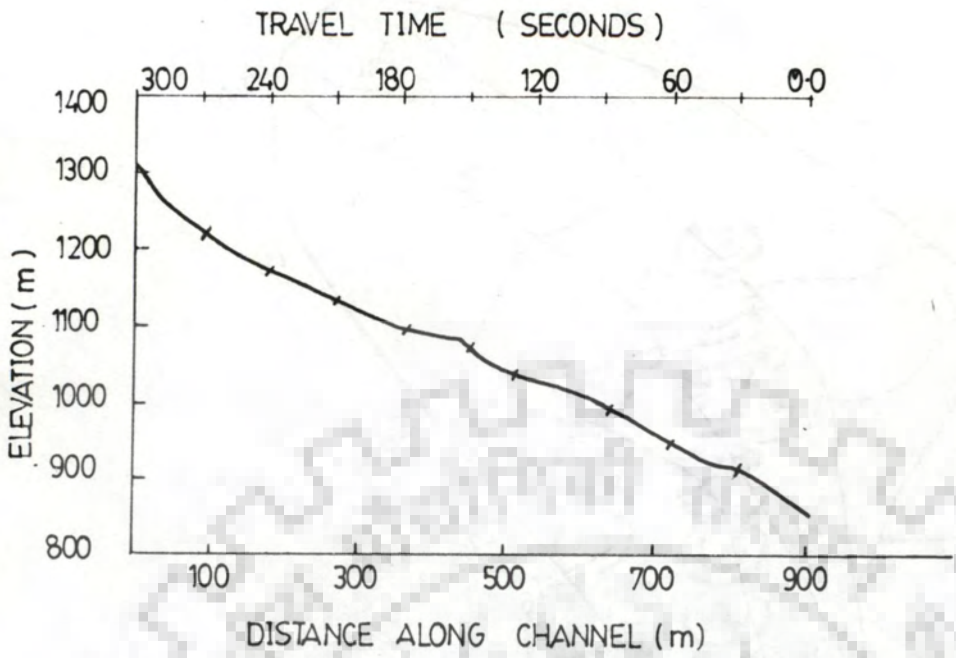


FIG. 5·4 - PROFILE OF MAIN CHANNEL AND TRAVEL TIME OF JHANDOO - NALA WATERSHED

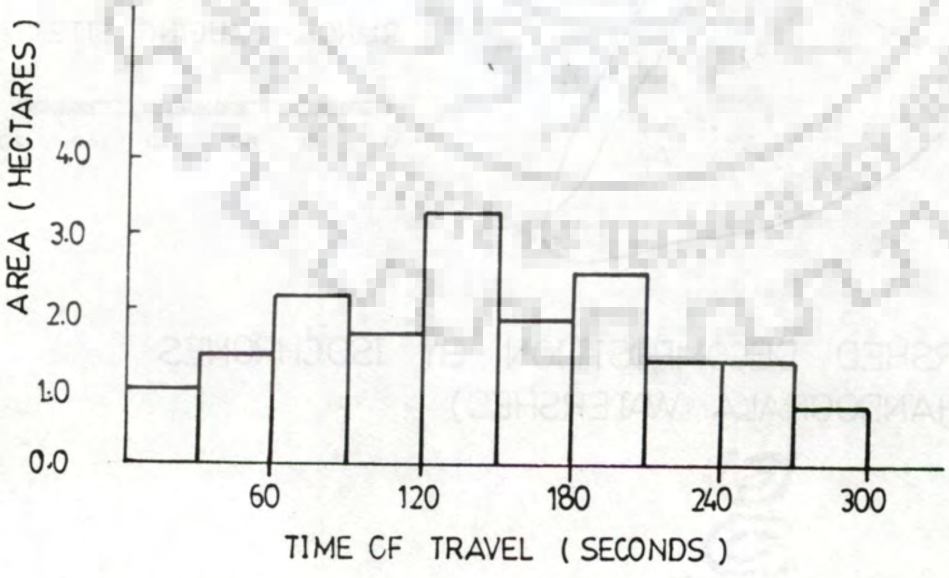


FIG.5.6 - TIME AREA HISTOGRAM OF JHANDOO NALA WATERSHED

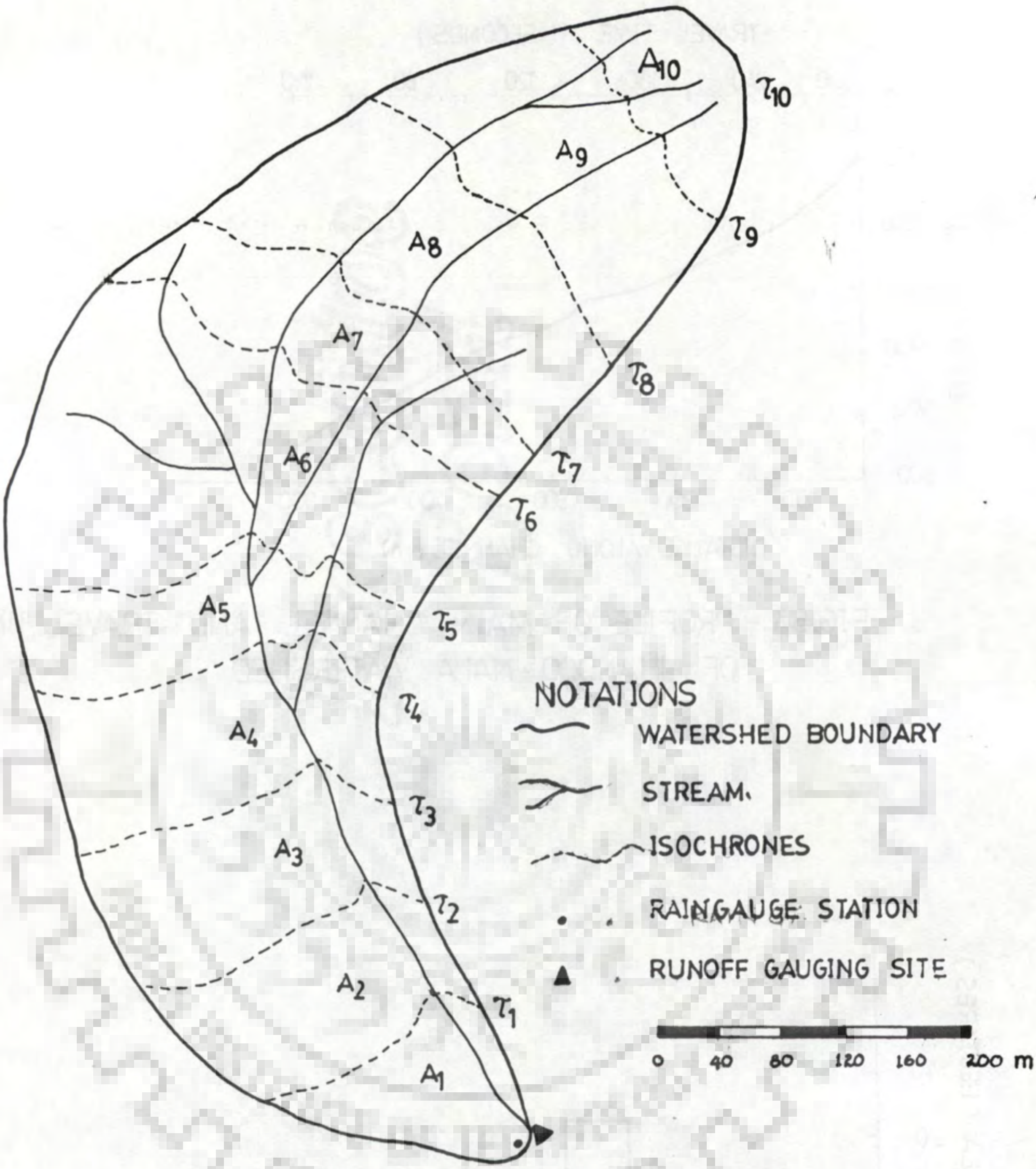


FIG. 5.5-WATERSHED DECOMPOSITION BY ISOCHRONES
(JHANDOONALA WATERSHED)

Table 5.1: Travel Time and Inter-isochronal Areas for Bhaintan and Jhandoo-Nala Watersheds.

Isochronal Strip number	Bhaintan Watershed Travel Time (sec.)	Bhaintan Watershed Area of Strip (ha)	Jhandoo-Nala Watershed Travel Time (sec.)	Jhandoo-Nala Watershed Area of Strip (ha)
(1)	(2)	(3)	(4)	(5)
1	60	1.059	30	0.79
2	120	1.914	60	1.41
3	180	3.736	90	1.41
4	240	9.654	120	2.52
5	300	11.876	150	1.90
6	360	19.840	180	3.33
7	420	32.293	210	1.68
8	480	37.540	240	2.19
9	540	18.496	270	1.54
10	600	20.743	300	0.94
11	660	27.552		
12	720	40.400		
13	780	23.362		
14	840	23.540		

approach has been used by various researchers in the Time-Area based models. Following the same lines the rainfall excess function is computed for both the watersheds using this approach for all the 25 storm events. For all these storm events, the rainfall depth, the rainfall excess, total runoff and the runoff factors are given in Appendix-C3.

Further, the variable rainfall infiltration approach is discussed in detail in Section 2.7.2. The computer programmes developed for this approach are given in Appendix-Al(d). The total rainfall excess, computed for 25 storms registered over the two watersheds, using the variable rainfall infiltration approach is given in column (5) of Appendix C3. As an illustration of the time distribution of rainfall function the rainfall hyetographs for storm events dated 8-8-1991 and 14-8-1979 for Jhandoo-Nala and Bhaintan watersheds are shown in Fig. 5.7 and 5.8.

It may be seen that the total rainfall excess and its time distribution computed by the ϕ-index approach as well as VRIM are not significantly different. For a storm event registered on 8.8.1991 at Jhandoo-nala watershed, the differences in time distribution of rain-fall excess function using these two approaches are given in Table 5.2.

5.2.3 Convolution Of Rainfall Excess Onto The Time-Area Histogram

The convolution of the rainfall excess onto the time-area histogram has been discussed in section 4.2. Equation 4.3 is used for the same and its software is given in Appendix-Al(a). Both the rainfall excess functions, i.e. using ϕ-index and VRIM were fed for the two randomly selected events (mentioned in section 5.2.2). Comparison of observed and computed peak flow rates and flood volumes are given in Table 5.3. The sum of difference in observed and computed hydrograph ordinates (F),

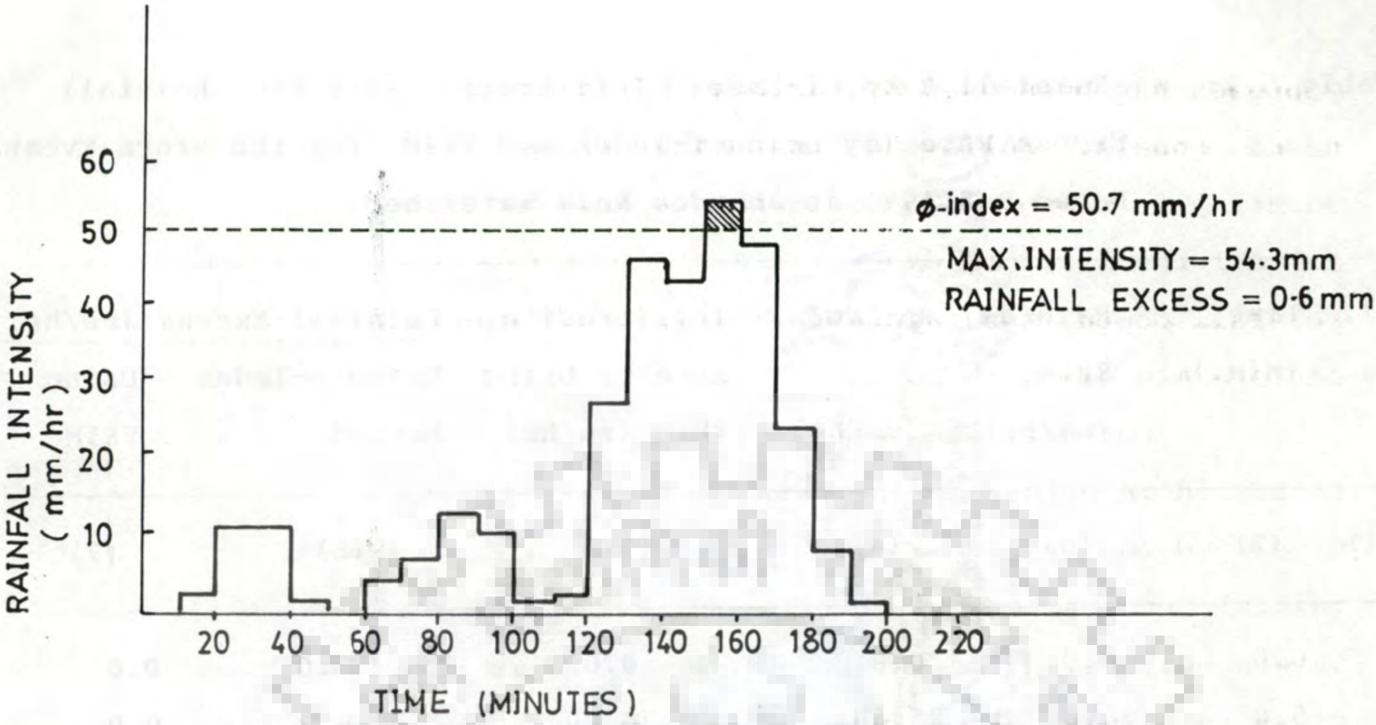


FIG 5·7- RAINFALL HYETOGRAPH REGISTERED ON AUGUST 14,1979 (TOTAL RAINFALL = 53·0 mm), AT BHAINTAN WATERSHED

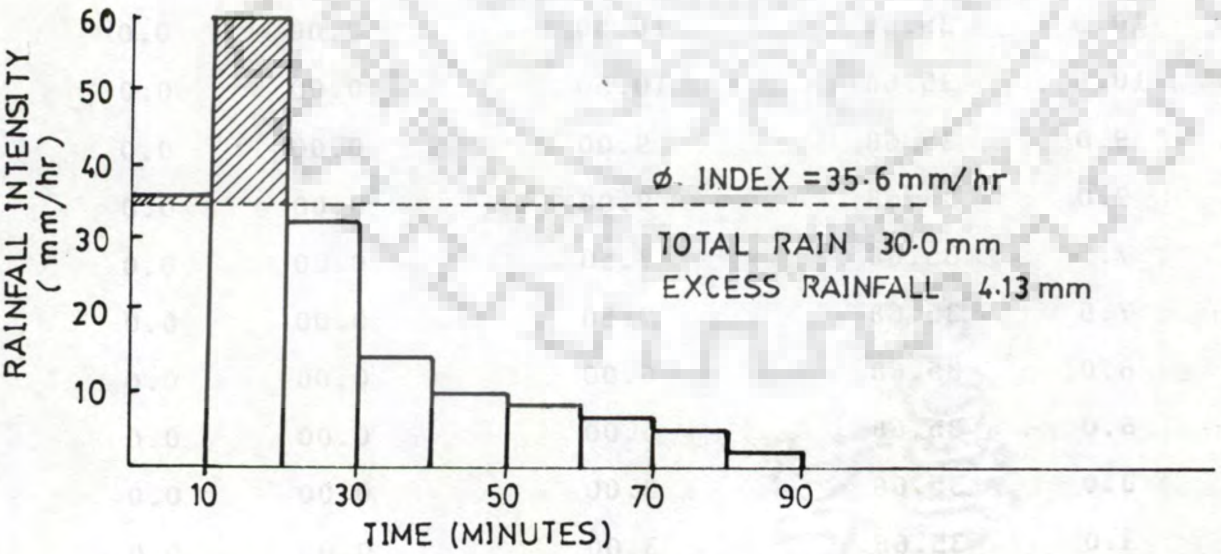


FIG 5·8- RAINFALL HYETOGRAPH REGISTERED ON AUGUST 8, 1991 AT JHANDOONALA WATERSHED

Table 5.2: Rainfall Rate, f-Index, Infiltration Rate and Rainfall Excess Rate (by using f-Index and VRIM) for the Storm Event Dated 8.8.1991 at Jhandoo Nala Watershed.

Sl. No.	Time (Min.)	Rainfall Rate (mm/hr)	ϕ-Index (mm/hr)	Infiltration Rate by Using VRIM (mm/hr)	Rainfall Excess (mm/hr) Using ϕ-Index Method	Rainfall Excess (mm/hr) Using VRIM
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0.0	0.0	0.0	0.00	0.0	0.0
2	5.0	36.0	35.68	36.00	0.32	0.0
3	10.0	36.0	35.68	36.00	0.32	0.0
4	15.0	60.0	35.68	36.69	24.32	23.31
5	20.0	60.0	35.68	36.39	24.32	23.61
6	25.0	33.0	35.68	33.00	0.00	0.0
7	30.0	33.0	35.68	31.85	0.00	1.15
8	35.0	15.0	35.68	15.00	0.00	0.0
9	40.0	15.0	35.68	15.00	0.00	0.0
10	45.0	10.5	35.68	10.50	0.00	0.0
11	50.0	10.5	35.68	10.50	0.00	0.0
12	55.0	9.0	35.68	9.00	0.00	0.0
13	60.0	9.0	35.68	9.00	0.00	0.0
14	65.0	7.5	35.68	7.50	0.00	0.0
15	70.0	7.5	35.68	7.50	0.00	0.0
16	75.0	6.0	35.68	6.00	0.00	0.0
17	80.0	6.0	35.68	6.00	0.00	0.0
18	85.0	3.0	35.68	3.00	0.00	0.0
19	90.0	3.0	35.68	3.00	0.00	0.0

Table 5.3 Observed and simulated peak flow rate, flood volume and Statistical parameters for the evaluation of Time-Area based model.

Sl. No.	Name of watershed	Event date	Excess Rain Method	Peak flow (lps) obser-ved	Peak flow (lps) simul-ated	Flood volume (cum)	Statistical parameters** F	F^2	R^2	EFF
1	Jhandoo-Nala	8-8-1991	ϕ Index	413	1260	726	-.0002	1.378	.026	-7.84
			VRIM*	413	1320	753	-.0979	1.485	.037	-8.53
2	Bhaintan	14-8-1979	ϕ Index	528	1630	1580	.0141	4.180	.001	-5.09
			VRIM*	528	1350	1493	.0339	3.059	.001	-3.46

* Variable Rainfall Infiltration Method

** Statistical parameters explained in Chapter-II coefficient of determination (R^2) and model efficiency (EFF) are also given. For visual comparison, observed and simulated hydrographs for both the events are shown in Fig. 5.9 and 5.10. It may be observed that the computed values do not match with the observed ones and the proposed approach has not yielded satisfactory results. Computer runs for other events have also showed similar tendencies.

5.2.4 Analysis Of Computed Results

It is observed that the time bases of the computed hydrographs are too much short. This has resulted into very high peaks of the simulated hydrographs. This is a clear indication that the time of concentration computed by using Kirpich formula has not given the desired results. It may be mentioned that this formula is quite popularly used in watershed management practices for computing the time of concentration, but in the case of steeply sloping Himalayan watersheds this has not given satisfactory results. Thus an alternate approach for arriving at the correct value of time of concentration needs to be adopted.

5.2.5 Approaches for Determination of Time of Concentration

As mentioned in earlier section, the correct value of time of concentration needs to be established. Therefore, this aspect needs further investigation. Theoretically the time of concentration, is the time required for water to travel from the remotest part of the watershed to the outlet. Clark (1945) has considered it to be the time elapsed between the end of rainfall excess up to the peak of the hydrograph. However, in practice, this refers to the pure translation time and needs routing through a pure storage element which was considered by Clark as a linear reservoir (without naming so). Thus, this can not be used in a TAC (Time-Area concentration) based model with a computational scheme given through equation 4.4.

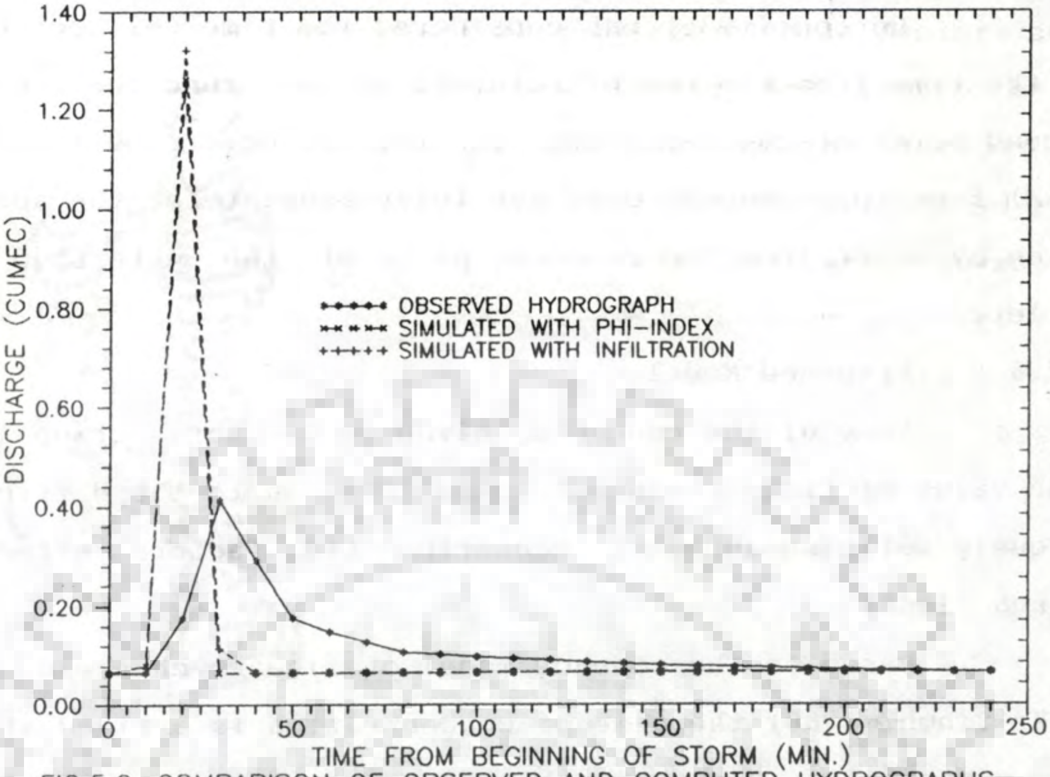


FIG.5.9-COMPARISON OF OBSERVED AND COMPUTED HYDROGRAPHS OF JHANDOO-NALA WATERSHED FOR STORM DATED 8-8-1991 USING TIME AREA BASED MODEL (Tc COMPUTED USING KIRPICH FORMULA)

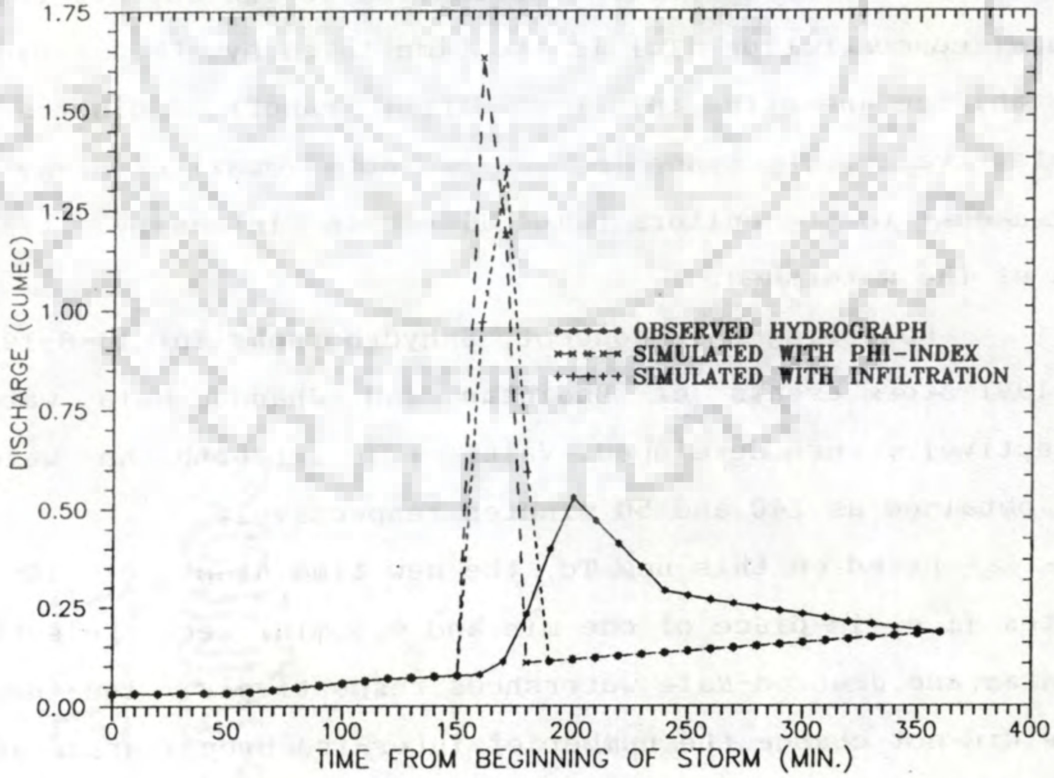


FIG.5.10-COMPARISON OF OBSERVED AND COMPUTED HYDROGRAPHS OF BHAINTAN WATERSHED FOR STORM DATED 14-8-1979 WITH TIME-AREA BASED MODEL(Tc CALCULATD BY USING KIRPICH FORMULA).

Horton (1935) has considered the time of concentration as the time from the end of rainfall excess function up to the second point of contraflexure on the Direct runoff hydrograph (DRH) Even this concept does not fully account for the actual time taken by water from the remotest part of the watershed to the outlet.

5.2.6 Proposed Model

None of the concepts, given in earlier section yield a true value of time of concentration (Tc) due to the difficulty of uniquely defining and then measuring the factors affecting Tc (Singh, 1988).

Based on the cascade model of linear channels (Mathur, 1972; Singh, 1988) the time of concentration is arrived at through the concept of S-hydrograph. For a uniform rainfall excess intensity, the S-hydrograph will attain the concentration ordinate at the instant of time of concentration. At this point of time, the entire watershed starts contributing to the outlet. Thus, the time of concentration (Tc) is the time taken by the S-hydrograph to stabilize and after this the direct runoff ordinates attain constant value. The concentration ordinate (Qmax) of S-hydrograph will amount to the uniform rainfall excess intensity, times the area of the watershed.

Following this concept, S-hydrographs for 14-8-1979 and 8-8-1991 storm events of Bhaintan and Jhandoo-Nala watersheds respectively, were developed. Value of Tc for both the watersheds were obtained as 140 and 50 minutes respectively.

Based on this new Tc, the new time steps of 10 and 5 minutes (i.e. in place of one min and 0.5 min) were selected for Bhaintan and Jhandoo-Nala watersheds respectively. The new time steps did not change the number of inter-isochronal areas as these were divided in 14 and 10 isochronal strips in accordance with the watershed physiography i.e. slope.

Using the same computer programme, the simulation was carried out for the events dated 14-8-1979 and 8-8-1991 (using the ϕ-index, as well as variable rainfall infiltration approach). Comparison of simulated hydrographs and observed one are shown in Fig. 5.11 and 5.12.

From the above, it may be concluded that both the approaches of rainfall excess computations give almost similar results. As the ϕ-index method with new criterion for estimating Tc is much simpler in computations than the variable rainfall infiltration approach, therefore, the ϕ-index approach has been used to simulate 26 storm events of the two watersheds. Comparison of observed peak flow rate (Qp) and simulated peak flow rate (Qs), F, R^2, and model efficiencies (EFF) are given in Table 5.4. Comparison of observed and simulated hydrographs for two storm events (2-9-1980 and 5-8-1982) of Bhaintan watershed and for four storm events (22-7-1992, 28-7-1992, 22-7-1993 and 2-9-1993) of Jhandoo-Nala watershed are given in Fig. 5.13, 5.14 and 5.15.

5.2.7 Conclusion

Time area based models may turn out to be powerful tool for runoff simulation of mountainous watersheds if Tc can be ascertained accurately. Empirical approaches for computation of Tc may not yield desired results. The rainfall excess function computation using the ϕ-index method yields satisfactory results when Tc is computed through S-hydrograph. The time-area method is very useful because of its simplicity. In disturbed watershed, if exact infiltration rates are available, rainfall excess function can be computed accurately.

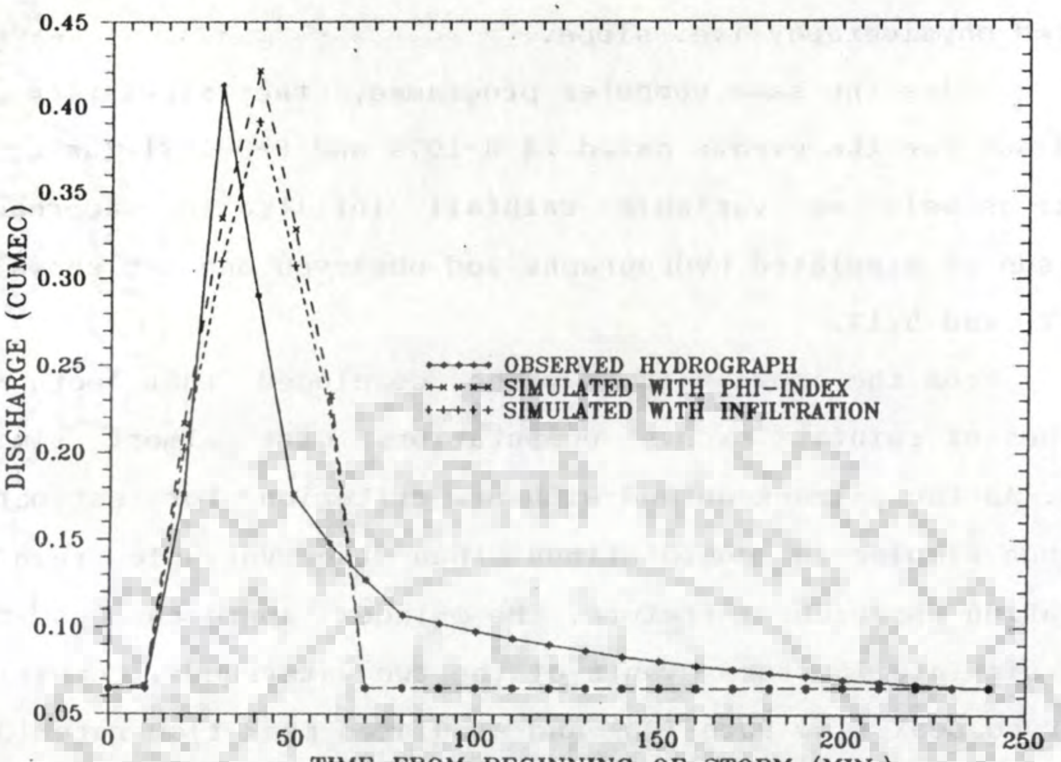


Fig.5.11–COMPARISON OF OBSERVED AND COMPUTED HYDROGRAPHS OF JHANDOO-NALA WATERSHED FOR STORM DATED 8-8-1991 USING TIME AREA BASED MODEL (Tc COMPUTED USING S-HYDROGRAPH METHOD).

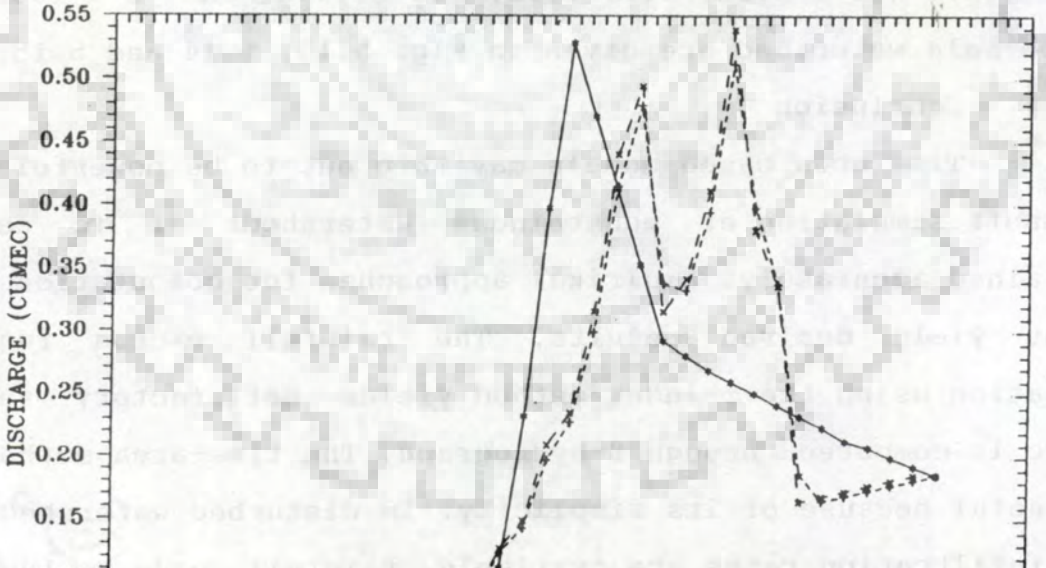


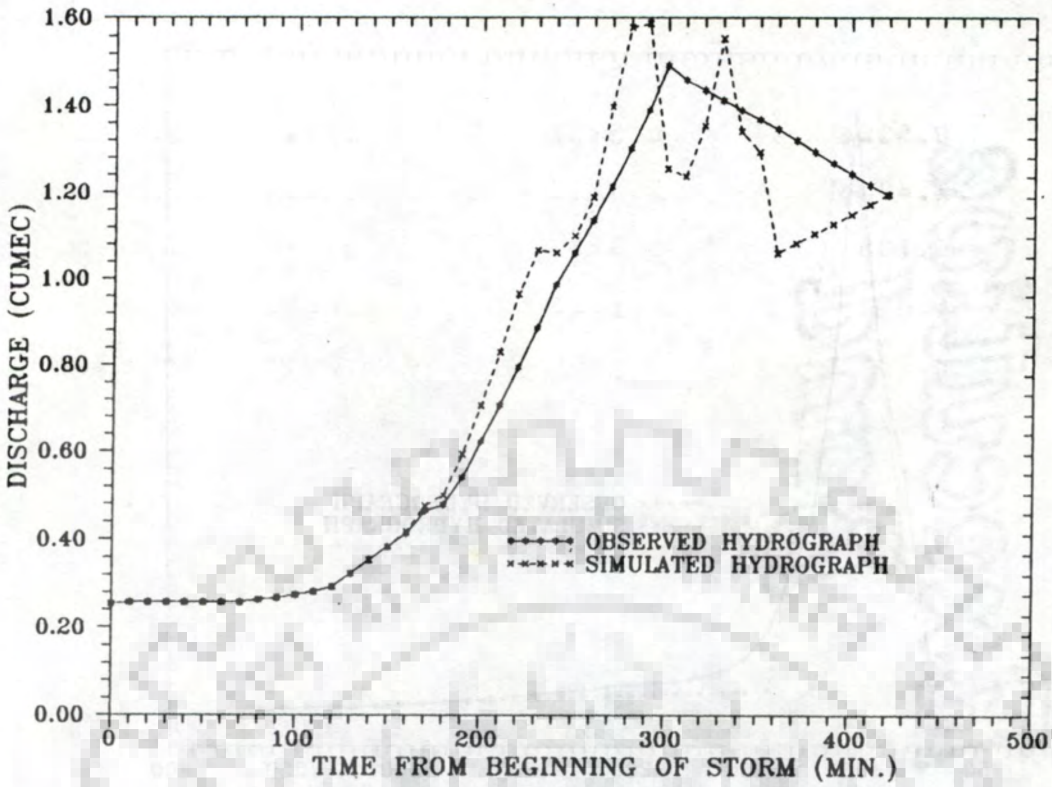
Fig.5.12–COMPARISON OF OBSERVED AND COMPUTED HYDROGRAPHS OF BHAINTAN WATERSHED FOR STORM DATED 14-8-1979 USING TIME AREA BASED MODEL (Tc COMPUTED USING S-HYDROGRAPH METHOD).

Table 5.4: Observed and Simulated Excess Rain and Peak Rate of Runoff (cumecs) Alongwith Statistical Parameters with Time-Area Based Model

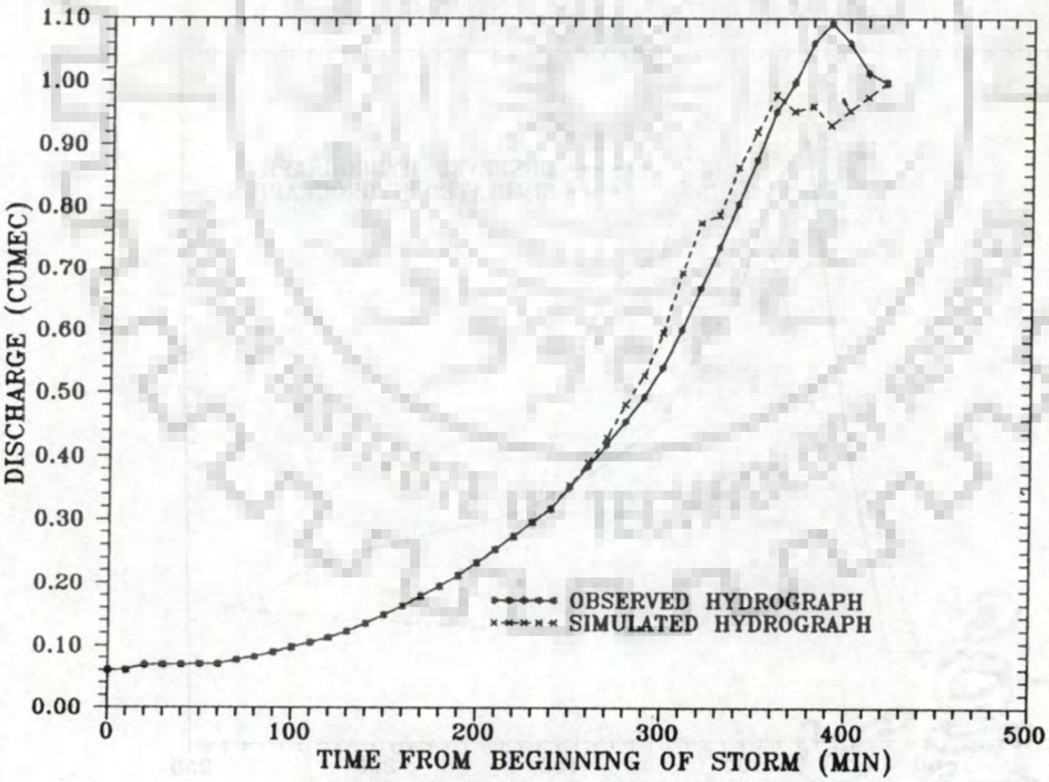
Watershed/ Date	Peak Rate of Runoff (cumecs) Observed Qpo	Simulated Qps (with ϕ index)	F	R^2	Efficiency
(1)	(2)	(3)	(4)	(5)	(6)
Jhandoo-Nala					
4.7.1990	0.1500	0.1930	-.0061	0.8510	0.5512
10.8.1990	0.1227	0.1335	-.0040	0.6744	0.5179
18.8.1990	0.1760	0.2025	-.0032	0.6714	0.3050
25.8.1990	0.08267	0.1013	-.0032	0.8431	0.7422
5 .7.1991	0.09067	0.08212	-.0039	0.0492	-0.5280
7 .8.1991	0.29335	0.3865	-.0107	0.8533	0.6486
8 .8.1991	0.4127	0.4211	-.0030	0.7928	0.6411
9 .8.1991	0.3777	0.3321	-.0056	0.7051	0.6244
15.8.1991	0.3119	0.2205	-.0026	0.3313	0.1783
16.8.1991	0.33135	0.3791	-.0007	0.7850	0.7220
22.7.1992	0.4567	0.4116	-.0023	0.8845	0.8490
28.7.1992	0.1952	0.2022	-.0014	0.6652	0.5543
7 .7.1993	0.0256	0.02311	-.0010	0.4379	0.2314
17.7.1993	0.1656	0.1616	-.0058	0.6518	0.5657
22.7.1993	0.1035	0.1331	-.0057	0.9027	0.7430
2 .8.1993	0.0528	0.0582	-.0033	0.6700	0.4267
23.8.1993	0.3181	0.3812	-.0040	0.6239	0.3578
24.8.1993	0.4762	0.472	-.0062	0.7755	0.6552
25.8.1993	0.2121	0.296	-.0042	0.898	0.6277
29.8.1993	0.5452	0.672	-.0051	0.8771	0.6249

Bhaintan

14.8.1979	0.5284	0.5457	.0223	0.6253	0.5484
2 9.1980	1.4934	2.3225	.2670	0.5468	0.3402
13.7.1981	3.105	3.577	.7945	0.6856	0.6730
5 .8.1982	1.092	1.1717	-.0222	0.8433	0.8400
29.7.1982	1.320	1.420	-.083	0.8674	0.8593
20.8.1982	1.0287	1.244	.0167	0.8694	0.8504

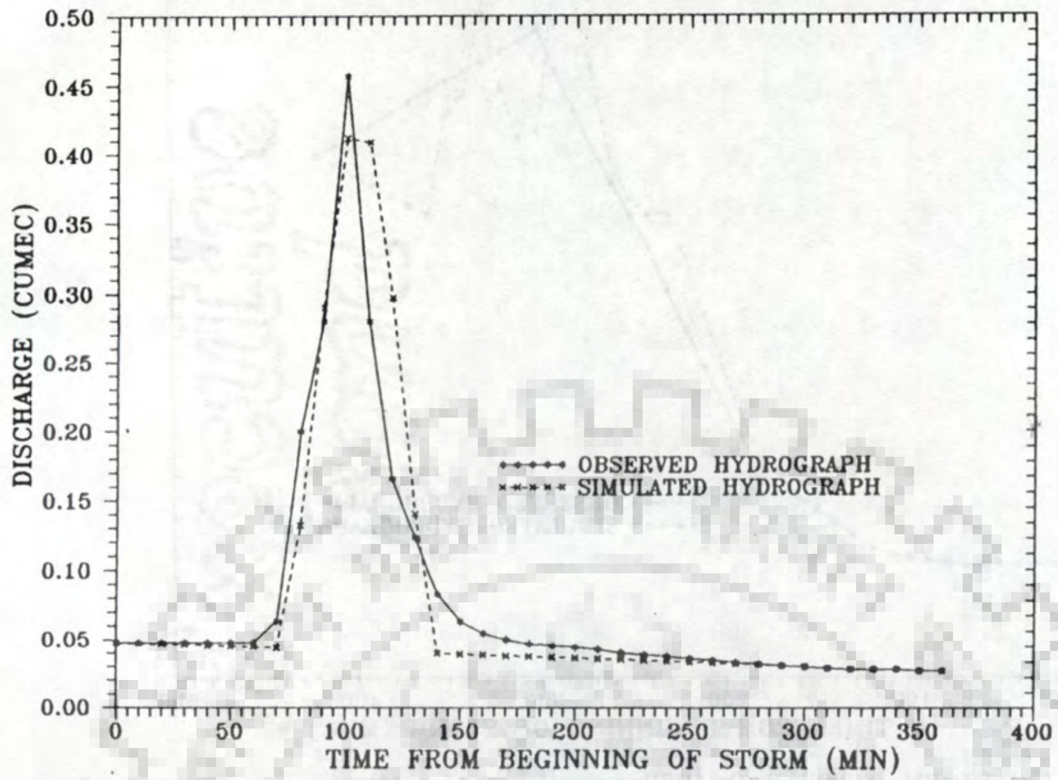


a) STORM DATED 2-9-1980

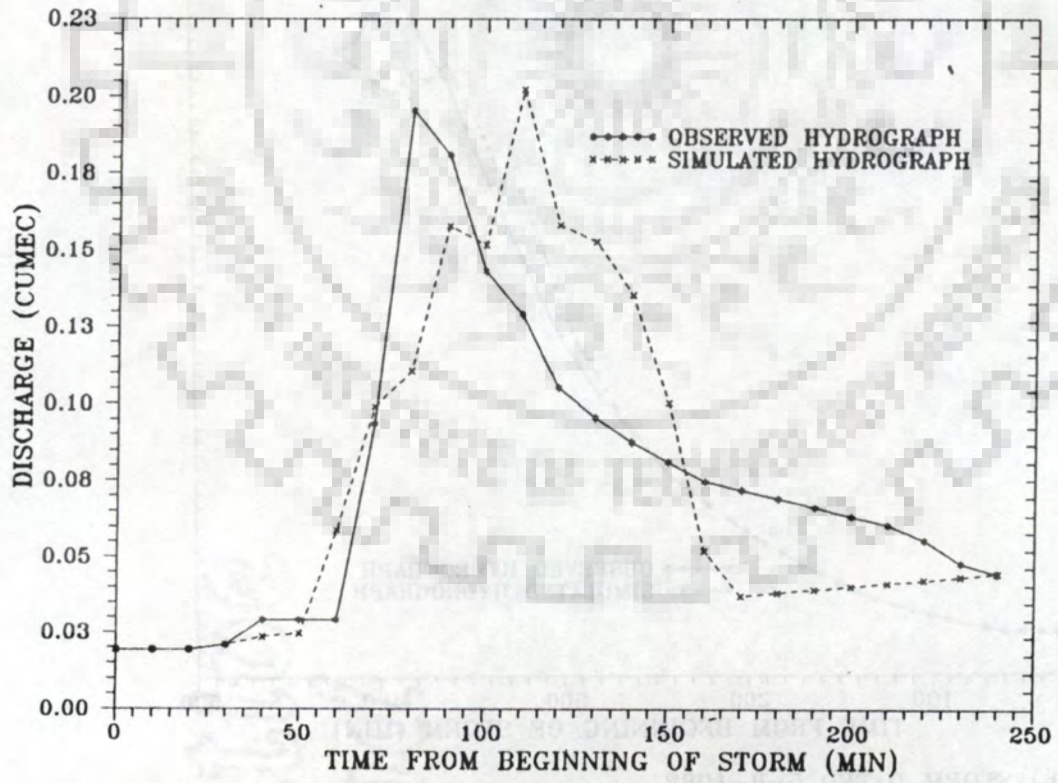


b) STORM DATED 5-8-1982

FIG.5.13- COMPARISON OF OBSERVED AND COMPUTED HYDROGRAPH USING TIME-AREA BASED MODEL (BHAINTAN WATERSHED).

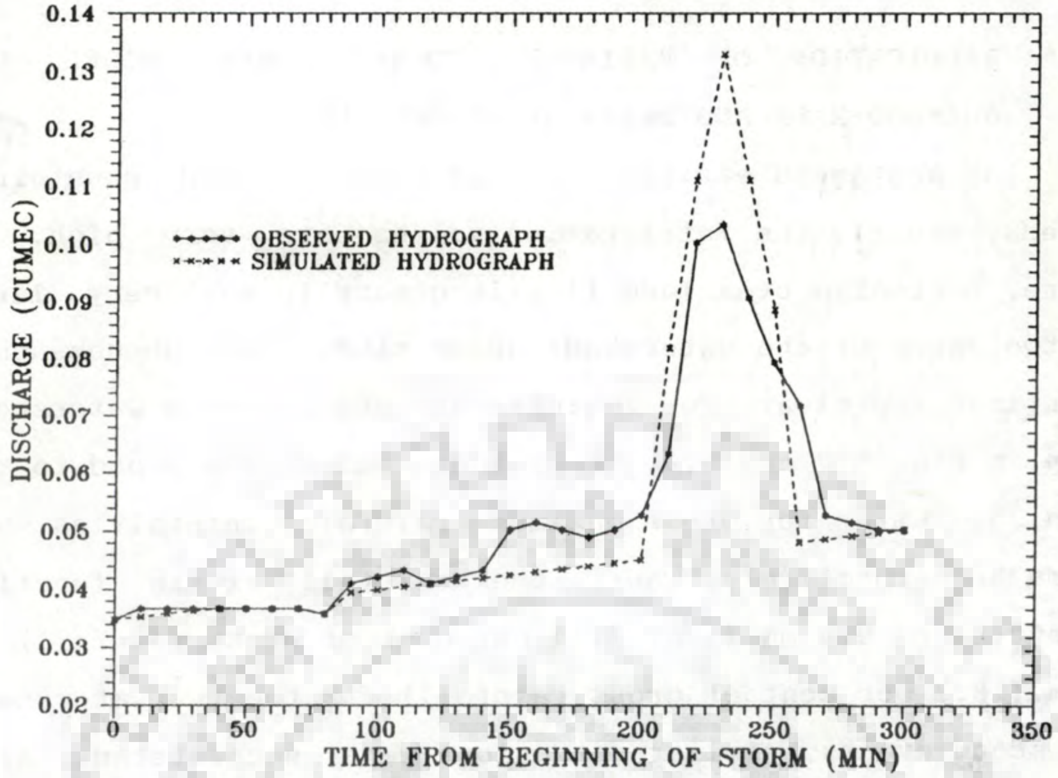


a) STORM DATED 22-7-1992

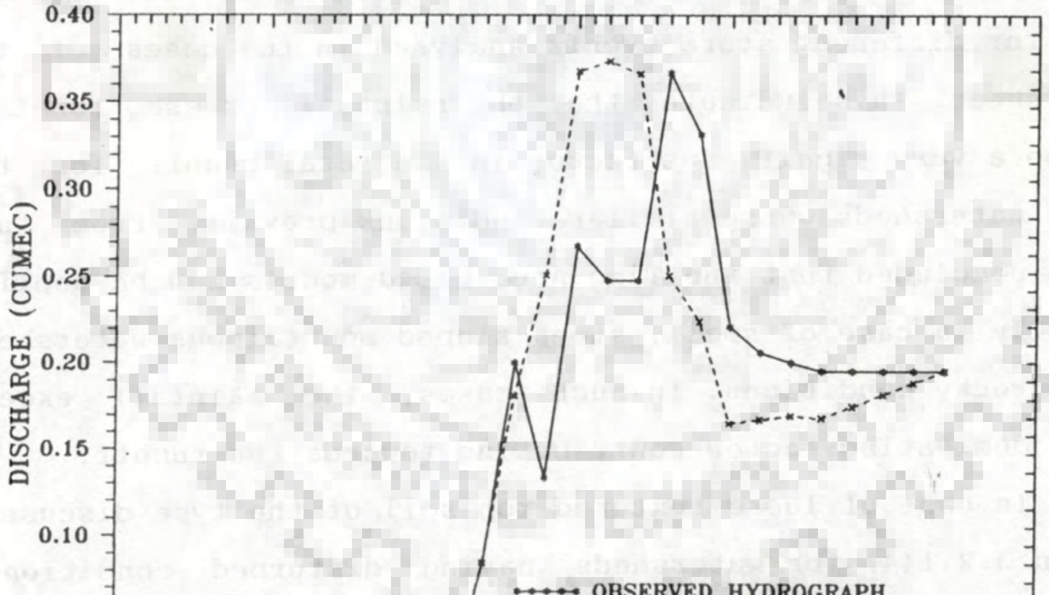


b) STORM DATED 28-7-1992

FIG. 5.14-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS USING TIME-AREA BASED MODEL (JHANDOO-NALA WATERSHED).



a) STORM DATED 22-7-1993



b) STORM DATED 2-9-1993

FIG.5.15-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS USING TIME-AREA BASED MODEL (JHANDOO-NALA WATERSHED).

5.3 APPLICATION OF VARIABLE SOURCE AREA MODEL ONTO JHANDOO-NALA AND BHAINTAN WATERSHEDS

As mentioned earlier, in case of disturbed mountainous watersheds, usually the infiltration values are very high, and therefore, Hortonian over land flow is generally not very large. In the two cases of the watersheds under study, this phenomenon is very distinct and clear. For Bhaintan and Jhandoo-Nala watersheds, as shown in Fig. 5.7 and 5.8, the ϕ-index values are found to be 50.7 and 35.7 mm/hr for gross maximum rainfall intensities 50.7 and 60 mm/hr respectively. Thus, the rainfall excess functions worked out to be 0.6 mm (i.e. 1.13 per cent of gross rainfall) and 4.107 mm (13.7 per cent of gross rainfall) for the two watersheds. In most storm events, similar situations were encountered. Also, the rainfall excess function has been found to spread over much smaller durations i.e. over one or two time steps of ten minutes duration for different storm events analysed in the cases of the two watersheds. This indicates that the rainfall excess function may not be a very significant factor in the total runoff for the disturbed watersheds where similar conditions prevail. From this it may be concluded that the Time-Area based models can be applied successfully in case of small, steep sloped mountainous watersheds with bare rocky conditions. In such cases, the rainfall excess will be a dominating factor contributing towards the runoff.

In case of loose textured top soil of the type discussed in section 3.2.1(4) for watersheds having disturbed conditions, most of the rainfall gets infiltrated, as seen in cases of the two watersheds under study. As thought of by Sloan et al. (1983) in case of the Variable Source Area model, the infiltration rates may thus be 'infinite'. Keeping the above points in view, the simulation model based on "Variable Source Area" Concept was suggested. The description of the model is presented in Section

4.2. The availability of data and description of watersheds are given in Chapter-III.

5.3.1 Parameter Estimation (Model Calibration)

As discussed in section 4.3.2, the proposed Variable Source Area event based model has 14 parameters. Also, there are two variables, namely USIN and SSIN, which vary from storm to storm depending on the actual water content in Soil and Groundwater zone. Some of these parameters were measured / estimated from the field data whereas the rest were obtained by following the procedure of trial and error i.e. the subjective method of optimization for a satisfactory match of the computed and observed hydrographs. In this study the 'split record technique' was used for the purpose. At Jhandoo-Nala watershed storm events of 1990 and 1991 monsoon season were adopted for calibration.

Storm events recorded during 1992 and 1993 monsoon season were used for the validation of the model. Since, the data of only five storm events registered at Bhaintan watershed were available, therefore, the same were used for calibration (parameter estimation) purposes as well as for the validation (testing) of the model. A brief description of the 14 parameters, the two variables, the procedure followed for their estimation together with the initial values adopted for the same are mentioned in Table 5.5.

The calibration of the proposed model was carried out using subjective optimization i.e. changing values of parameters in such a way that the parameter values are 'reasonable ' and a close fit of observed and computed hydrograph for the storm event is obtained. For goodness of fit, the criterion of minimization of difference between the observed and computed runoff volume was adopted. The ranges of parameter values alongwith their optimum

Table 5.5: **Source Information Used for Estimation of Parameters and Variables in the Variable Source-Area Model.**

Sl. No.	Parameters/ Variables	Description	Procedure of Determination	Initial Values adopted: Bhaintan Watershed	Initial Values adopted: Jhandoo Nala Watershed
(1)	(2)	(3)	(4)	(5)	(6)
[A]	Parameters used for the estimation of the extent of 'Saturated Area'				
1.	SC	Source area coefficient	Optimization	$4x10^{-3}$	$6.0x10^{-3}$
2.	SAC	Source area exponent	Optimization	10.0	8.0
3.	CSMAX	Sum of maximum soil Zone and groundwater storage (mm)	Optimization	2000.0	3000.0
4.	USZT	Soil zone thickness (mm)	Soil survey	700.0	900.0
5.	K3	Fraction of soil zone storage contributing to expansion of area	Optimization	0.6	0.5
6.	K4	Fraction of Groundwater Zone storage contributing towards expansion of source area.	Optimization	0.4	0.3
7.	PCAR	Fraction of area always contributing to channel precipitation (Stream area)	Toposheet and field measurement.	0.010	0.005
[B]	Parameters Related to Soil Zone Storage				
8.	USIN	Actual soil water volume (mm)	Estimated based on soil properties and API	240	220

Sl. No.	Parameters/ Variables	Description	Procedure of Determination	Initial Values adopted	
				Bhaintan Watershed	Jhandoo Nala-Water-shed
(1)	(2)	(3)	(4)	(5)	(6)
9.	KU	Soil water conductivity exponent	Values adopted from the model of Sloan et al. (1983)	12.0	8.0
10	FU	Soil water conductivity coefficient		$1.5x10^7$	$2.0x10^7$
11	K1	Fraction Capacity of soil zone drainage becoming interflow	Estimated on the basis of soil properties and API.	0.20	0.20
12	USFC	Field Capacity of Soil (mm)	Estimated on the basis of soil pro-perties within the watershed	200.0	210.0
[C]	Parameters/Variables Related to Groundwater Zone				
13	SSIN	Actual groundwater volume (mm)	Estimated on the basis of soil proper-ties and API	260.0	280.0
14	KS	Groundwater Exponent	Estimated on the basis of baseflow of the watershed and soil properties.	0.30	0.25
15	FS	Groundwater Recession coefficient		0.004	0.002
16	K2	Fraction of groundwater flow becoming baseflow		0.50	0.60

values obtained during the calibration are given in Table 5.6. Optimum values could not be assigned for USIN and SSIN as these were found to be highly variable and changed from storm to storm depending on the antecedent moisture conditions of the watershed.

The results of the calibration for the proposed model are given in Table 5.7 for the storm events used in the case of the two test watersheds The results are given in terms of relative percent error in volume and peak flow rates.

Standard error of estimate and model efficiency for each storm event included in calibration are also given. Expression for standard error of estimate and model efficiency are given in Chapter-II in its section 2.7. Minimum model efficiency has been found to be 77.3 per cent while the maximum efficiency is 93.6 per cent. Relative percent error in runoff volume varies between -1.66 to 4.22 per cent which is quite low. However, in case of Bhaintan watershed, relative percent error in runoff volume ranged from -3.74 to 17.40 percent. It may be seen in the Table 5.7 that except for the storm event of 13.7.1981 where a maximum relative percent error of 17.4 percent was observed, this value remained within ± 5.0 percent in cases of other events. Relative per cent errors in peak flow rates varied between -2.7 to 12.9 percent for the events registered at Jhandoo-Nala watershed and between -33.00 to 8 per cent for the storms of Bhaintan watershed. Again, the same storm event (i.e. 13.7.1981) gave a high relative percent error of -33.9 percent whereas for other events errors were within reasonable limits. Standard error of estimate remained between 0.001 to 0.0116.

5.3.2 Model Testing

Dawdy and Lichty (1968) suggested the following criteria that need be used for testing the usefulnesses (validity) of hydrologic models. These included, accuracy of prediction,

Table 5.6 **Parameters/Variables, Their Ranges and Optimum Values Obtained During Calibration for Different Storm Events Registered at the Jhandoo-Nala and Bhaintan Watersheds.**

Sl. No.	Parameters/ Variables	Range of Parameters/ Variable for the two Watersheds		Optimum Value of Parameter for the Watersheds	
		Lower	Upper	Jhandoo-Nala	Bhaintan
(1)	(2)	(3)	(4)	(5)	(6)
1	K1	0.10	0.27	0.24	0.20
2	K2	0.10	0.60	0.40	0.40
3	K3	0.40	1.20	0.60	0.60
4	K4	0.20	0.80	0.40	0.40
5	PCAR	0.002	0.025	0.01	0.005
6	SAC	1.0	16.0	6.0	1.00
7	SC	0.0002	0.004	0.003	0.001
8	USZT	500.0	1000.0	700.0	900.0
9	USFC	180.0	220.0	200.0	200.0
10	CSMAX	1000.0	3000.0	1500.0	2500.0
11	FU	$1.0x10^{7}$	$2.0x10^{7}$	$1.5x10^{7}$	$1.5x10^{7}$
12	KU	10.0	20.0	11.6	12.0
13	FS	0.001	0.01	0.003	0.005
14	KS	0.10	0.30	0.20	0.10
15	USIN	220.0	360.0	*	*
16	SSIN	240.0	500.0	*	*

*** Values of these variables (USIN and SSIN)changed from storm to storm as these depend on the antecedent moisture conditions of the watershed i.e. actual water content in the Soil Zone and the Groundwater Zone respectively prior to events.-**

Table 5.7: Results of Model Calibration for Variable Source Area Model onto the Two Test Watersheds

Sl.No.	Storm Event	Peak Flow Rate(lps) Observed	Peak Flow Rate(lps) Computed	Relative Error (%) in Peak flow	Percent in Runoff volume	Standard Error of Estimate (SE)	Model Efficiency (EFF)(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[A]	JHANDOO-NALA WATERSHED						
1	4.7.1990	150.0	150.9	-0.27	0.20	0.0044	83.81
2.	10.8.1990	122.7	116.7	4.89	4.22	0.0039	77.26
3.	11.8.1990	126.0	129.4	-2.70	3.08	0.0030	85.31
4.	16.8.1990	176.1	168.0	4.60	2.35	0.0050	86.81
5.	18.8.1990	176.1	158.7	9.88	1.84	0.0040	85.33
6.	25.8.1990	82.7	79.0	4.47	0.37	0.0039	78.90
7.	7.8.1991	293.4	280.8	4.29	-1.51	0.0080	87.82
8.	8.8.1991	412.9	399.3	3.29	-1.66	0.0060	93.59
9.	9.8.1991	377.7	330.6	12.47	-0.74	0.0116	79.42
10	15.8.1991	248.0	221.1	10.85	0.30	0.0110	82.65
11	16.8.1991	331.5	326.5	1.51	1.76	0.0055	86.68
[BHAINTAN WATERSHED]							
12	14.8.1979	528.6	486.5	7.96	4.00	0.0009	90.84
13	2.9.1980	1494.1	2000.4	-33.89	-2.33	0.0027	87.93
14	13.7.1981	3106.0	3102.3	0.09	17.40	0.0101	78.89
15	29.7.1982	1320.7	1381.8	-4.63	2.68	0.0029	89.58
16	20.8.1982	1029.0	1049.0	-1.92	-3.74	0.0021	88.20

consistency of parameter estimate, sensitivity of results to changes in parameter values, and the same criteria are being adopted for the present study .

The proposed Variable Source Area model was applied onto the two test watersheds to test the model for accuracy of prediction and consistency of parameter estimates. Accuracy of prediction is expressed in terms of relative per cent error in observed and predicted values for the runoff volume as well as for the Peak flow rates.

As mentioned in the previous section 11 storm events registered at Jhandoo-Nala watershed during the 1992 and 1993 monsoon season were used for the validation of Variable source area model onto the Jhandoo-Nala watershed whereas all the 5 variable storm events registered at Bhaintan watershed were used for the same purpose. Optimum parameter values for the watersheds obtained during calibration (Table 5.7) were used for the simulation of runoff hydrographs to test the validity of the proposed watershed model. The storm characteristics and the resulting runoff alongwith API values as well as the baseflows for the storm events under consideration are included in the Table given in Appendix-C4. The data are fed into the mathematical formulation described in section 4.3 and the simulated responses were computed.

The observed and simulated peak flow rates, relative percentage of errors in peak flow rates and runoff volumes, standard error of estimates and model efficiencies for different events are given in Table 5.8.

a) Accuracy Efficiency and Consistency of the model

It may be observed that the relative per cent errors in runoff volume lie within $\pm$ 10 percent limits for both the watersheds, where as this error in peak flow rates is higher.

Table 5.8: Model Variation Results of Variable Source Area Model Onto the Two Test Watersheds

Sl.No.	Storm Event	Peak Flow Rate(lps) Observed	Simulated	Relative Error (%) Peak flow	Percent in Runoff volume	Standard Error of Estimate (SE)	Model Efficiency (EFF)(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[A] JHANDOO-NALA WATERSHED							
1	22.7.1992	456.9	384.8	15.8	-1.6	0.0125	76.78
2	28.7.1992	195.2	202.1	-3.5	6.3	0.0028	96.06
3	4.8.1992	165.7	148.5	10.4	-1.5	0.0037	82.27
4	22.7.1993	103.5	111.9	-8.1	-0.2	0.0032	73.42
5	2.8.1993	52.8	54.0	-2.3	-2.6	0.0019	75.16
6	23.8.1993	318.2	267.8	15.8	0.1	0.0124	72.75
7	24.8.1993	476.2	376.7	20.9	4.5	0.0148	80.17
8	29.8.1993	545.2	477.2	12.5	-1.5	0.0067	95.89
9	2.9.1993	366.9	332.9	9.3	1.2	0.0129	86.43
10	8.9.1993	297.0	269.8	9.2	9.5	0.0065	92.17
11	9.9.1993	227.1	227.8	-0.3	-2.3	0.0059	88.21
[BHAINTAN WATERSHED]							
12	14.8.1979	528.6	448.9	15.1	-2.50	0.0009	90.92
13	2.9.1980	1494.1	1740.1	-16.5	0.8	0.0031	86.70
14	13.7.1981	3106.0	3423.6	-10.2	6.20	0.0117	77.18
15	29.7.1982	1320.7	1493.0	-13.0	-3.88	0.0031	85.94
16	20.8.1982	1029.0	1051.6	-2.2	-2.37	0.0021	87.44

Relative percent error in peak flow rates for Jhandoo-Nala watershed varies between -8.1 to 20.9 per cent and -16.5 to 15.1 per cent for Bhaintan watershed. The maximum and minimum model efficiencies obtained are 96.06 and 72.75 per cent respectively for the storm events of Jhandoo-Nala watershed. Except for the 13.7.1981 storm event, other events registered at Bhaintan watershed gave model efficiencies (Nash and Sutcliffe, 1970) above 85 per cent. standard error of estimate varied between .01 per cent and 1.48 percent.

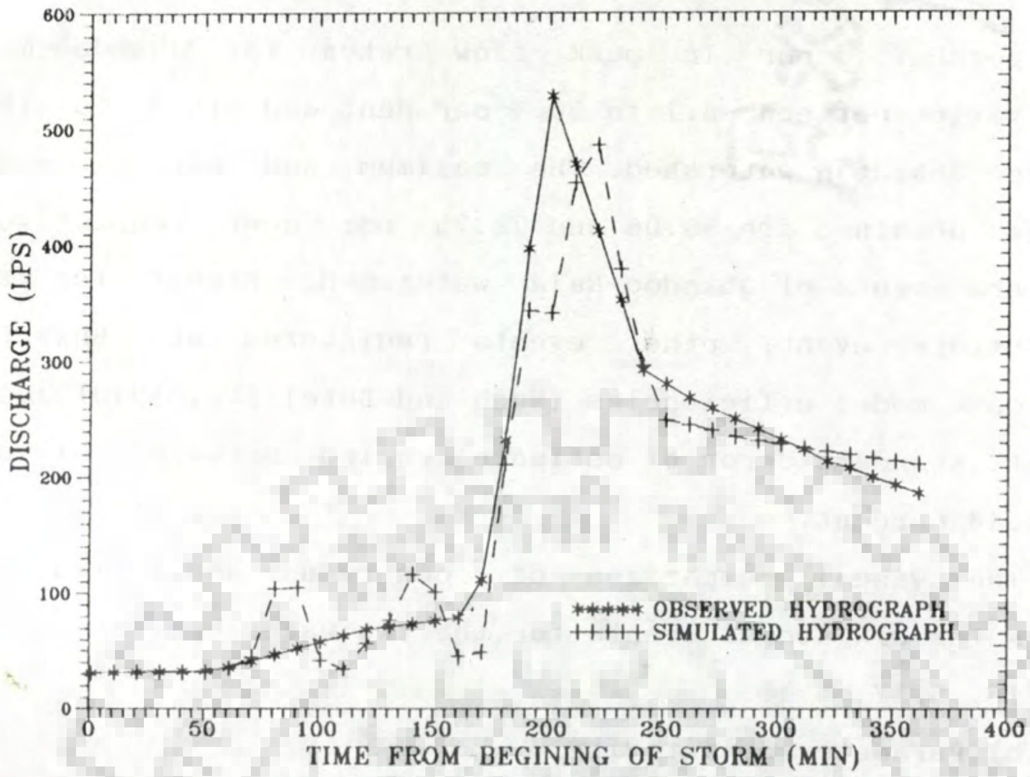
The visual comparison of observed and simulated hydrographs for six storms events for the two watersheds are shown in Fig. 5.16, 5.17, 5.18.

b) Parameter Sensitivity

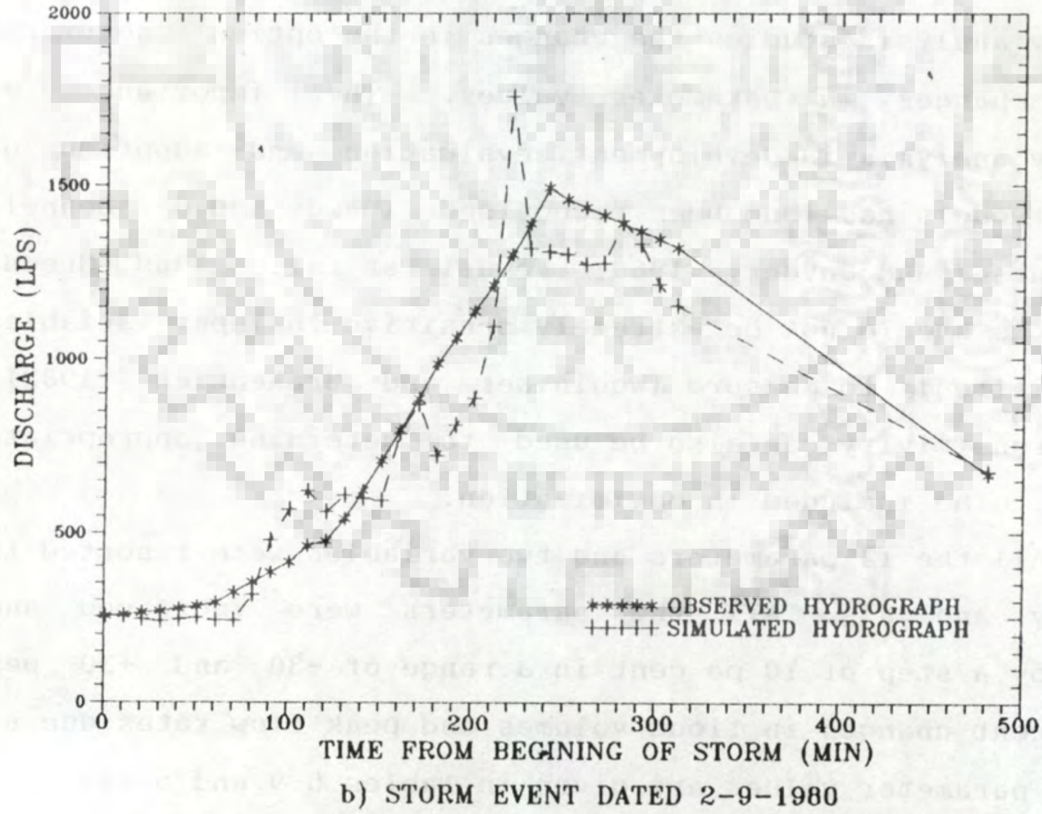
Sensitivity analysis should be a part of every effort in hydrologic modelling of small watersheds (Osborn et al., 1982). Sensitivity analysis studies the changes in the optimal solutions with the changes in parameter values. The importance of sensitivity analysis in development, evaluation and adoption of hydrologic models has long been recognised (Dawdy and O 'Donnel, 1965; Decoursey and Snyder, 1969; Vemuri et al., 1969 Green, 1970). Models should not be extremely sensitive to input variables that are difficult to measure (Woolhiser and Brakensiek, 1982). Parameter sensitivity can also be used to determine appropriate parameters to be included in optimization.

All the 14 parameters and two variables were resorted to sensitivity analysis. All the parameters were increased and decreased by a step of 10 pe cent in a range of -30 and +30 per cent. Per cent changes in flood volumes and peak flow rates due to changes in parameter values are given in Tables 5.9 and 5.10.

The variable USIN affects a maximum change i.e. -61 to 240 per cent in case of flood volume and -41.6 to 360 per cent in

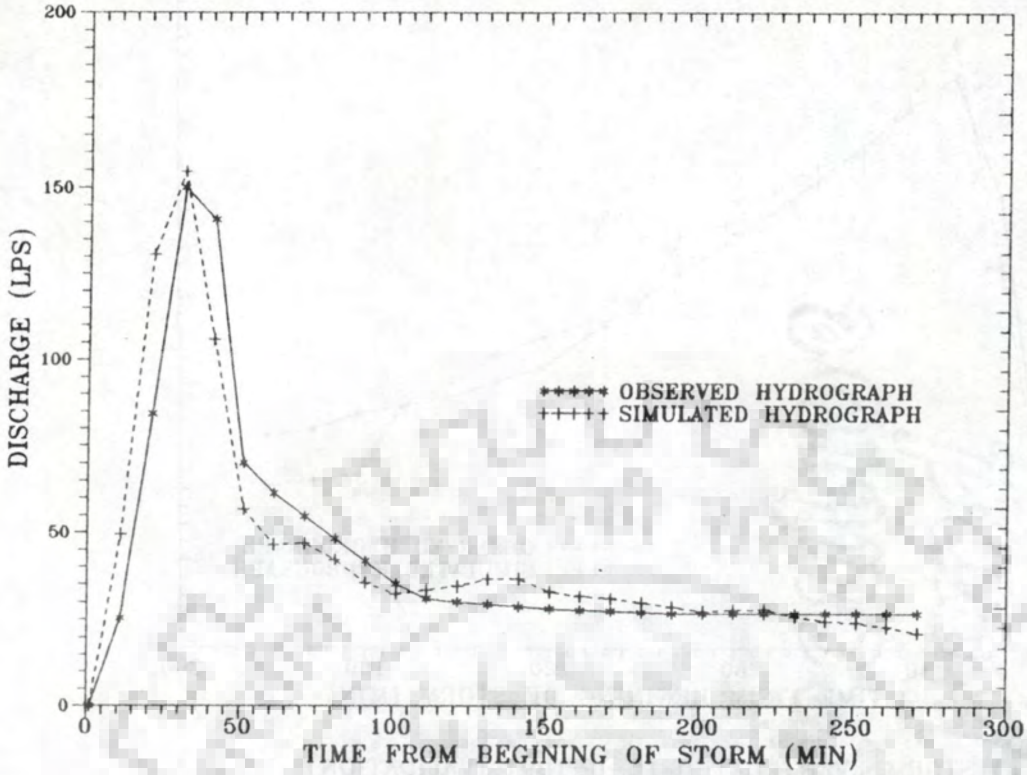


a) STORM EVENT DATED 14-8-1979

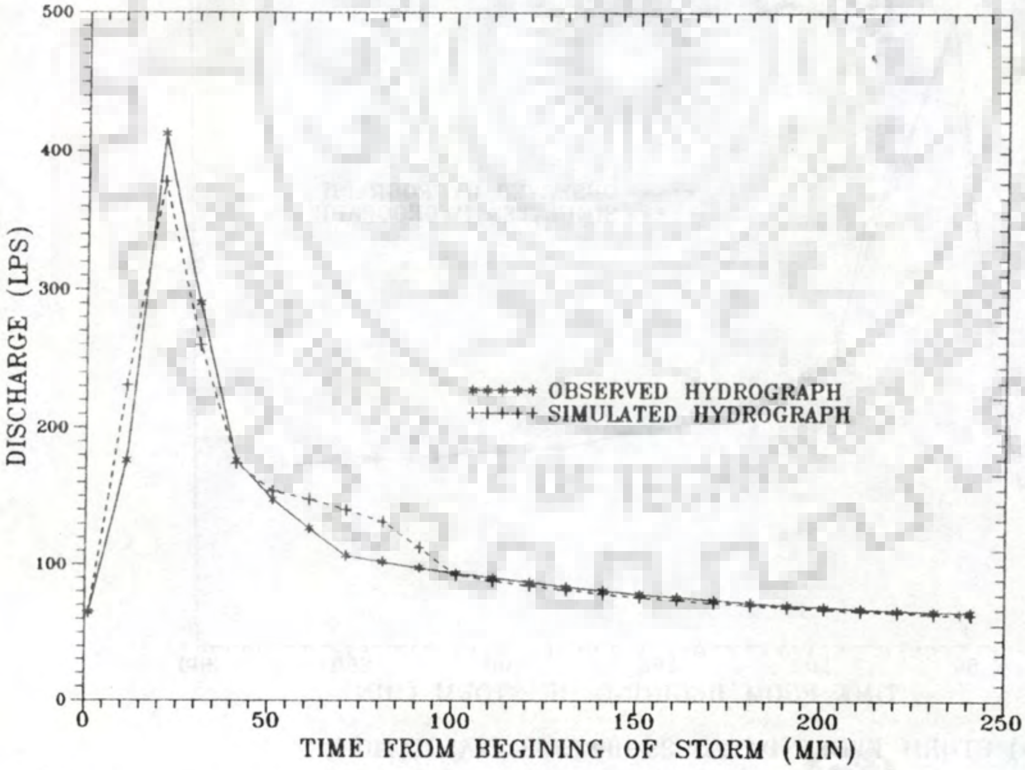


b) STORM EVENT DATED 2-9-1980

FIG.5.16-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING VARIABLE SOURCE AREA MODEL (BHAINTAN WATERSHED).

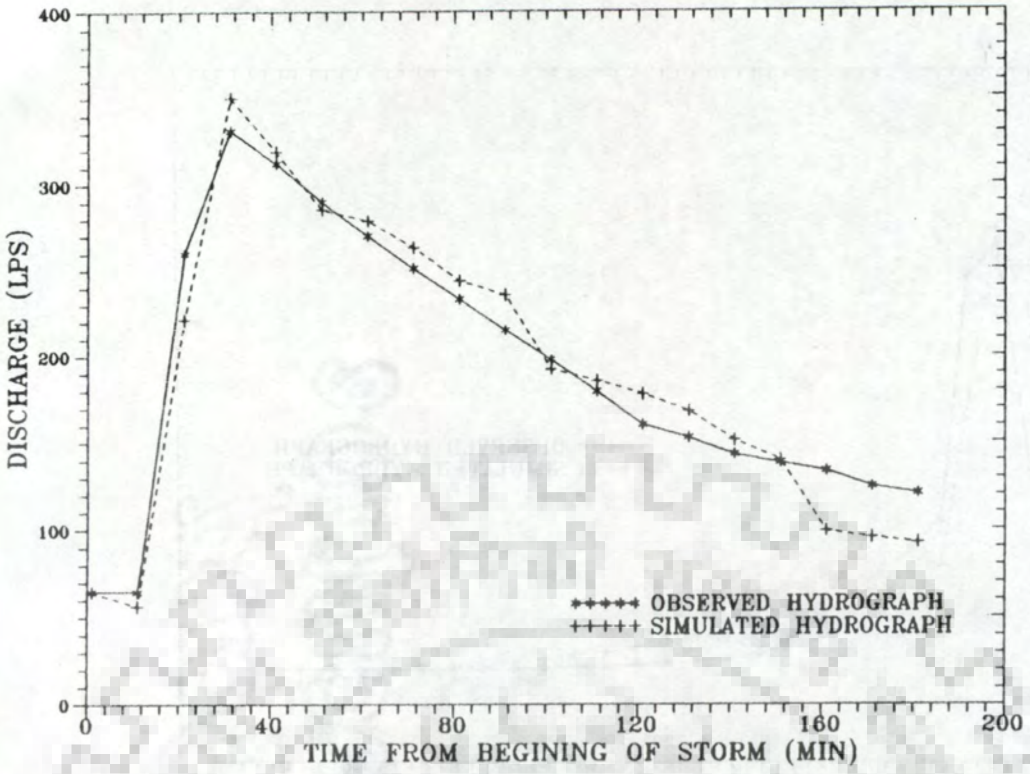


a) STORM EVENT DATED 4-7-1990 (CALIBRATION)

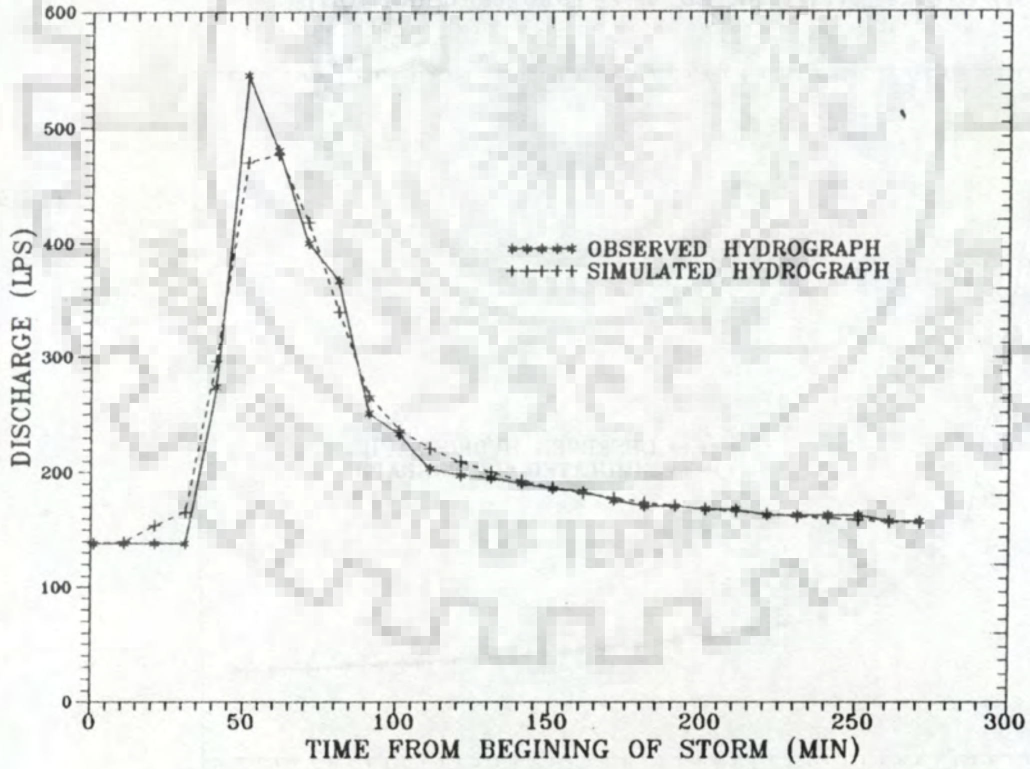


b) STORM EVENT DATED 8-8-1991 (CALIBRATION)

FIG.5.17-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING VARIABLE SOURCE AREA MODEL (JHANDOO-NALA WATERSHED).



a) STORM EVENT DATED 16-8-1991 (VALIDATION)



b) STORM EVENT DATED 29-8-1993 (VALIDATION)

FIG. 5.18–COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS USING VARIABLE SOURCE AREA MODEL (JHANDOO-NALA WATERSHED).

Table 5.9 Sensitivity Analysis of the Variable Source Area Model for Sensitivity in Flood Volumes

		CHANGE IN VOLUME (%)					
Sl.	Parameters	Percent changes in parameter					
No.	Name	-30	-20	-10	+10	+20	+30
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	PCAR	-1.03	-0.51	-0.31	0.20	0.41	0.72
2	CSMAX	54.40	22.00	7.81	-4.83	-7.91	-9.97
3	SAC	-11.82	-9.04	-5.24	6.90	16.24	28.80
4	SC	-5.96	-4.01	-2.05	1.95	3.90	5.86
5	USZT	95.80	63.00	30.32	-81.62	-85.26	-87.04
6	USIN	-61.05	-58.40	-49.23	77.80	158.80	240.10
7	SSIN	-9.66	-6.58	-3.40	3.60	7.60	12.13
8	FS	-6.06	-4.01	-2.05	1.95	3.90	5.96
9	KS	-5.65	-4.01	-2.16	2.26	4.83	7.71
10	FU	-7.81	-4.93	-2.36	2.05	4.01	5.86
11	KU	152.41	99.38	47.27	-33.81	-47.80	-51.18
12	K1	-15.52	-10.40	-5.24	5.14	10.30	15.42
13	K2	- 6.06	- 4.01	-2.05	1.95	3.91	5.96
14	K3	- 7.60	- 5.45	-2.98	3.39	7.40	12.02
15	K4	- 6.88	- 4.93	-2.67	2.98	6.37	10.38
16	USFC	143.50	94.55	46.04	-35.35	-49.95	-52.82

Table 5.10 Sensitivity Analysis of the Variable Source Area Model for Sensitivity in Peak Flow Rates.

		PERCENT CHANGE IN VOLUME (%)					
Sl.	Parameters	Percent changes in parameter					
No.	Name	-30	-20	-10	+10	+20	+30
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	PCAR	-2.46	-1.63	-0.82	0.81	1.63	2.45
2	CSMAX	170.07	73.37	26.10	-15.80	-26.07	-33.11
3	SAC	-39.34	-29.90	-17.16	23.09	54.11	95.66
4	SC	-19.83	-13.21	-6.61	6.60	13.19	19.78
5	USZT	166.63	108.41	34.96	-11.26	-14.72	-15.84
6	USIN	-41.60	-34.46	-25.60	40.16	224.06	360.0
7	SSIN	-23.78	-16.81	- 8.94	10.20	21.87	35.23
8	FS	-2.04	-1.36	-0.68	0.68	1.35	2.03
9	KS	-1.90	-1.33	-0.70	0.78	1.66	2.63
10	FU	-4.68	-3.10	-1.54	1.51	2.99	4.47
11	KU	260.71	162.04	61.51	-13.84	-16.09	-16.43
12	K1	- 4.97	- 3.32	-1.66	1.66	3.31	4.97
13	K2	- 2.05	- 1.37	-0.68	0.68	1.36	2.04
14	K3	-25.18	-18.07	-9.75	11.41	24.74	40.33
15	K4	-22.79	-16.24	-8.68	9.99	21.45	34.65
16	USFC	238.20	144.44	55.21	-14.33	-16.53	-16.86

peak flow rate. The parameter KU affects a considerable change i.e. in a range of -51.2 to 152 pe cent in case of flood volume and between - 16.4 to 260 per cent in peak flow rates. In addition to these, the parameters, USFC, USZT, CSMAX, and SAC i.e. the soil related parameters effect appreciable changes in volume as shown in Fig. 5.19(a). Other parameters viz. Kl, SSIN, KS, SC, FS, and FU effect moderate changes which may be seen in Fig. 5.19(b). However, the parameters PCAR, K2, K3 and K4 were found to be least sensitive to effect changes in flood volume (Fig. 5.19(c)).

In a nut shell variable USIN has been found to be most sensitive to peak flow rate as mentioned above. This is followed by the sensitivities of KU, USFC, CSMAX, USZT and SAC (refer Fig. 5.20(a)). The peak flow rate is moderately sensitive to parameters K3, K4, SSIN and SC as shown in Fig. 5.20(b). Peak flow rate is least sensitive to parameters Kl, K2, KS, FU, FS and PCAR in the model (Fig. 5.20(c)).

For consistency of the model, first the parameters should not be very sensitive to the period of the record. In the proposed model and its application, it may be seen from Table 5.7 and 5.8 that the model has computed runoff accurately and efficiently during calibration period (i.e. monsoon season of 1990 and 1991) as well as during the testing (i.e. monsoon season of 1992 and 1993). Further, for the general applicability of any model, the model parameters should remain confined to `narrow' ranges. It may be seen that in the proposed model the ranges of parameters are quite narrow and the accuracies and efficiencies in both the watershed are also of the same order. The optimum parameter values for the two watersheds are also not much different (Table 5.6) and the same can be applied to similar watersheds as the model parameter are quite consistent.

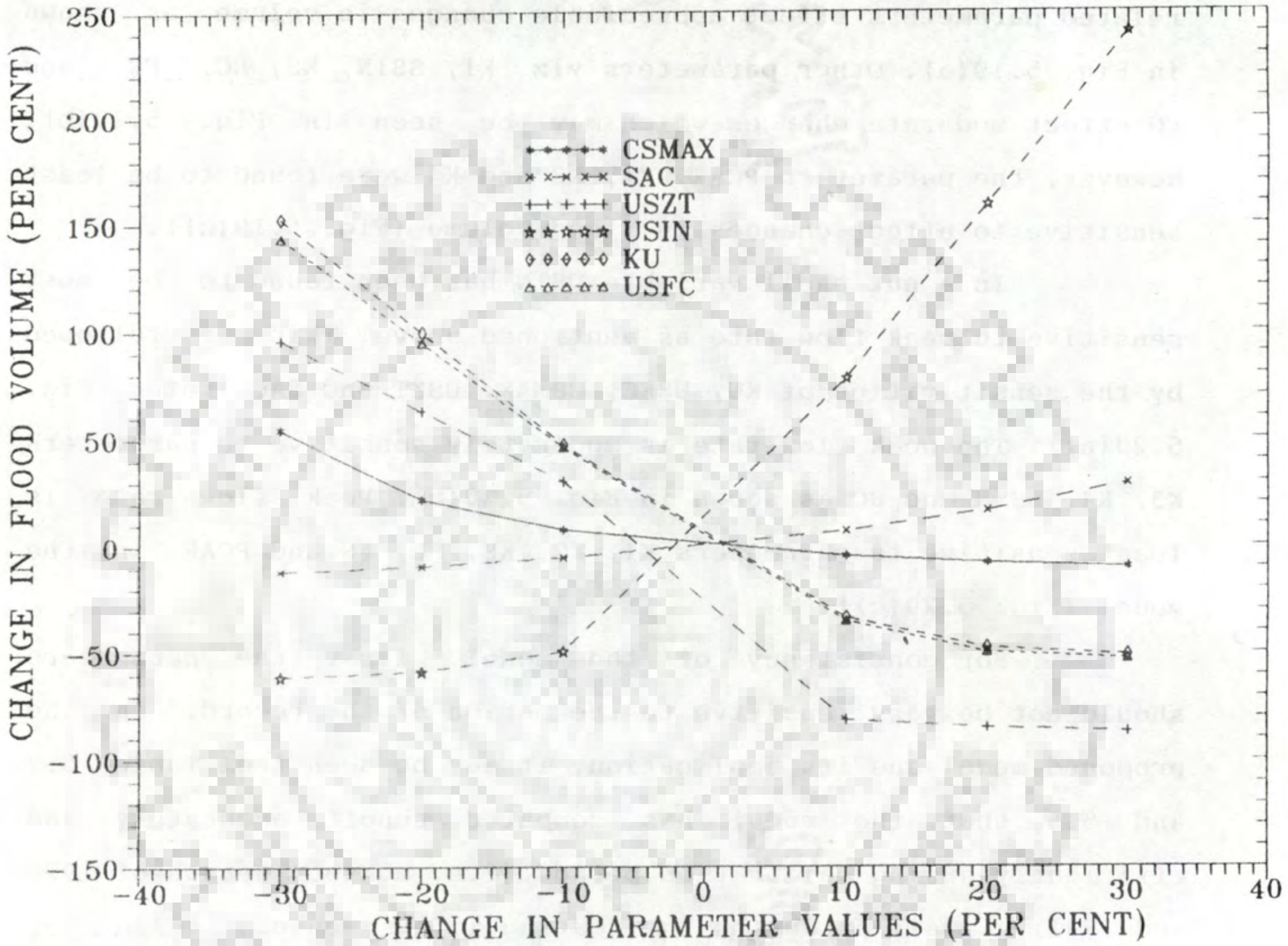


FIG.5.19(a)-SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR FLOOD VOLUME).

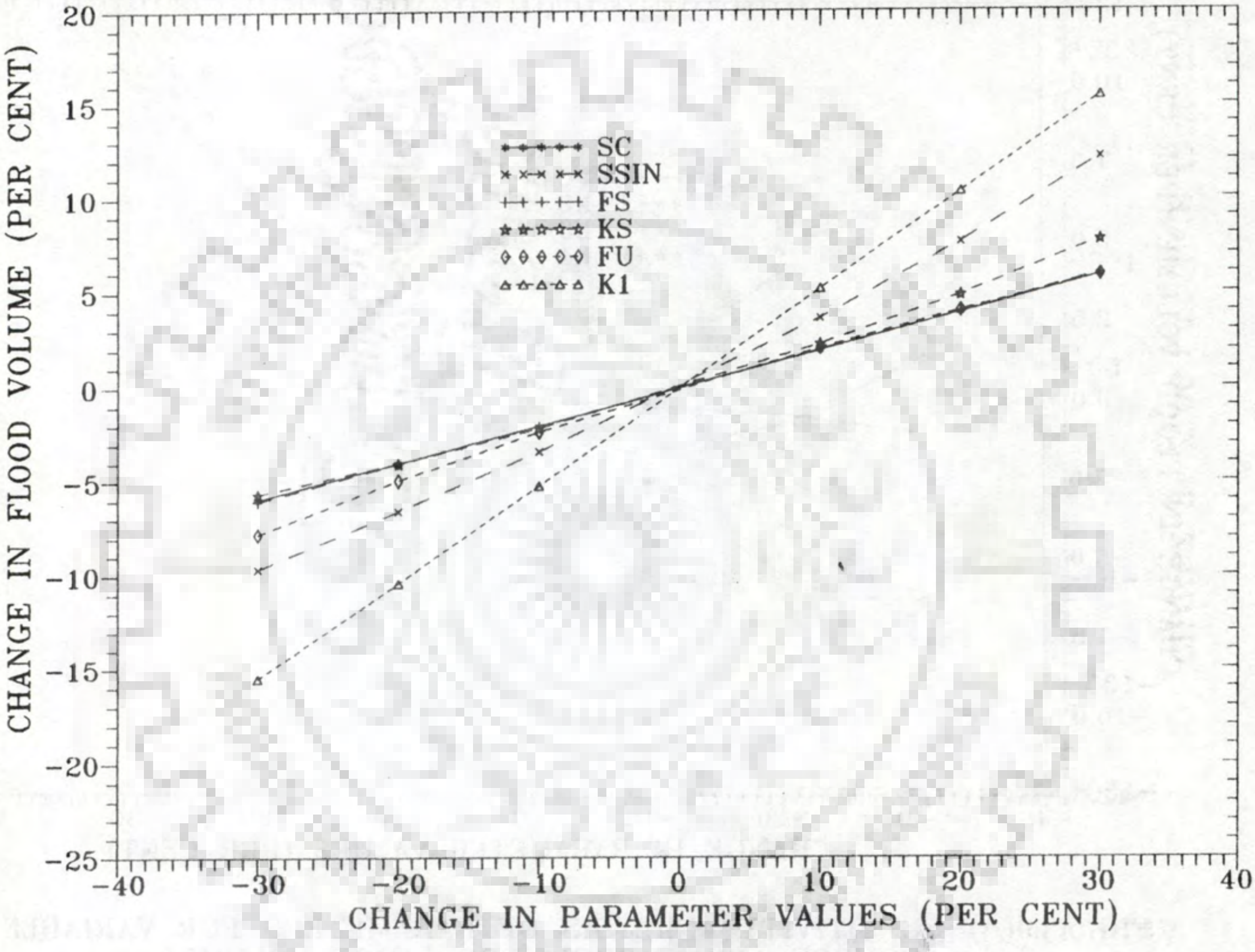


FIG.5.19(b)–SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR FLOOD VOLUME).

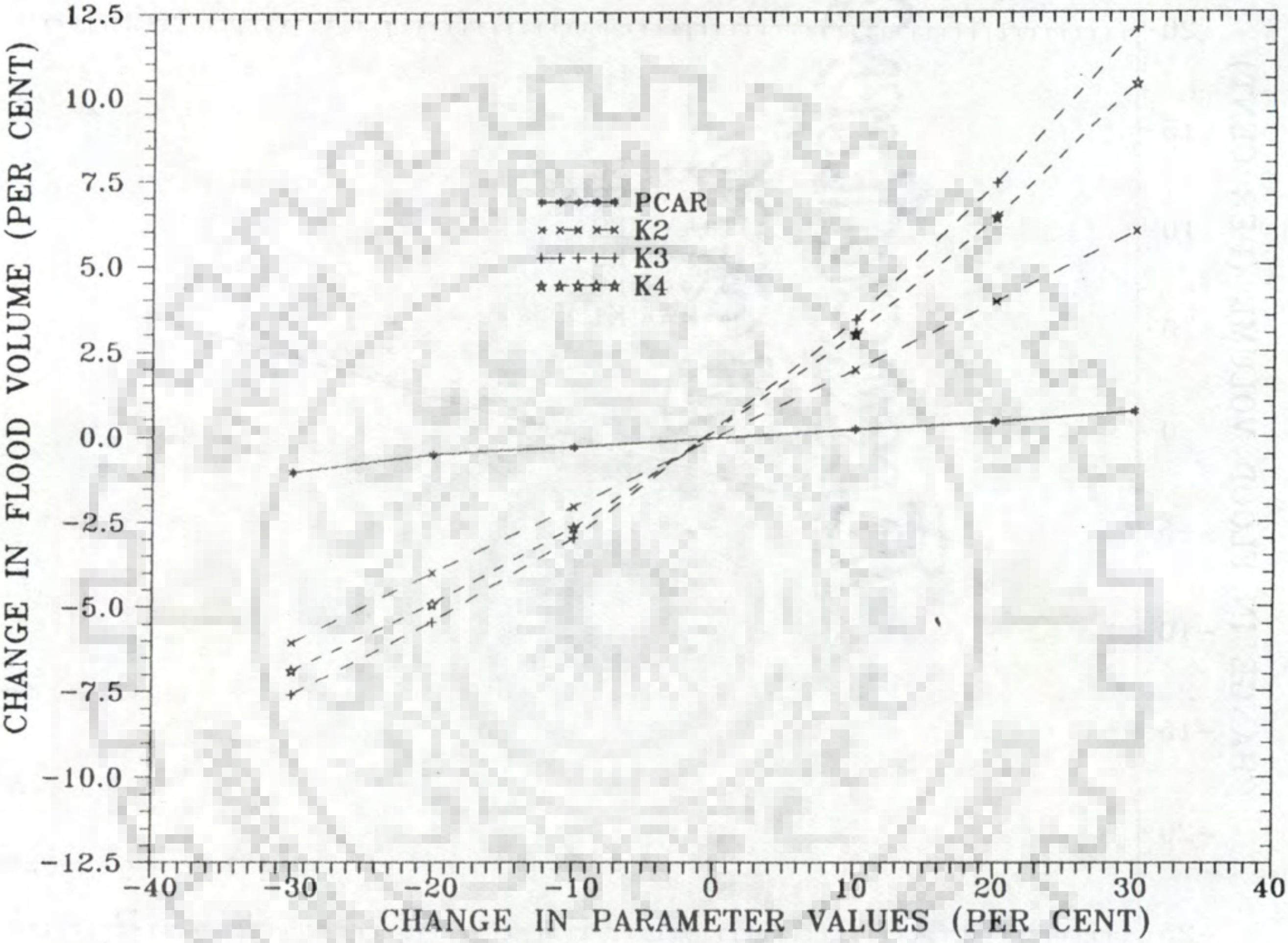


FIG.5.19(c)-SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR FLOOD VOLUME).

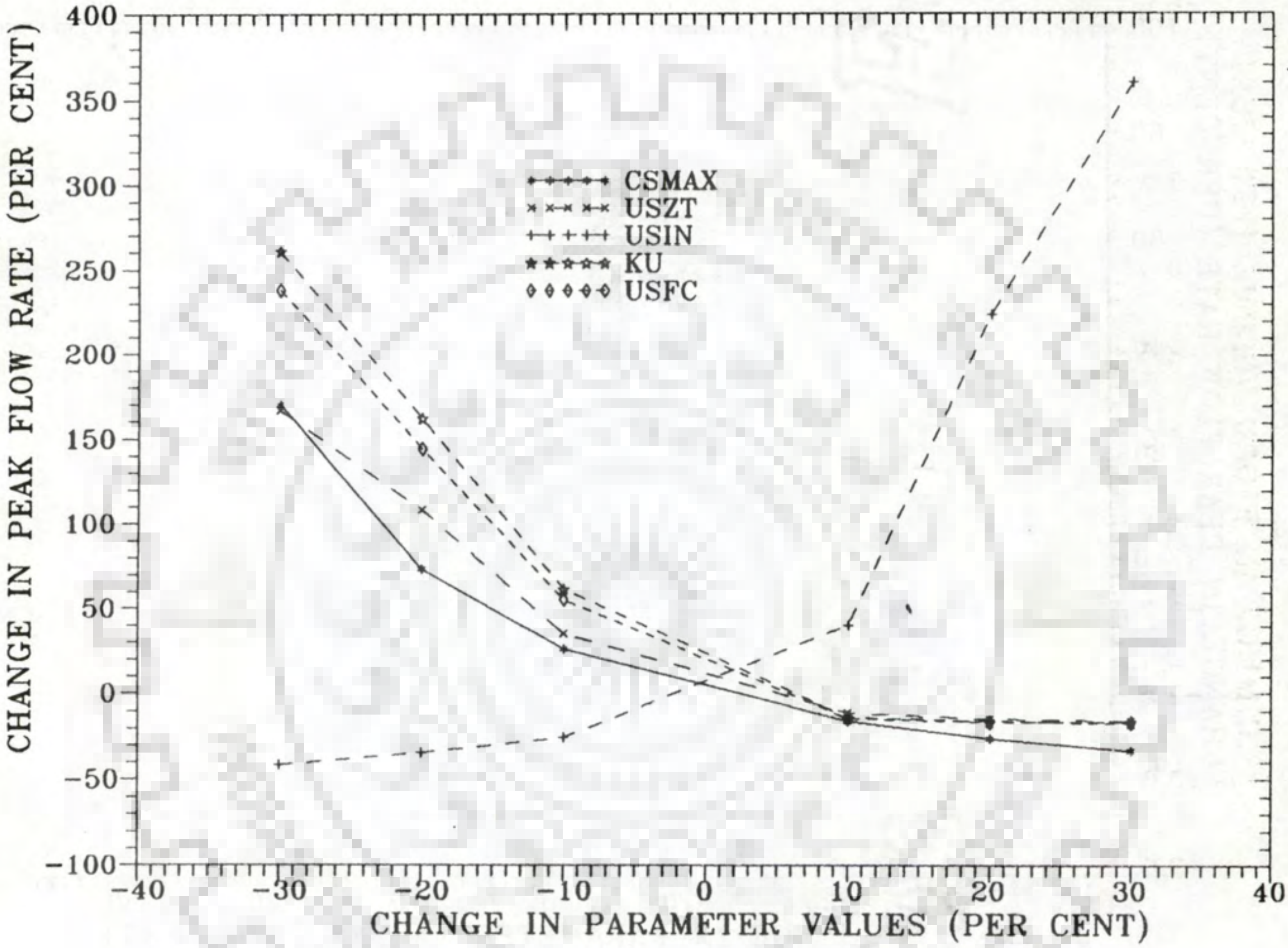


FIG.5.20(a)–SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR PEAK FLOW RATE).

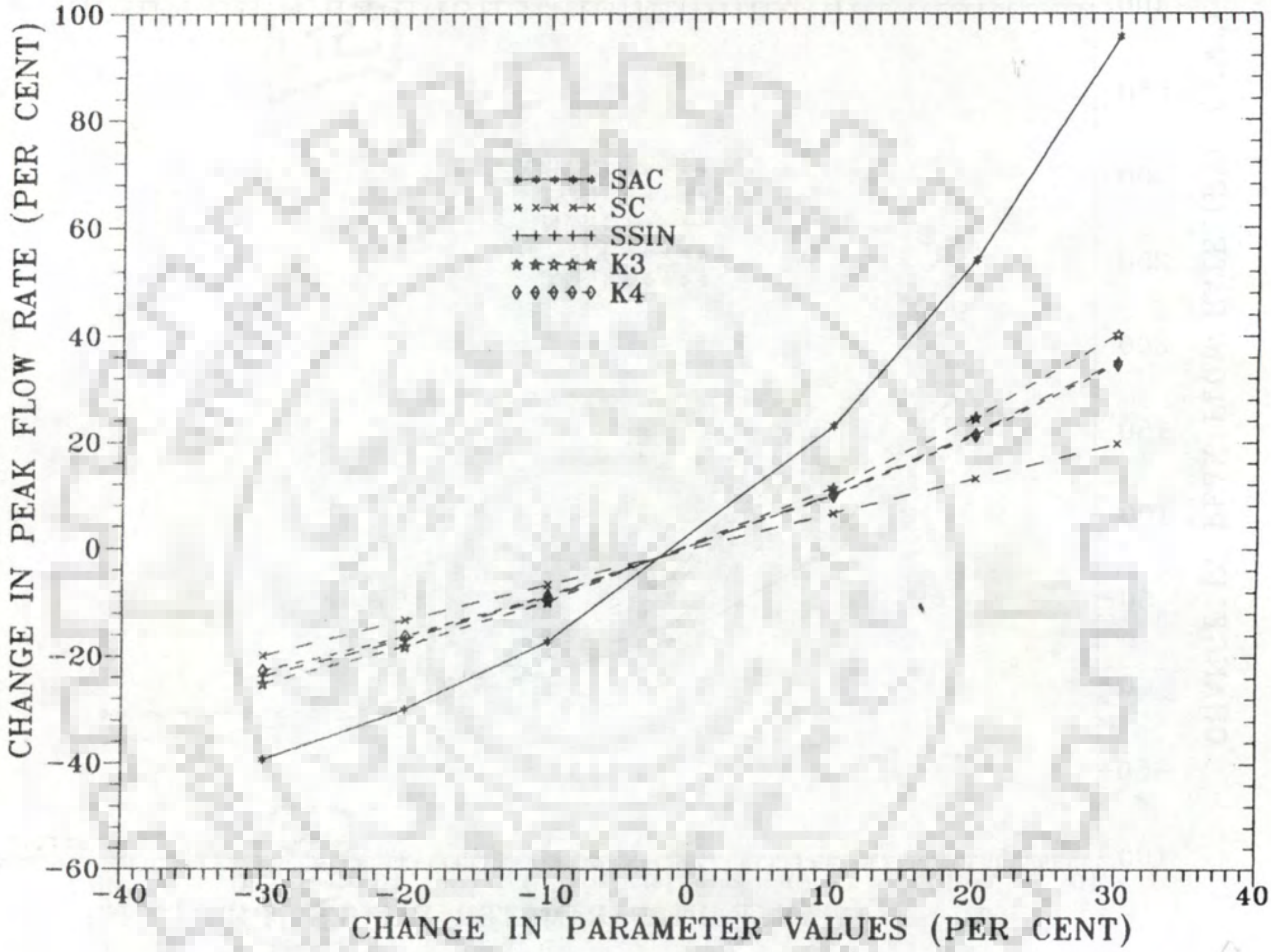


FIG.5.20(b)-SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR PEAK FLOW RATE).

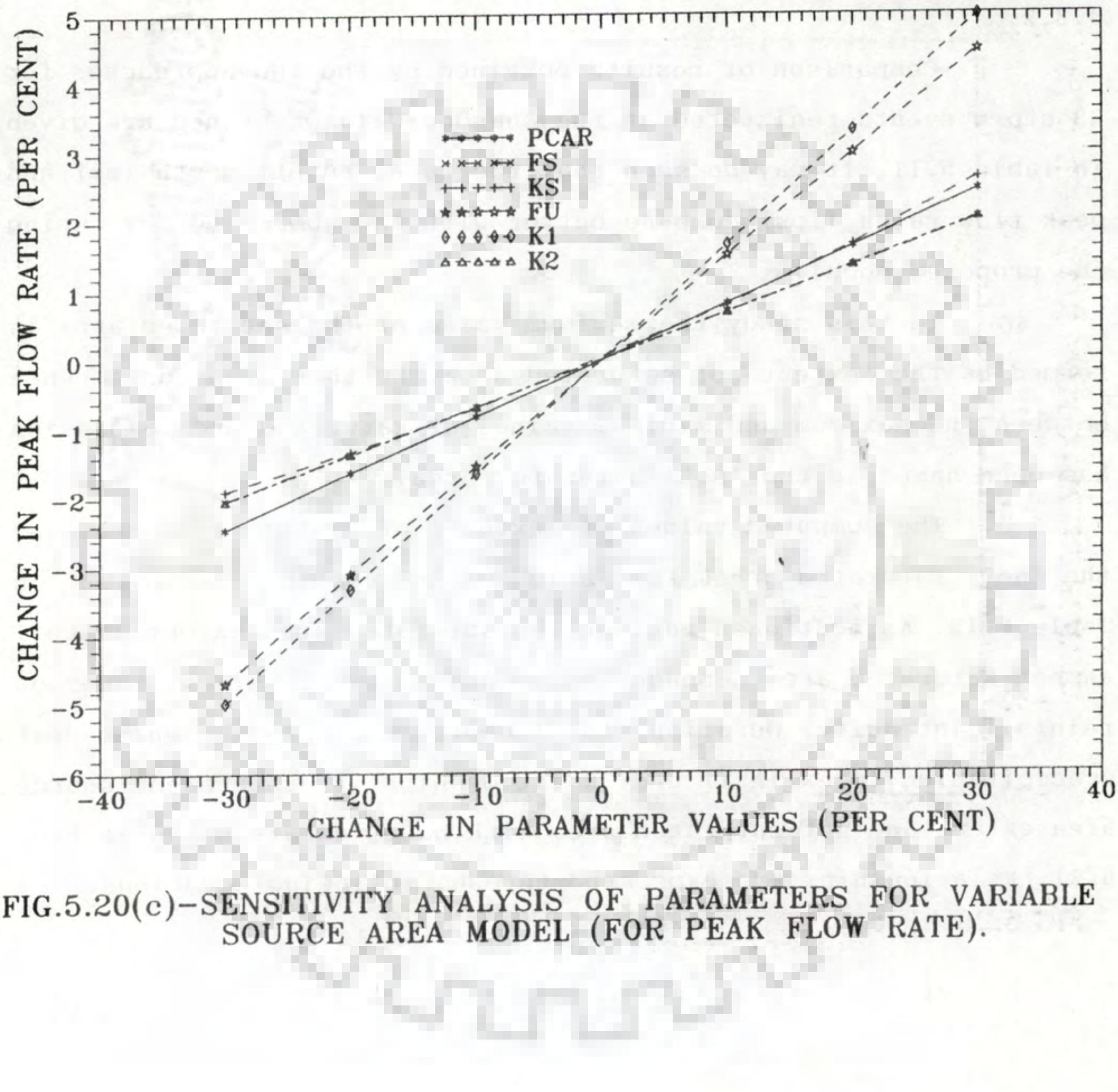


FIG.5.20(c)-SENSITIVITY ANALYSIS OF PARAMETERS FOR VARIABLE SOURCE AREA MODEL (FOR PEAK FLOW RATE).

5.3.3 Interpretation of Computed results

The Variable Source Area model proposed by Sloan et al. (1983) has been modified by Putty and Rama Prasad (1992) in which 15 parameters and two variables were used. In the proposed model the modifications made have already been discussed in section 4.3.2.

Comparison of results obtained by the two approaches for 23 storm events registered at the Jhandoo-Nala watershed are given in Table 5.11. It may be seen that the total runoff depth (mm) and peak flow rates (lps) compare better with the observed by using the proposed model.

In this study the maximum value of the saturated area is termed as the 'extent' of saturated area. Further the difference between the maximum and minimum values of saturated area expansion has been named as the 'net' saturated area.

The computed values of 'extent' of saturated area and the 'net' saturated areas for various storm events are given in Table 5.12. As mentioned earlier the saturated area extent as well as net saturated area depends on factors like baseflow, average rainfall intensity, duration, total depth of rainfall, antecedent precipitation index (API) etc. Relationships of saturated source area extent and net saturated area with baseflow are shown in Fig. 5.21. Relationships are expressed through following equations.

$$Y1 = 0.581\,(x)^{0.5338} \qquad \ldots\ldots \quad (5.2)$$

$$Y2 = 0.1003\,(x)^{0.4691} \qquad \ldots\ldots \quad (5.3)$$

Where,

Y1 = extent of saturated area (%),

Y2 = net saturated area (%) and

Table 5.11: Comparison of Observed and Simulated Total Runoff Depth and Peak Flow Rate Using Putty et al. (1992) Model and Proposed Model for Various Events Registered at Jhandoo-Nala Watershed

Sl.No.	Storm Event	Total Runoff (mm)			Peak Flow Rate (lps)		
		Observed	Simulated		Observed	Simulated	
			Putty et al. Model	Proposed Model		Putty et al. Model	Proposed Model
1	4.7.1990	4.00	3.95	4.02	150.0	118.8	150.4
2	10.8.1990	3.34	3.20	3.40	122.7	141.8	116.7
3	11.8.1990	5.71	5.52	5.61	126.0	134.0	129.4
4	16.8.1990	3.38	3.05	3.28	176.1	118.3	168.0
5	18.8.1990	5.23	5.19	5.25	176.1	141.0	158.7
6	25.8.1990	1.82	1.77	1.81	82.7	75.4	79.0
7	7.8.1991	7.96	7.91	8.00	293.4	244.6	280.8
8	8.8.1991	9.39	8.93	9.24	412.9	340.0	399.3
9	9.8.1991	7.92	7.82	7.98	377.7	321.9	330.6
10	15.8.1991	6.06	5.63	6.03	248.0	179.4	221.1
11	16.8.1991	12.13	12.46	11.91	331.5	381.5	326.5
12	22.7.1992	8.79	8.16	8.93	456.9	318.8	384.8
13	28.7.1992	6.24	5.79	5.85	195.2	204.2	202.1
14	4.8.1992	5.32	5.42	5.40	165.7	136.7	148.5
15	17.7.1993	2.81	2.74	2.81	1565.7	94.0	107.0
16	22.7.1993	5.38	5.41	5.37	103.5	114.0	111.9
17	2.8.1993	1.16	1.190	1.190	52.8	53.9	54.0
18	23.8.1993	8.01	7.88	8.00	318.2	260.1	267.8
19	24.8.1993	9.87	9.44	9.43	476.2	326.4	376.7
20	29.8.1993	15.14	14.84	15.36	545.2	413.9	477.2
21	2.9.1993	14.80	14.55	14.62	366.9	315.5	332.9
22	8.9.1993	4.20	3.76	3.80	297.0	266.1	269.8
23	9.9.1993	6.47	6.71	6.62	227.1	293.0	227.8

Table 5.12: Baseflow and Saturated Area Expansion for the Two Watersheds During Various Storm Events.

Sl.No.	Storm Event	Base flow (lps)	Saturated Area Expansion (%)		
			Minimum	Maximum	Net
[A] JHANDOO-NALA WATERSHED					
1	4.7.1990	12.67	1.42	1.68	0.26
2	10.8.1990	27.20	2.97	3.28	0.31
3	11.8.1990	38.90	5.16	5.88	0.72
4	16.8.1990	21.60	4.06	4.77	0.71
5	18.8.1990	27.20	4.06	4.99	0.93
6	25.8.1990	9.40	1.30	1.43	0.13
7	7.8.1991	12.70	4.46	5.84	1.38
8	8.8.1991	64.70	9.27	10.41	1.14
9	9.8.1991	64.70	7.34	8.42	1.08
10	15.8.1991	6.70	3.09	4.44	1.35
11	16.8.1991	64.70	7.06	10.51	3.45
12	22.7.1992	47.70	6.85	9.30	2.18
13	28.7.1992	19.20	1.42	1.70	0.28
14	4.8.1992	36.70	3.69	3.92	0.23
15	17.7.1993	3.70	1.40	1.65	0.25
16	22.7.1993	34.80	3.42	3.97	0.55
17	2.8.1993	7.50	1.40	1.50	0.10
18	23.8.1993	47.70	1.79	2.34	0.55
19	24.8.1993	52.70	7.03	8.85	1.82
20	29.8.1993	138.50	7.86	9.06	1.20
21	2.9.1993	12.67	6.13	7.33	1.20
22	8.9.1993	49.00	5.59	6.33	0.74
23	9.9.1993	36.70	5.42	6.86	1.44

[B] BHAINTAN WATERSHED

24	14.8.1979	31.10	0.33	0.35	0.02
25	2.9.1980	253.5	0.51	0.61	0.10
26	13.7.1981	41.3	0.35	1.18	0.83
27	29.7.1982	14.00	0.12	0.13	0.01
28	20.8.1982	248.1	0.48	0.51	0.03

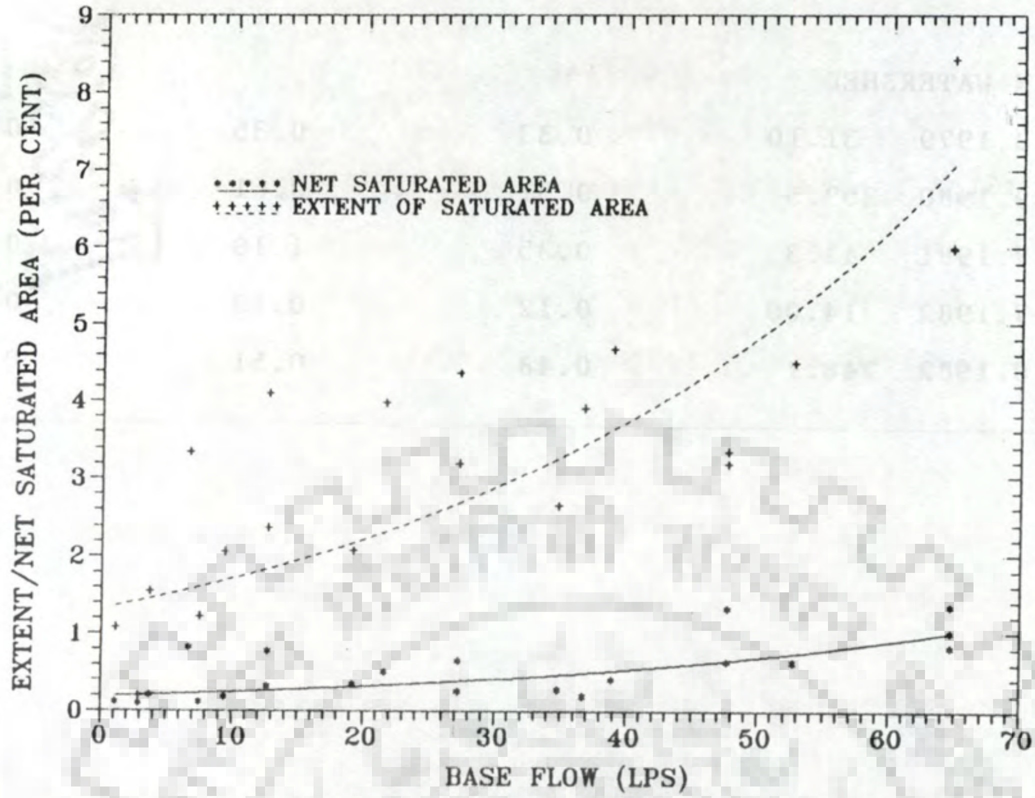


FIG.5.21-RELATIONSHIP OF SATURATED AREA EXTENT AND NET SATURATED AREA WITH BASE FLOW (JHANDOO-NALA WATERSHED).

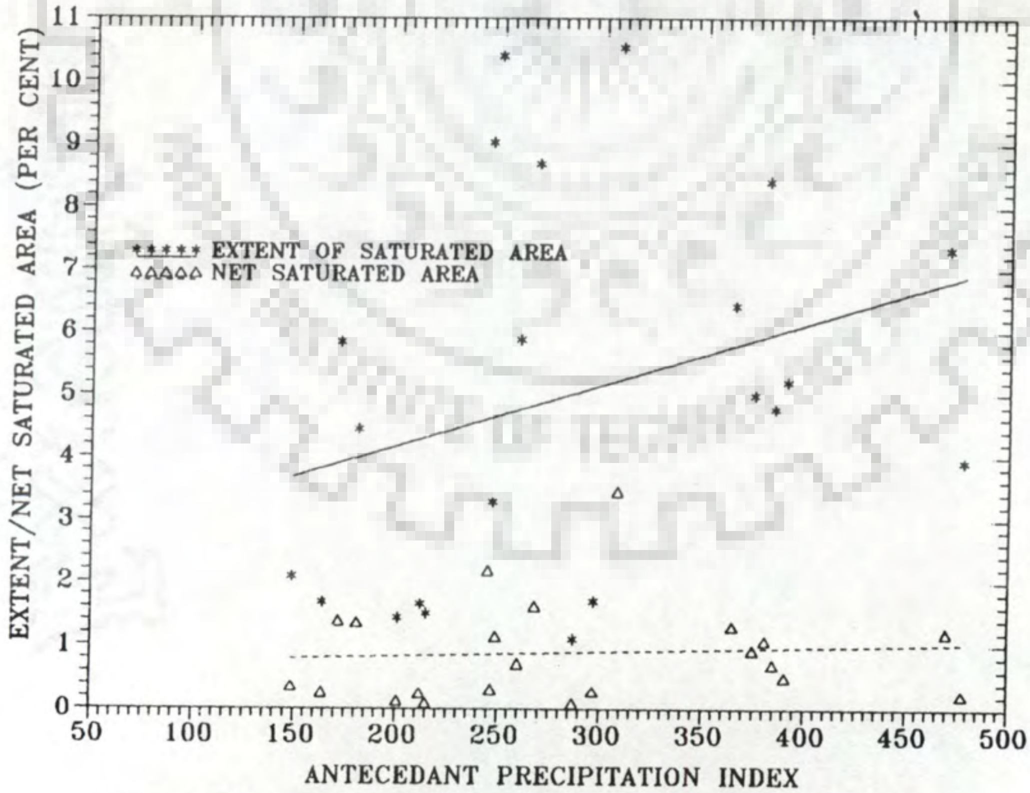


FIG.5.22-RELATIONSHIP OF SATURATED AREA EXTENT AND NET SATURATED AREA WITH A.P.I. (JHANDOO-NALA WATERSHED).

X = baseflow (lps).

Graphical relationships of 'extent' and 'net' saturated areas with API have also been tried as shown in Fig. 5.22. The relationship between the 'extent' of saturated area and API though fitted with a linear curve the fit is not very encouraging. However, the relationship between 'net' saturated area and API is linear (Fig. 5.22).

The relationship between average rainfall intensity and saturated areas (i.e. extent as well as net) have been tried as shown in Fig. 5.23. It may be seen that the extent of saturated area do increase with the increase in average rainfall intensity. However, the scatter has been found to be quite large. The relationship between the net saturated area and the average rainfall intensity has been found to be linearly increasing. Equations for the relationships of average rainfall intensities and extent of saturated area and net saturated area are given below:

$$Y1 = 0.1798\ X + 2.0271 \qquad ....(5.4)$$

$$Y2 = 0.0688\ X - 0.284 \qquad ....(5.5)$$

where,

X is average rainfall intensity in mm/hr and other variables have already been defined.

There is a wide range of scatter on plots in most of the relationships mentioned above. It may be due to the fact that the saturated areas ('extent' as well as 'net') do not depend on a single factor as considered in these relationships. These depend on multiple factors as mentioned earlier in this section.

Considering the extent of saturated area (Y1) and the

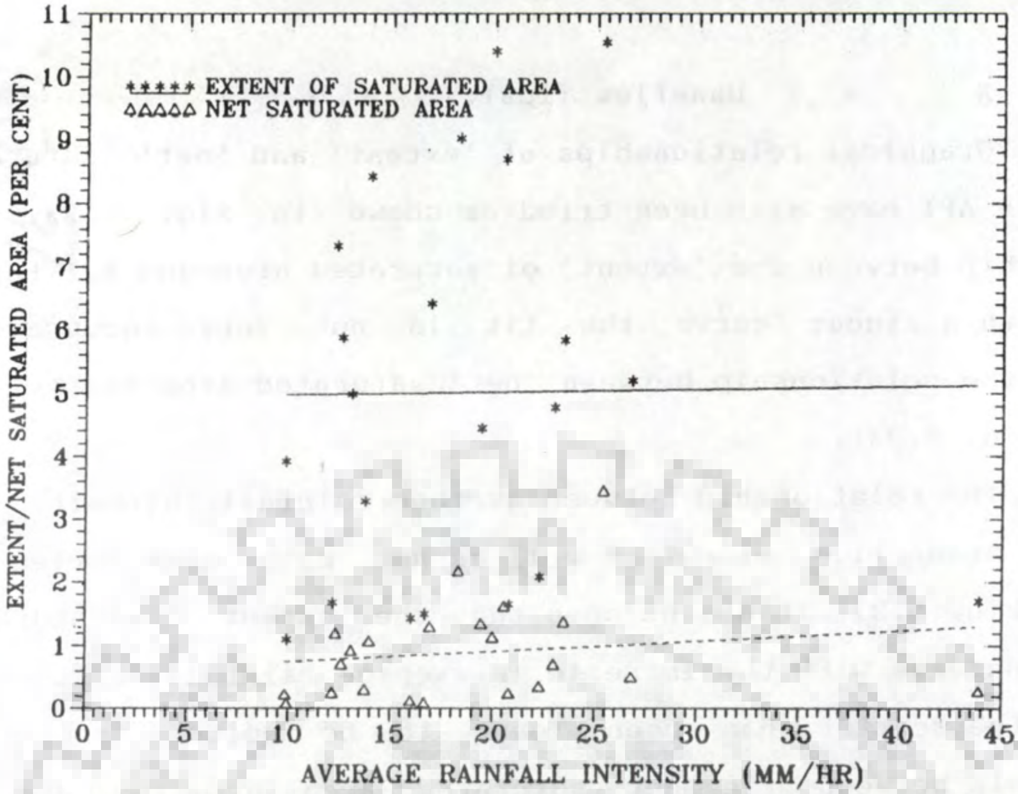


FIG.5.23-RELATIONSHIP OF SATURATED AREA EXTENT AND NET SATURATED AREA WITH AVERAGE RAINFALL INTENSITY (JHANDOO-NALA WATERSHED).

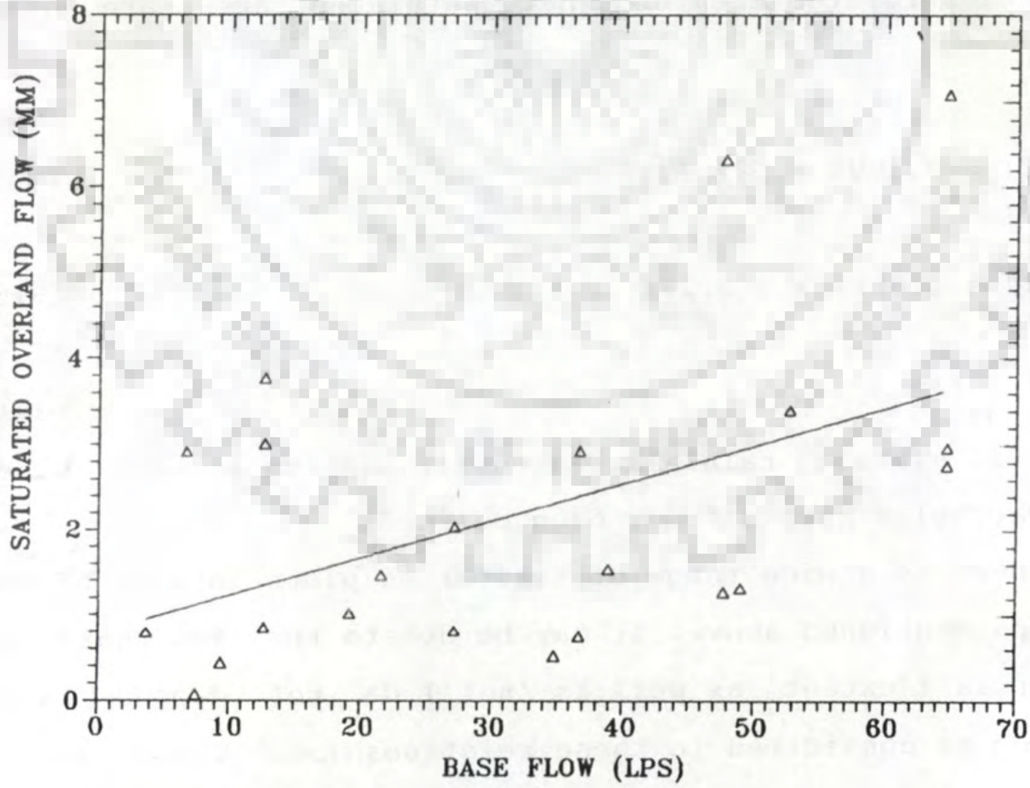


FIG.5.24- RELATIONSHIP OF SATURATED OVERLAND FLOW WITH BASE FLOW (JHANDOO-NALA WATERSHED).

net saturated area (Y2) to be the dependent functions of independent variables namely, total rainfall depth (X1), API (X2), baseflow (X3) and average rainfall intensity (X4), multiple regression (linear) analysis was carried out. The relationships so worked out alongwith their R^2 values are given as under.

$$Y1 = 0.049X1 + 0.008X2 + 0.067X3 - 0.047X4 - 0.90804 \quad (\text{with } R^2 = 0.6963) \qquad \ldots\ldots \quad (5.6)$$

$$Y2 = 0.034X1 + 0.002X2 + 0.012X3 - 0.015X4 - 1.38543 \quad (\text{with } R^2 = 0.6962) \qquad \ldots\ldots \quad (5.7)$$

Where,

Y1 = extent of saturated area,

Y2 = net saturated area,

X1 = total rainfall depth of event (mm),

X2 = antecedent precipitation index (mm),

X3 = baseflow (lps) at the beginning of storm event and

X4 = average rainfall intensity (mm/hr).

It has been found that the baseflow accounts for a variation in the 'extent' of the saturated area by 64.4 per cent whereas in case of 'net' saturated area it explains a variation by 38 per cent. Total rainfall depth is responsible for a variation in net saturated area by 45.3 per cent.

Computed Runoff Components

Total runoff has been computed through four different components, namely direct runoff (i.e. Channel precipitation), Saturated area flow, Interflow and Groundwater flow. These runoff components (mm) for the 28 rainstorms under consideration for the two watersheds are given in Table 5.13. It may be seen in model configuration that the surface runoff has two components namely,

Table 5.13: Runoff Components Computed using Variable Source Area Model for the Two Watersheds During Various Storm Events.

Sl.No.	Storm Event	Channel Precipitation or Direct Runoff (mm)	Saturated runoff (mm)	Interflow (mm)	Ground water flow (mm)	Total Runoff (mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
		[A] JHANDOO-NALA WATERSHED				
1	4.7.1990	0.547	0.850	1.890	0.713	4.000
2	10.8.1990	0.275	0.815	1.728	0.524	3.342
3	11.8.1990	0.315	1.545	2.952	0.898	5.710
4	16.8.1990	0.345	1.469	0.855	0.707	3.376
5	18.8.1990	0.455	2.035	2.031	0.712	5.233
6	25.8.1990	0.320	0.437	0.515	0.545	1.817
7	7.8.1991	0.587	3.011	2.910	1.453	7.961
8	8.8.1991	0.300	2.971	4.708	1.414	9.393
9	9.8.1991	0.349	2.763	3.309	1.501	7.922
10	15.8.1991	0.777	2.917	1.644	0.720	6.058
11	16.8.1991	0.787	7.087	2.720	1.533	12.127
12	22.7.1992	0.549	6.321	0.745	1.172	8.787
13	28.7.1992	0.658	1.018	3.356	1.206	6.238
14	4.8.1992	0.197	0.751	2.700	1.674	5.322
15	17.7.1993	0.520	0.791	0.929	0.574	2.814
16	22.7.1993	0.496	0.524	0.938	3.417	5.375
17	2.8.1993	0.500	0.074	0.131	0.456	1.161
18	23.8.1993	0.669	1.278	5.300	0.761	8.008
19	24.8.1993	0.514	3.407	4.748	1.202	9.871
20	29.8.1993	0.392	3.310	3.890	7.545	15.137
21	2.9.1993	0.554	3.770	9.689	0.788	14.801
22	8.9.1993	0.268	1.323	1.335	1.278	4.204
23	9.9.1993	0.508	2.929	1.520	1.517	6.474

Sl.No.	Storm Event	Channel Precipitation of Direct Runoff (mm)	Saturated runoff (mm)	Interflow (mm)	Ground water flow (mm)	Total Runoff (mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
[B]	BHAINTAN WATERSHED					
24	14.8.1979	0.266	0.074	0.800	0.230	1.37
25	2.9.1990	0.530	0.168	6.618	2.293	9.61
26	13.7.1981	0.914	1.354	8.845	4.740	15.85
27	29.7.1982	0.239	0.072	4.168	0.248	4.73
28	20.8.1982	0.451	0.141	2.580	2.210	5.37

the channel precipitation and saturated area flow. The channel precipitation (direct runoff) is much smaller as compared to saturated area flow in case of Jhandoo-Nala watershed. Further, the subsurface runoff comprises of the interflows and the groundwater flows. Results given in Table 5.13 indicate that the interflows are much more compared to groundwater flows. In many events these are 2 to 3 times or even more. Saturated overland (or saturated area) flow has been found to vary linearly increasing with the baseflow but the relationship does not seem to be of direct use due to wide scatter over the plot. The trend is significant for intense storms for both the components (Fig. 5.24), The runoff factor is found to be very well related to the baseflow as shown in Fig. 5.25. This type of relationship may be used for prediction purposes. The baseflow is adopted as a runoff value at the onset of storm event. Accordingly the runoff factor can be obtained. This on multiplication with the observed gross rainfall will give the total runoff in mm. Using this relationship for a few storms the runoff has been computed and is compared with the observed and the plot is shown in Fig. 5.26. The relationship between runoff factor and baseflow established is given as under.

$$Y = 0.231X + 6.8557$$
$$(\text{with } R^2 = .77) \qquad \ldots \qquad (5.8)$$

Relationship of 'saturated area flow' and 'Interflow' with the average rainfall intensity of the rainstorm has been shown in Fig. 5.27. It may be seen from the trends of the curves that the interflow decreases with the increase in average rainfall intensity and saturated area flow increases with the increase in average rainfall intensity.

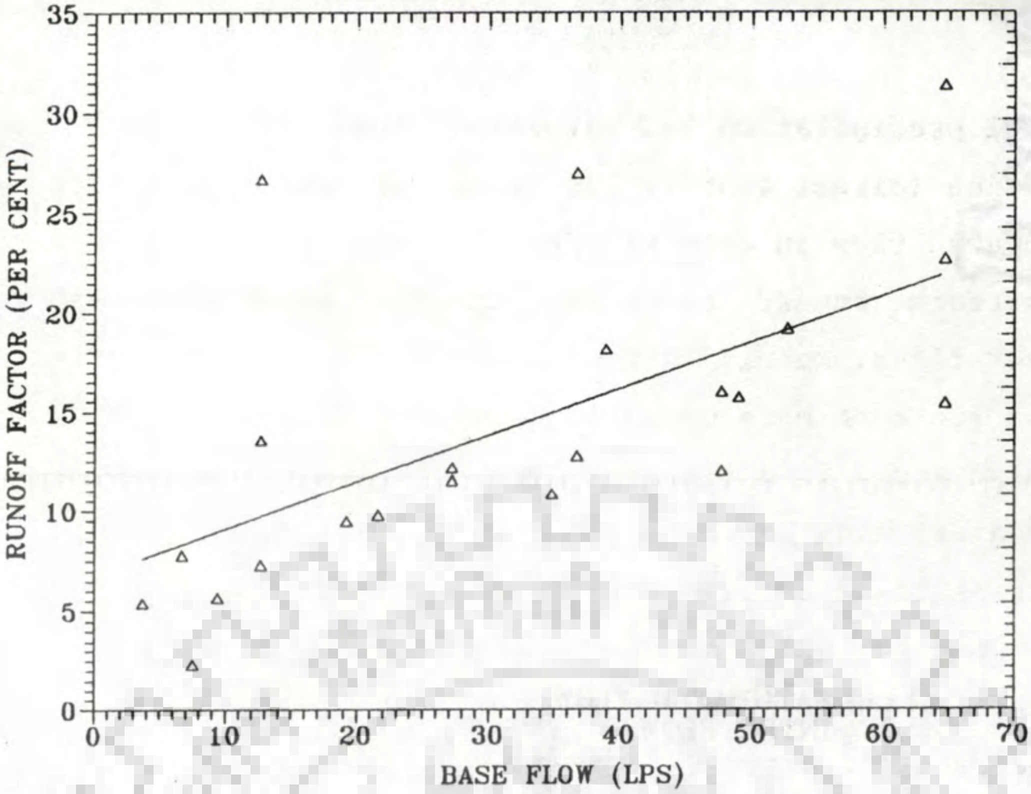


FIG.5.25- RELATIONSHIP OF RUNOFF FACTOR WITH BASE FLOW (JHANDOO-NALA WATERSHED).

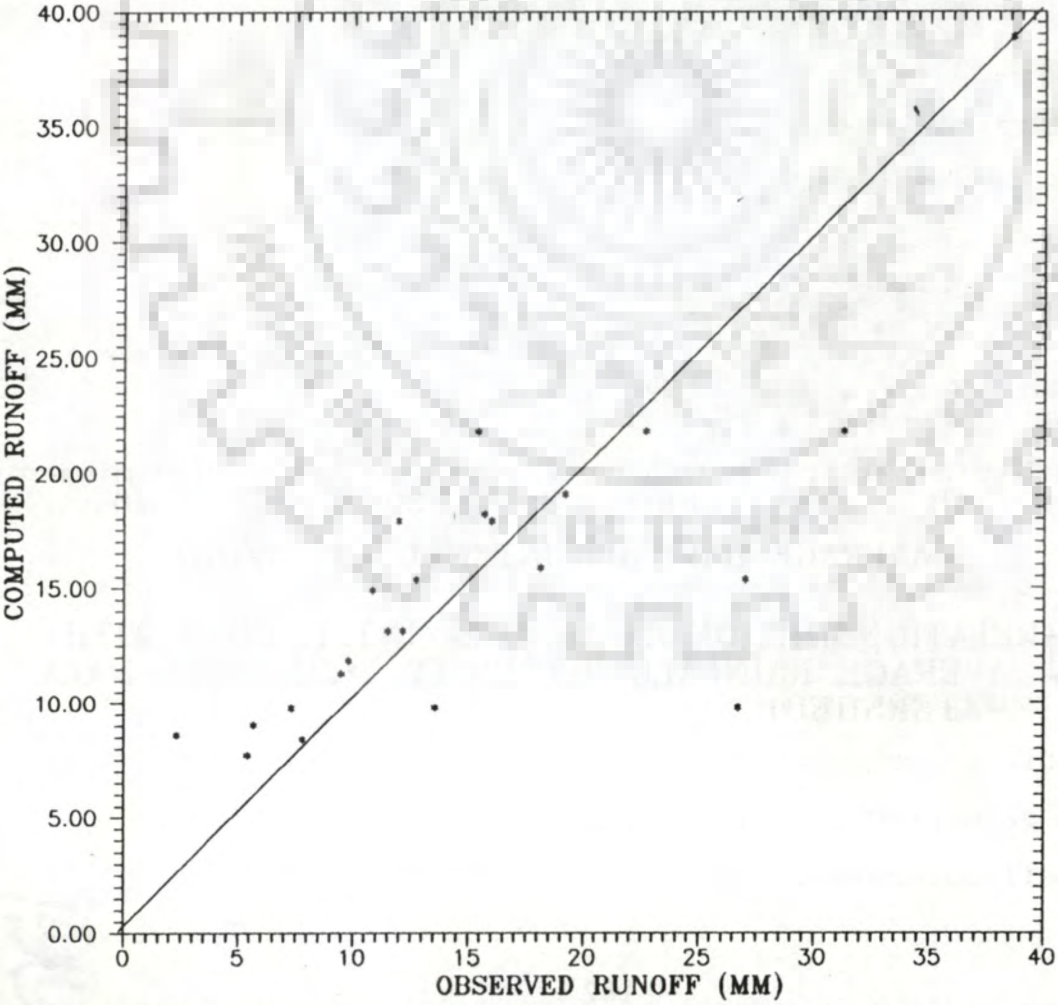


FIG.5.26-COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING VARIABLE SOURCE-AREA MODEL (JHANDOO-NALA WATERSHED).

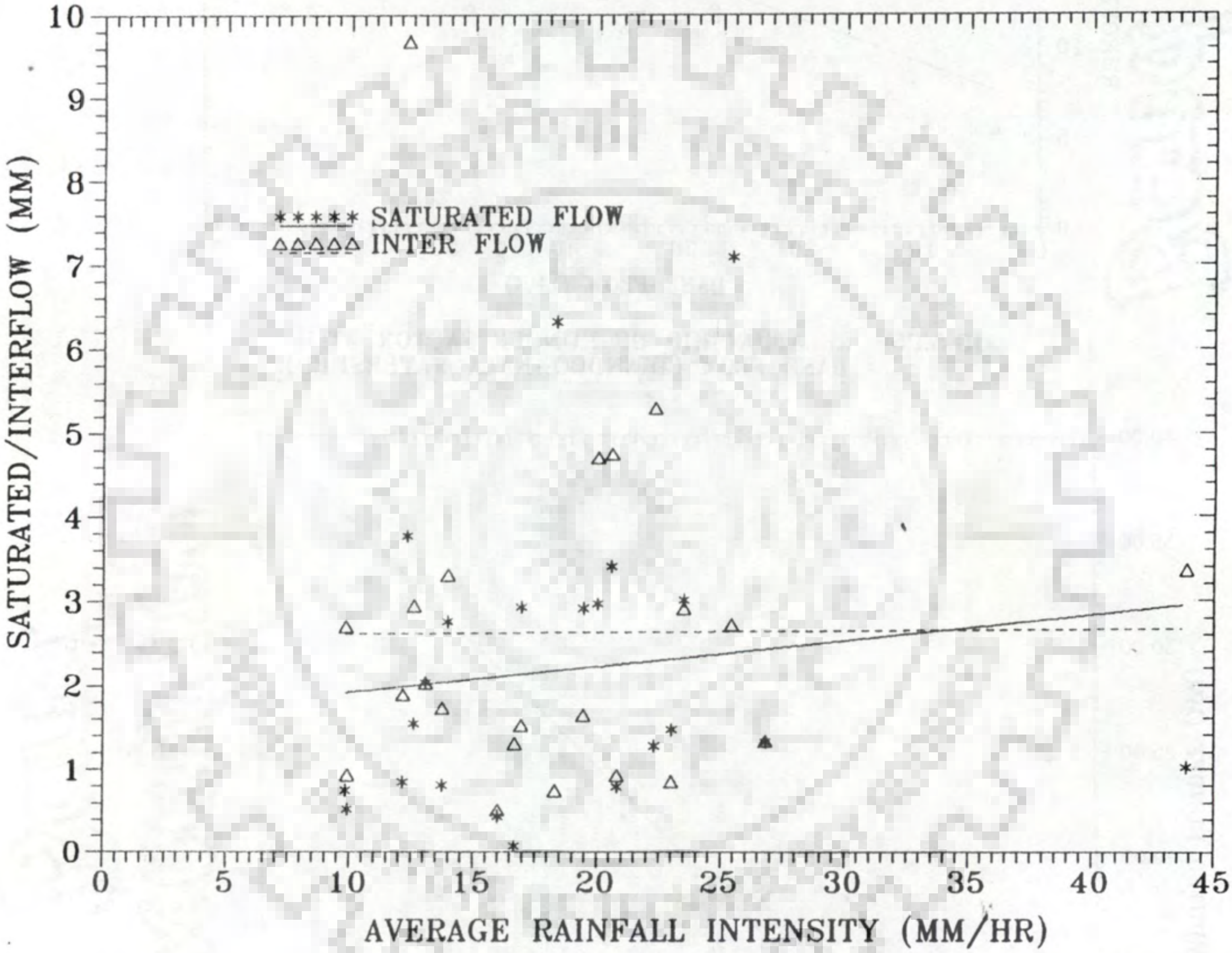


FIG.5.27-RELATIONSHIP OF SATURATED/INTER FLOW WITH AVERAGE RAINFALL INTENSITY (JHANDOO-NALA WATERSHED).

c) **Comparison of Run off Behaviour of the two watershed**

Runoff behaviour of the two watersheds has been found to be different. It is interesting to note that the saturation area expansions minimum 'extent' and 'net' given in Table 5.12 for most of the storm events are significantly larger in case of Jhandoo-Nala watershed as compared to Bhaintan watershed. It may be pertinent to note that as mentioned in Chapter-I and Chapter-III, the Jhandoo-Nala watershed is very much disturbed due to mining activities in the past. The top soil formation has been loosened with practically no compactness. Thus the rainfall occurring over it quickly saturates the formations thus causing more expansion of the saturated area.

On the other hand in case of Bhaintan watershed disturbances are of much lower order. These are caused mostly due to faulty agricultural practices, overgrazing, deforestation etc. resulting into the formation of landslides and formation of gullies. Thus, the expansion of saturated areas remains confined to much smaller degraded areas. The rest of the area which forms a much larger of the total is subjected to Hortonian flow and therefore, may not be ideal for the application of Variable Source Area concept. This is also clear from the observed and computed runoff in Table 5.13 and Fig. 5.16, 5.17 and 5.18.

d) **Effect of Soil Conservation treatment on saturated flows**

As mentioned in Chapter-II, both the disturbed watersheds have been treated with different soil conservation measures like construction of check dams, sediment detention basins, logwood crib-structures and plantation of quick growing species. The effect of these treatment can be seen from the trends of best fits as given in Fig. 5.28 and 5.29. The relationships of 'saturated area extent' and 'net saturated areas' with baseflows for the monsoon months of the years 1990 and 1993 are shown in the above

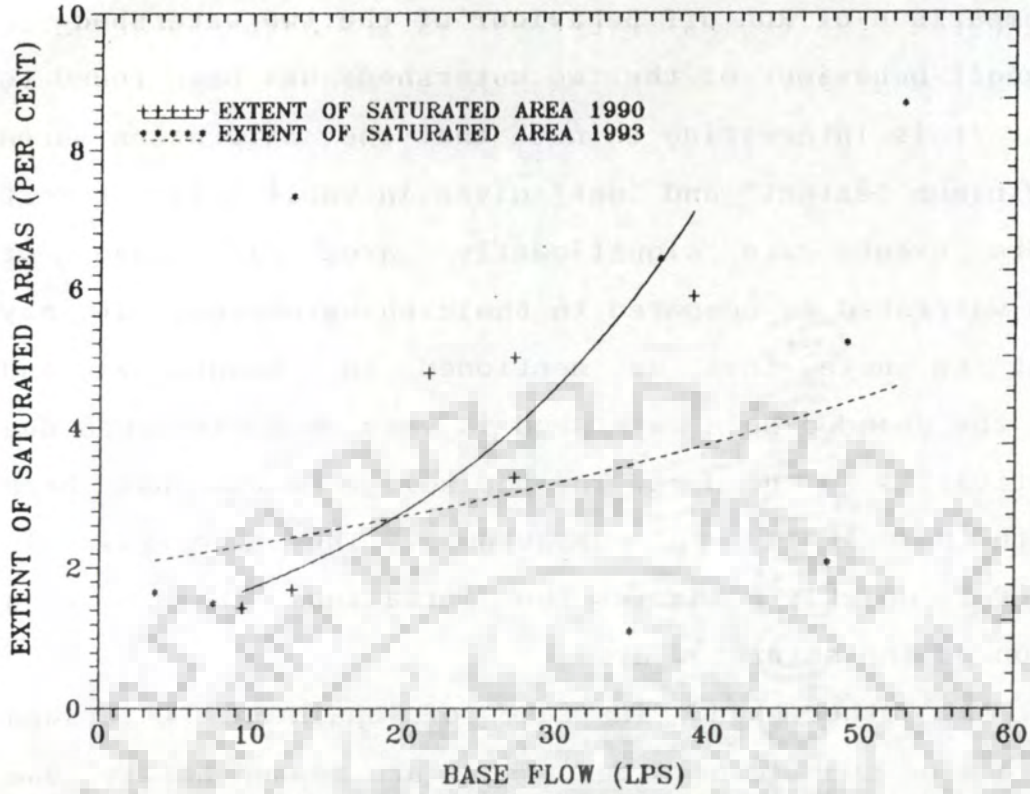


FIG. 5.28-COMPARISON OF EXTENT OF SATURATED AREAS WITH BASE FLOW DURING MONSOON OF 1990 AND 1993 (JHANDOO-NALA WATERSHED).

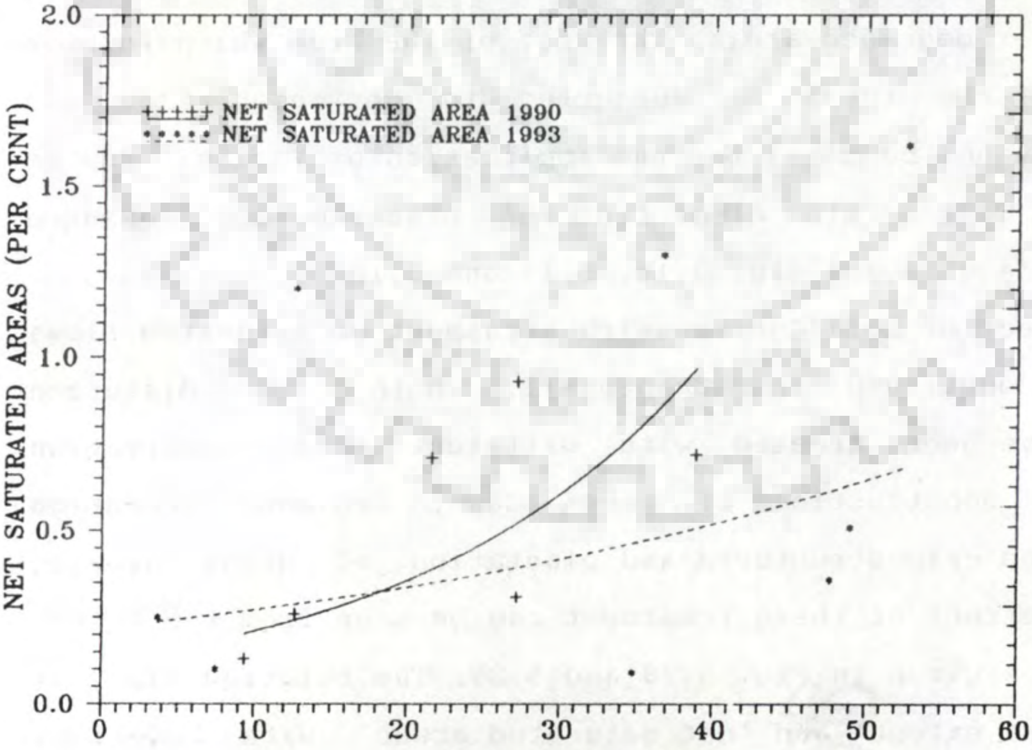


FIG. 5.29-COMPARISON OF NET SATURATED AREAS WITH BASE FLOW DURING MONSOON OF 1990 AND 1993 (JHANDOO-NALA WATERSHED).

mentioned figures. The trends of the curves indicate the reduction in the 'extent (maximum)' and 'net saturated area' for the same baseflow from the monsoon of 1990 to 1993. It may be seen from the Table 5.13 that the saturated overland flow decreased and the interflow increased during 1993 when compared to the monsoon month of 1990. It may be remarked that the soil conservation measures have reduced the saturated overland flow i.e. surface runoff.

5.3.4 Model Improvement

In this study, the optimized values of model parameters obtained by using subjective method of optimization, may not be 'optimum' for all the storm events. As the method employs trial and error procedure, the fitted parameters may not yield satisfactory results in the matching of peak flow rates. Therefore, it was considered appropriate "automatic optimization" technique for finding the optimum set of parameter values. To improve the simulation results Rosenbrock (1960) Hill-climb procedure was used for the purpose. A brief discussion of Rosenbrock optimization procedure is given in the following paragraphs.

a) Rosenbrock's Automatic Optimization Technique

In this study, the "Automatic Optimization" technique, developed by Rosenbrock (1960)is used. Selection of this procedure was based on the findings of Ibbitt (1970) who examined all systematic parameter fitting procedures available for optimizing conceptual watershed models. It was revealed that the Rosenbrock's direct search algorithm has the capability of handling the complex hydrologic 'objective function response surface' which results from all possible combinations of different parameters.

Further, Wilde (1964) referred to the method as "The method of rotating co-ordinates". It is a Hill climbing procedure that does not require evaluation of partial derivatives of the objective function with respect to the parameters. All parameters are bounded for this method. Thus, parameter values may be constrained to the range of "reasonable values".

The Rosenbrock technique consists of a search in a n - dimensional space for fitting n parameters. These spaces are defined initially by the n orthogonal parameter axes. The search is repetitive as it proceeds in 'repetitive stages'. During the first stage, each parameter represents one axis until arbitrary end-of-stage criteria are satisfied. At the end of each stage, a new set of orthogonal direction is computed which is based on the experience of parameter movement during the proceeding stage. The main feature of this procedure is that after the first stage, one axis is aligned in a direction reflecting the net parameter movement experienced during the previous stage.

To start the fitting process, the hydrologic model is assigned an initial set of parameter values, and the resulting simulated flood hydrograph response is computed. The objective function is calculated and then stored in the computer memory as a reference value and later this reference value is used to evaluate the results of subsequent trials. A step of arbitrary length is attempted in the first search direction. If the resulting value of the objective function is less than or equal to the reference value, the trial is registered as a success and the appropriate step size, λs is multiplied by $-\beta s$ where $0 < \beta s < 1$. If a failure results, the step is multiplied by $(\alpha s > 1.0)$. An attempt is made for the next search directions. The process continues until the end of stage criterion is satisfied. The procedure may be terminated when convergence of objective function is obtained. The optimization procedure discussed above forms the main programme and it calls the model discussed in section 4.3 as a subroutine. Computer code was used in the study developed by C.B.Yancey et al.

reported by Carnahan et al. (1969).

b) Optimization of Parameter values

Objective function for optimization was chosen as the absolute difference in the observed and computed discharge. This objective function was minimized. All the parameters were constrained between 0 and 1 except USIN and SSIN. The lower value of USIN and SSIN was 0.33 and upper bound was 1.0.

For one run of optimization data at least two storm events are required. The first event initialises the model variables. The second set of data (i.e. of succeeding storm event) are used for the iterative procedure for parameter optimization. In all data of six storm events of the monsoon months of 1990 were used for optimization of parameters.

Root zone depth (soil depth, USZT), field capacity of soil (USFC) and stream area (PCAR) were not included in optimization programme as these were measured accurately for both the watersheds. Following this methodology the twelve model parameters were optimized and the optimum values for the two watersheds are listed in columns (3) and (5) of Table 5.14. These parameter values are compared with the parameter values obtained by subjective optimization.

c) Runoff Simulation using Objective Optimization

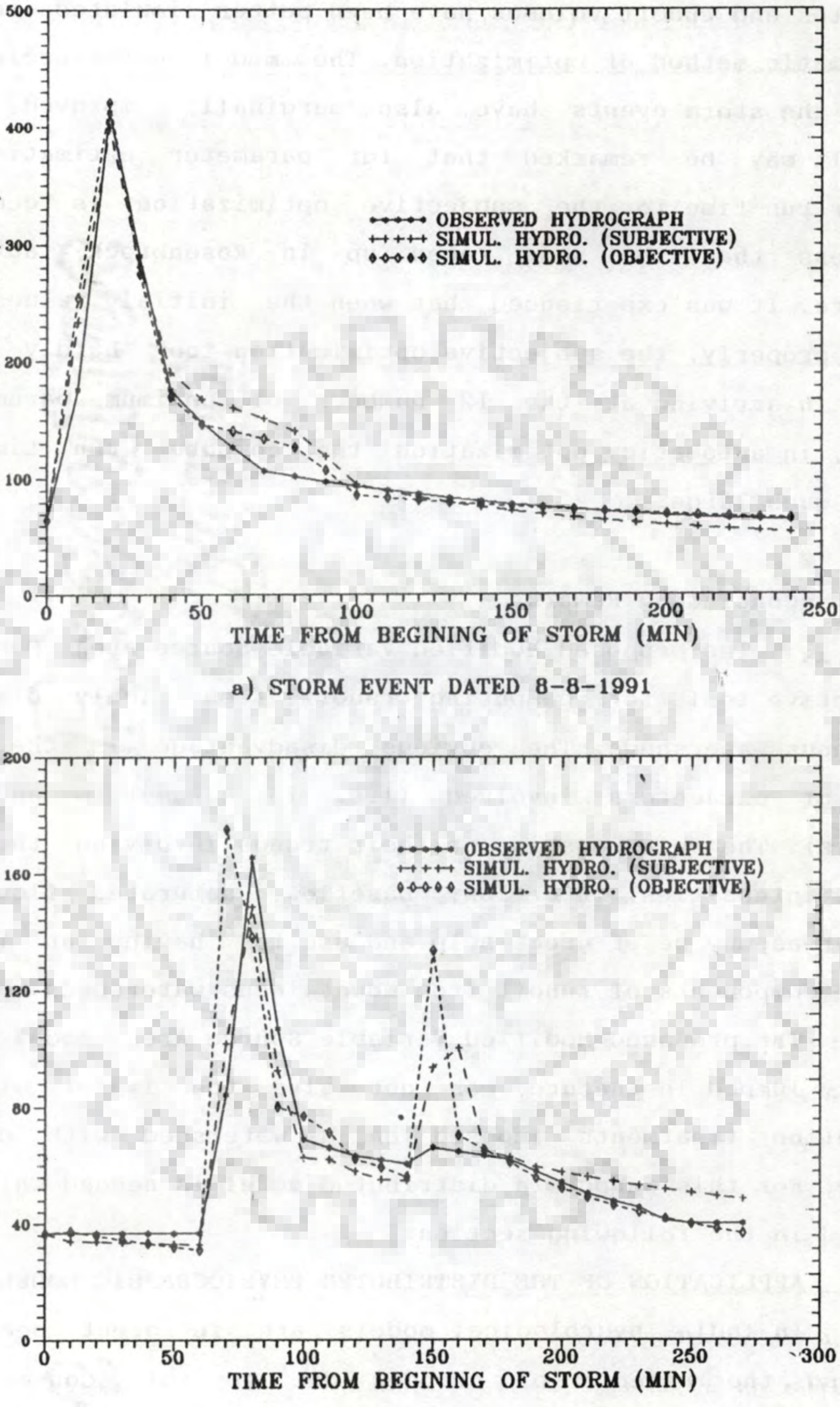
Nine storm events registered at Jhandoo-Nala during the years 1991, 1992 and 1993 were randomly selected for runoff simulation using the optimum parameter values (Table 5.14) obtained through Rosenbrock's Hill climb procedure. Also all the five storm events registered at Bhaintan watershed were used for the purpose. The computer programme given in Appendix-A3 is used for simulation. The visual comparison of the results of simulation using subjective and objective methods of optimization is shown in Fig. 5.30. From this comparison it may be inferred that the peak

Table 5.14: Optimum Parameter Values in the Variable Source Area Model for the Two Test Watersheds.

Sl.No.	Parameter	OPTIMUM VALUE OF PARAMETERS			
		Jhandoo-Nala Watershed		Bhaintan Watershed	
		Objective Optimization	Subjective Optimization	Objective Optimization	Subjective Optimization
(1)	(2)	(3)	(4)	(5)	(6)
1	K1	0.28	0.24	0.32	0.20
2	K2	0.44	0.40	0.37	0.40
3	K3	0.64	0.60	0.67	0.60
4	K4	0.45	0.40	0.36	0.40
5	KU	12.40	11.60	12.60	12.00
6	FU	1.54E+7	1.5E+7	2.16E+7	1.5E+7
7	KS	0.25	0.20	0.20	0.10
8	FS	0.0043	0.003	0.003	0.005
9	SAC(*)	4.5	6.0	2.0	1.0
10	SC(*)	0.0054	0.0030	0.0020	0.0010
11	USIN(*)	300.0	290.0	310.0	300.0
12	SSIN(*)	240.0	370.0	270.0	380.0
13	PCAR(**)	0.010	0.010	0.005	0.005
14	USZT(**)	700.0	700.00	900.0	900.0
15	USFC(**)	200.0	200.0	200.0	200.0
16	CSMAX	1500.0	1500.0	2500.0	2500.0

* Average value of parameters given as these vary from storm to storm depending on antecedent moisture conditions of the watershed.

** Measured values of parameters adopted in the model and these have not been optimised.



a) STORM EVENT DATED 8-8-1991

b) STORM EVENT DATED 4-8-1992

FIG.5.30-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS USING VARIABLE SOURCE AREA MODEL WITH SUBJECTIVE & OBJECTIVE OPTIMISATION (JHANDOO-NALA WATERSHED).

flow rates and runoff volumes have been better simulated in case of automatic method of optimization. The model efficiencies for most of the storm events have also marginally improved (Table 5.15). It may be remarked that for parameter estimation the computer run time for the subjective optimization is generally much less than the same taken up in Rosenbrock automatic procedure. It was experienced that when the initial values were guessed properly, the subjective optimization took hardly a few minutes in arriving at the 12 numbers of optimum parameters. However, in automatic optimization the computer run time was usually much large.

5.3.5 Concluding Remarks

The proposed Modified Variable Source Area Model is an effective tool for computing runoff from highly disturbed mountainous watersheds. The obvious disadvantage is the large number of parameters involved (i.e. 13 parameters and two variables). The relationships or their trends involving the API, rainfall intensities, interflow, baseflow, saturated flows and source areas may be of great help and use for having an insight into the components of runoff from mountainous watersheds.

The proposed Modified Variable Source Area model being basically lumped in nature can not give the impact of soil conservation treatments imposed on a watershed with desired accuracy. For this purpose a distributed model is needed which is discussed in the following section.

5.4 APPLICATION OF THE DISTRIBUTED PHYSIOGRAPHIC MODEL

In India, hydrological models are in great need for monitoring the effects of changes due to soil conservation treatments resorted to in degraded watersheds. As mentioned in the previous section, the lumped parameter models cannot predict the

Table 5.15: Comparison of Observed and Simulated Runoff Volumes Peak Flow Rate and Model Efficiency for Various Storm Events Using Subjective and Objective Method of Optimization.

Sl. No.	Storm Event	Peak Flow Rate (lps)			Runoff (mm)			Efficiency	
		Observed	Objective	Subjective	Observed	Objective	Subjective	Objective	Subjective
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
[A]	JHANDOO-NALA WATERSHED								
1	8.8.91	412.9	421.6	399.3	9.39	9.47	9.24	95.10	93.59
2	9.8.91	377.7	344.2	330.6	7.92	7.94	7.98	84.21	79.42
3	16.8.91	331.5	318.6	326.5	12.13	11.98	11.91	85.30	86.68
4	22.7.92	456.9	421.3	384.8	8.79	8.85	8.93	85.26	76.78
5	28.7.92	195.2	198.3	202.1	6.24	6.12	5.85	95.23	96.06
6	4.8.92	165.7	175.2	148.5	5.32	5.38	5.40	95.83	82.27
7	2.9.93	366.9	340.3	332.9	14.80	14.71	14.62	86.83	86.43
8	8.9.93	297.0	301.2	269.8	4.20	3.93	3.80	92.66	92.17
9	9.9.93	227.1	232.3	227.8	6.47	6.44	6.62	88.43	88.21
[B]	BHAINTAN WATERSHED								
10	14.7.79	528.6	520.1	448.9	1.37	1.40	1.41	91.82	90.92
11	2.9.90	1494.1	1452.0	1740.1	9.61	9.53	9.43	89.64	86.70
12	13.7.81	3106.0	3150.4	3423.6	15.85	15.05	13.97	78.54	77.18
13	29.7.82	1320.7	1469.7	1493.0	4.73	4.81	4.92	86.00	85.94
14	20.8.82	1029.0	1016.1	1051.6	5.37	5.27	5.50	93.48	87.44

impact of soil conservation treatments imposed on different parts on a disturbed watershed.

Therefore, a distributed parameter model has been proposed under section 4.4. The proposed physiographic model has been applied onto the two test watersheds namely Jhandoo-Nala and Bhaintan watersheds. Availability of data on these watersheds has already been described in Chapter-III. The details of the application of the physiographic model are given below.

5.4.1 Physiographic Configurations of the Proposed Model for the Two Test Sub-Watersheds

In order to apply the proposed physiographic model onto the two watersheds, the drainage areas are divided into tributary subwatersheds (TSWi) and main channel subwatersheds (MCWi) as shown in Fig. 5.31 and 5.32. Total number of tributary subwatersheds (TSWi) delineated for Bhaintan and Jhandoo-Nala watersheds are respectively 13 and 4 in number. These subwatersheds are of different areas and are of different shapes as shown in Fig. 5.33(a) and 5.33(b). As mentioned in section 4.4, the portions of the subwatershed areas left out of tributary subwatersheds, and which directly drain into the main drainage channel, have been named as main channel subwatersheds (MCSWi). The Bhaintan watershed comprises of 14 such main channel subwatersheds while Jhandoo-Nala watershed has only five. The discretised shapes of the main channel subwatersheds for the Bhaintan and Jhandoo-Nala are shown in Fig. 5.34(a) and 5.34(b) respectively.

5.4.2 Estimation of Parameters through Runoff Synthesis

In general, the conceptual rainfall-runoff (CRR) models, require calibration for specific applications. It refers to the parameter identification phase of watershed modelling to make a given CRR model specific to a given site. Some of these model

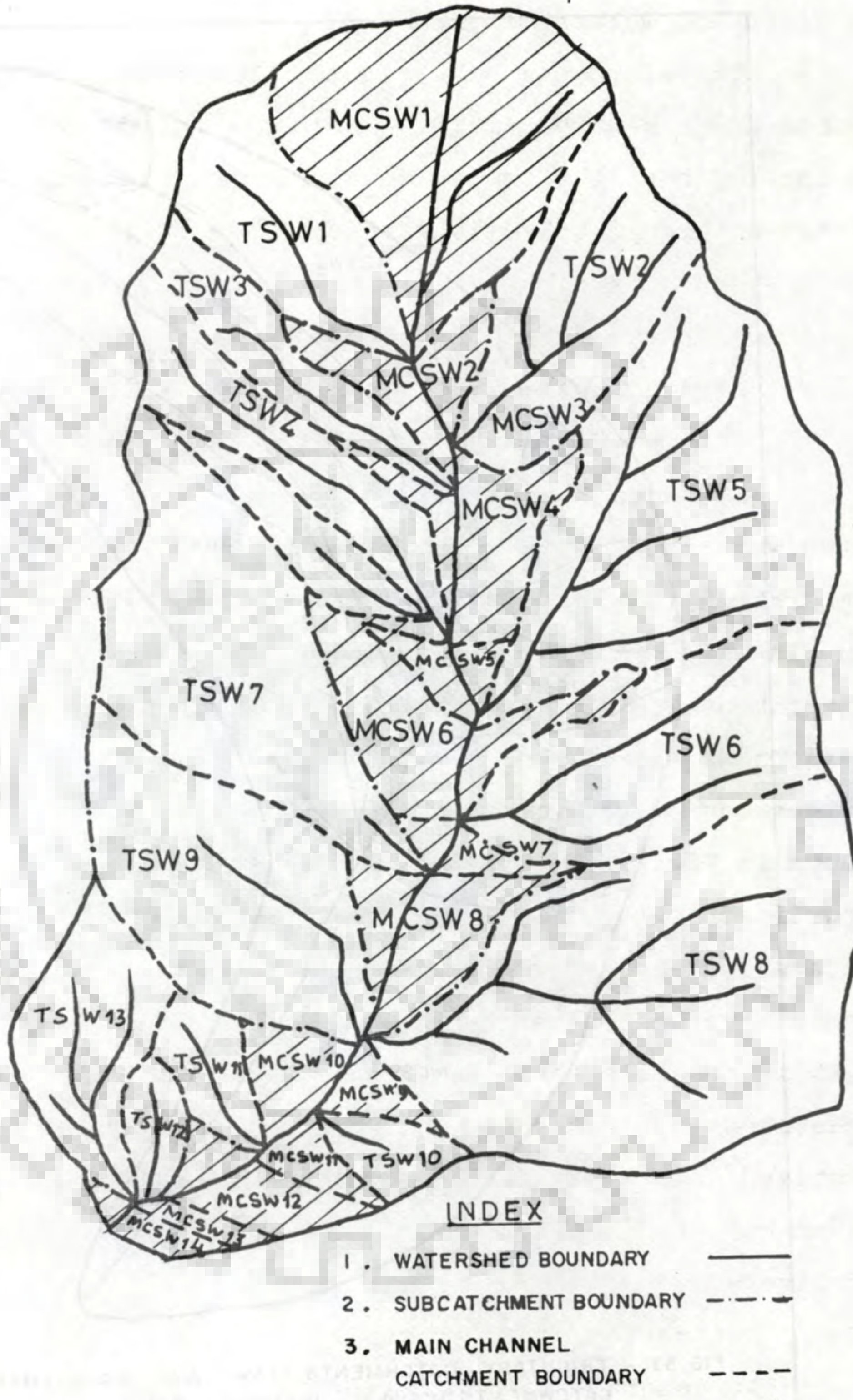


FIG. 5·31 – BHAINTAN WATERSHED DIVIDED INTO TRIBUTARY CATCHMENTS AND MAIN CHANNEL CATCHMENTS.

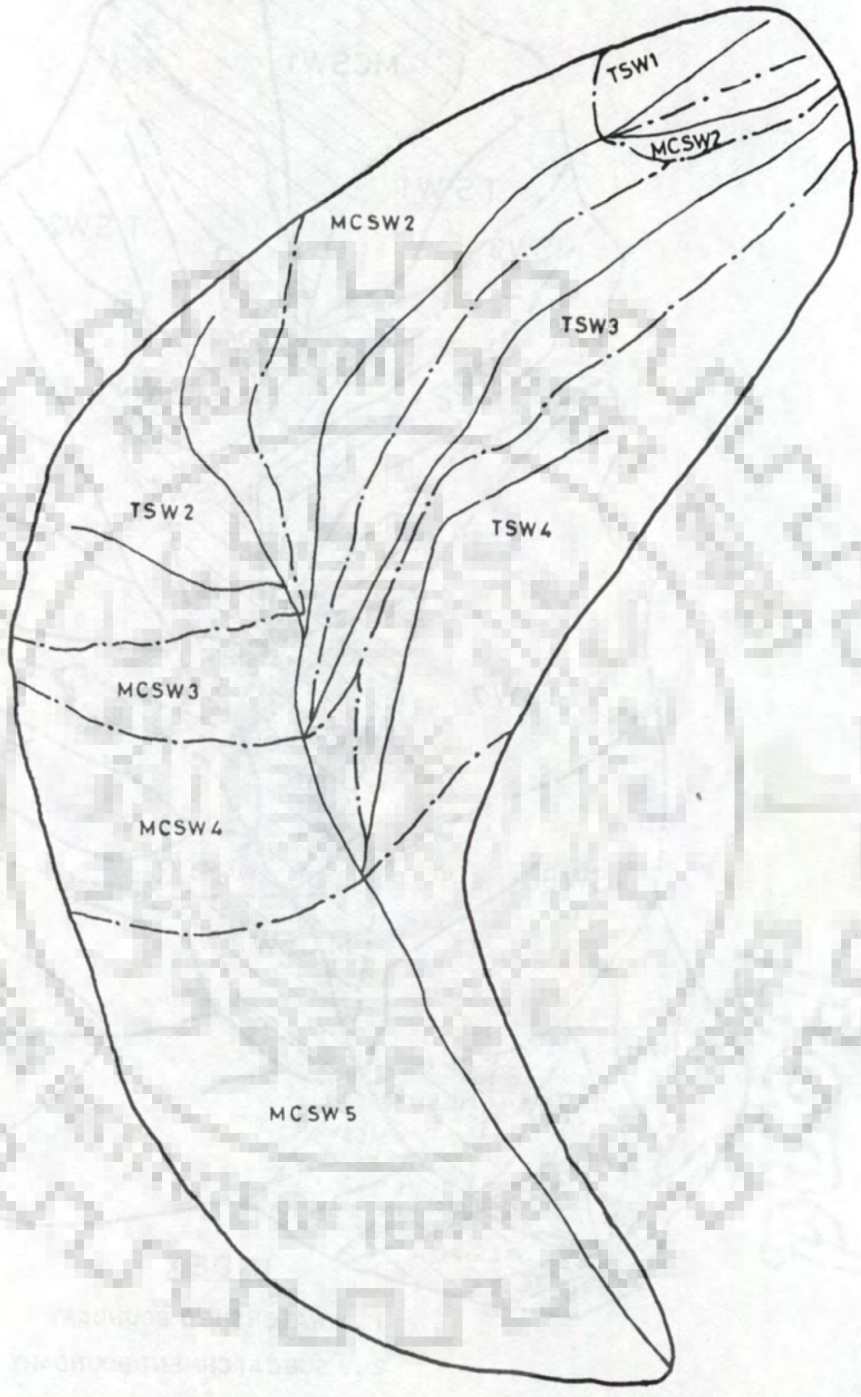


FIG. 5·32 – TRIBUTARY CATCHMENTS (TSW) AND MAIN CHANNEL CATCHMENTS (MCSW) IN JHANDOO – NALA WATERSHED.

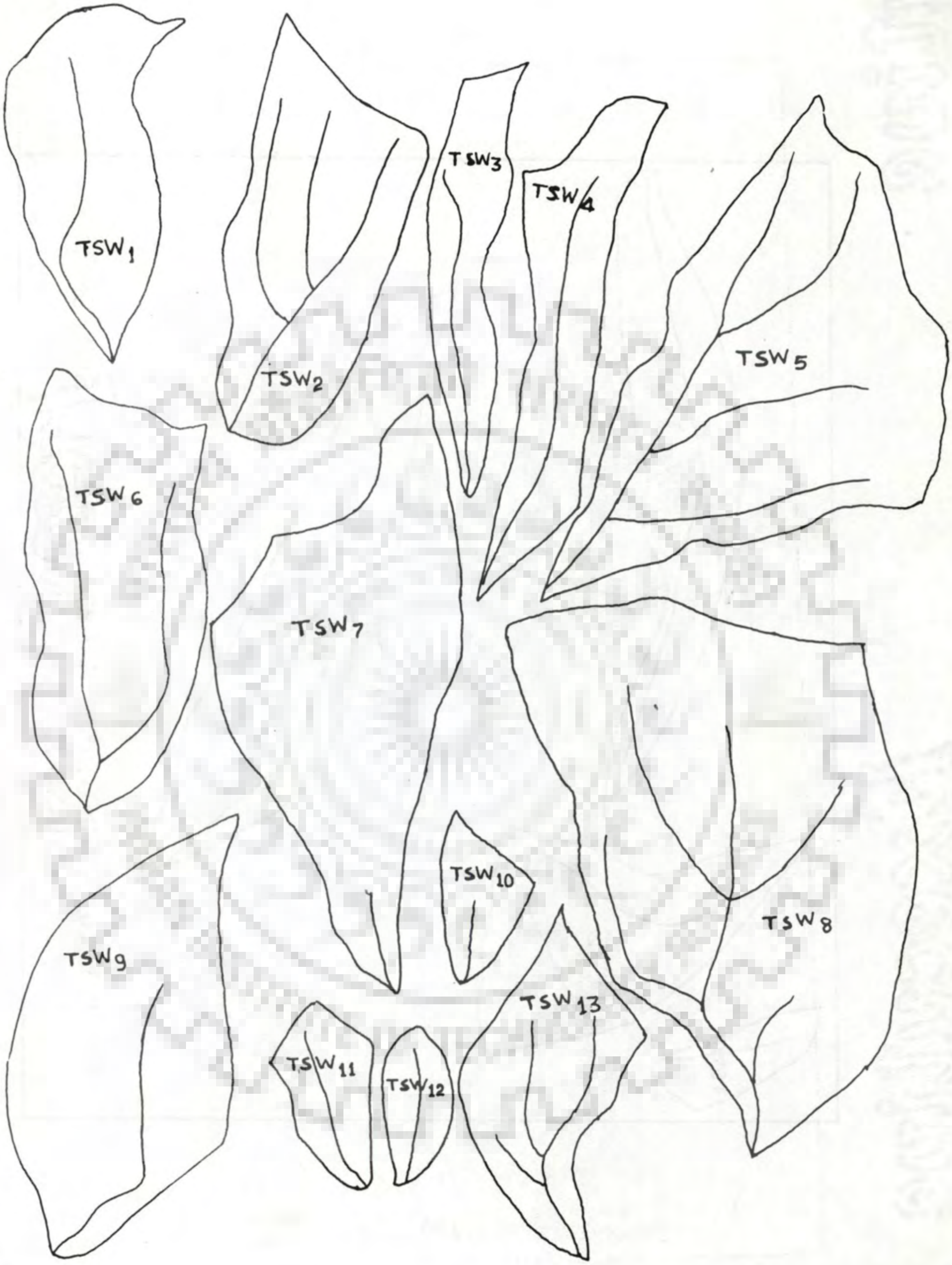


FIG. 5·33 (a) TRIBUTARY SUB-WATERSHED (TSW) BHAINTAN WATERSHED.

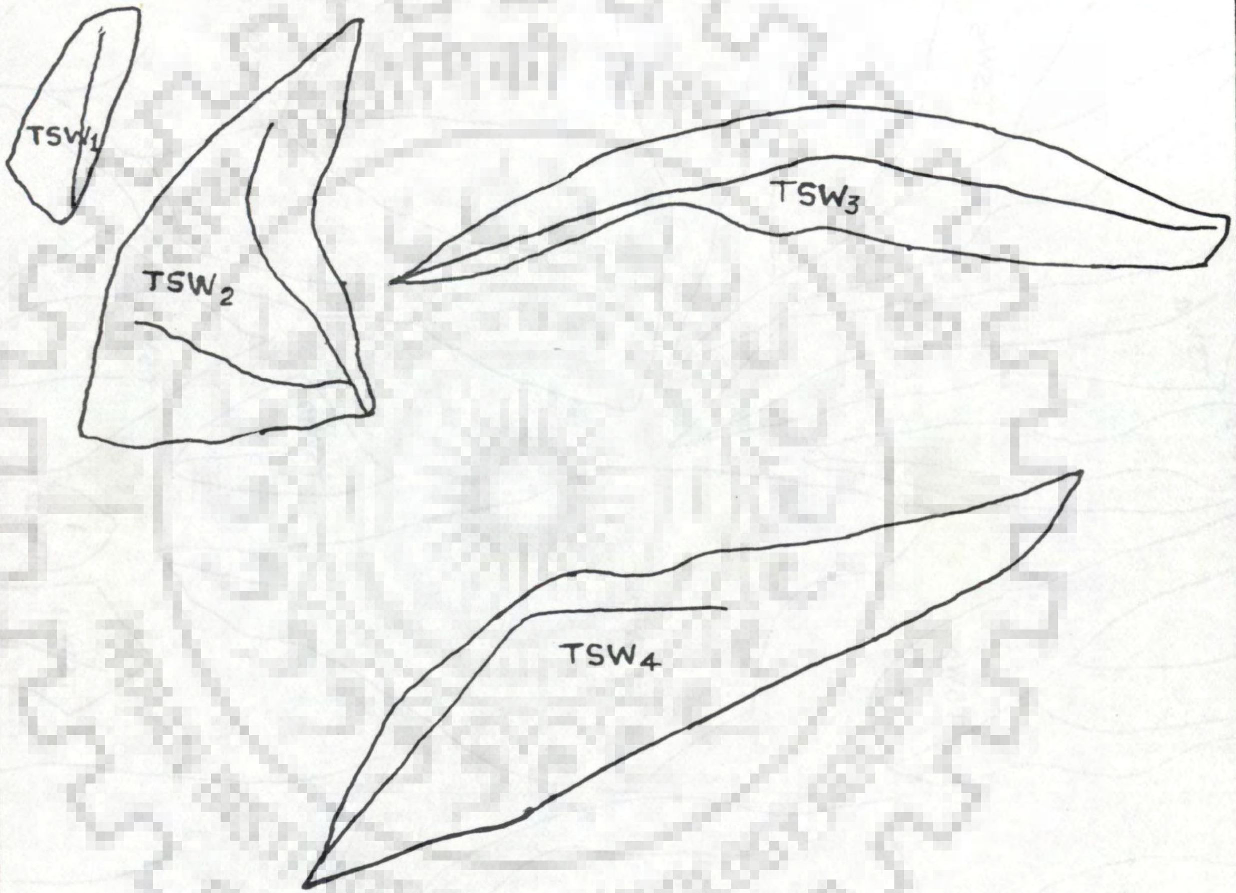


FIG. 5·33 (b) – TRIBUTARY SUBWATERSHEDS (TSW) OF JHANDOO-NALA WATERSHED.

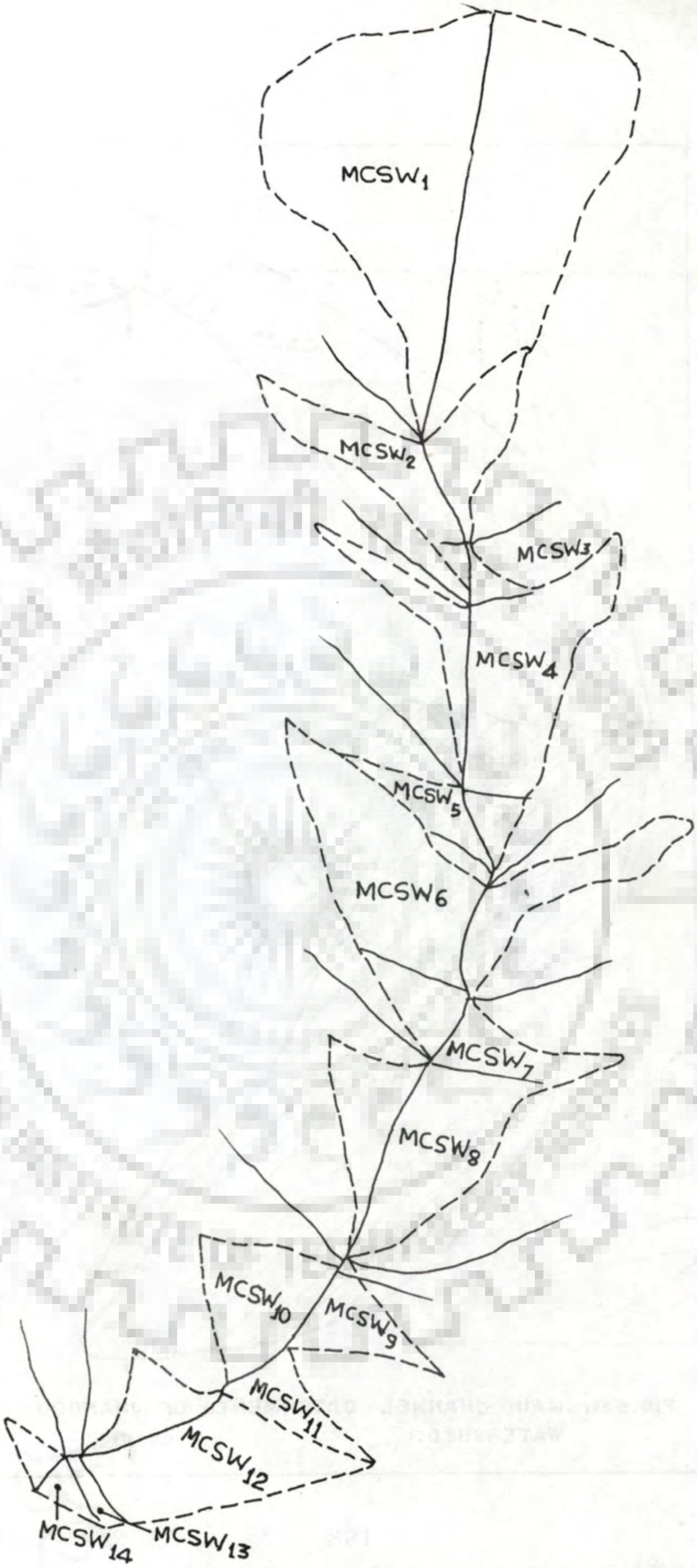


FIG. 5·34.(a)-MAIN CHANNEL SUBWATERSHED (MCSW) OF BHAINTAN WATERSHED.

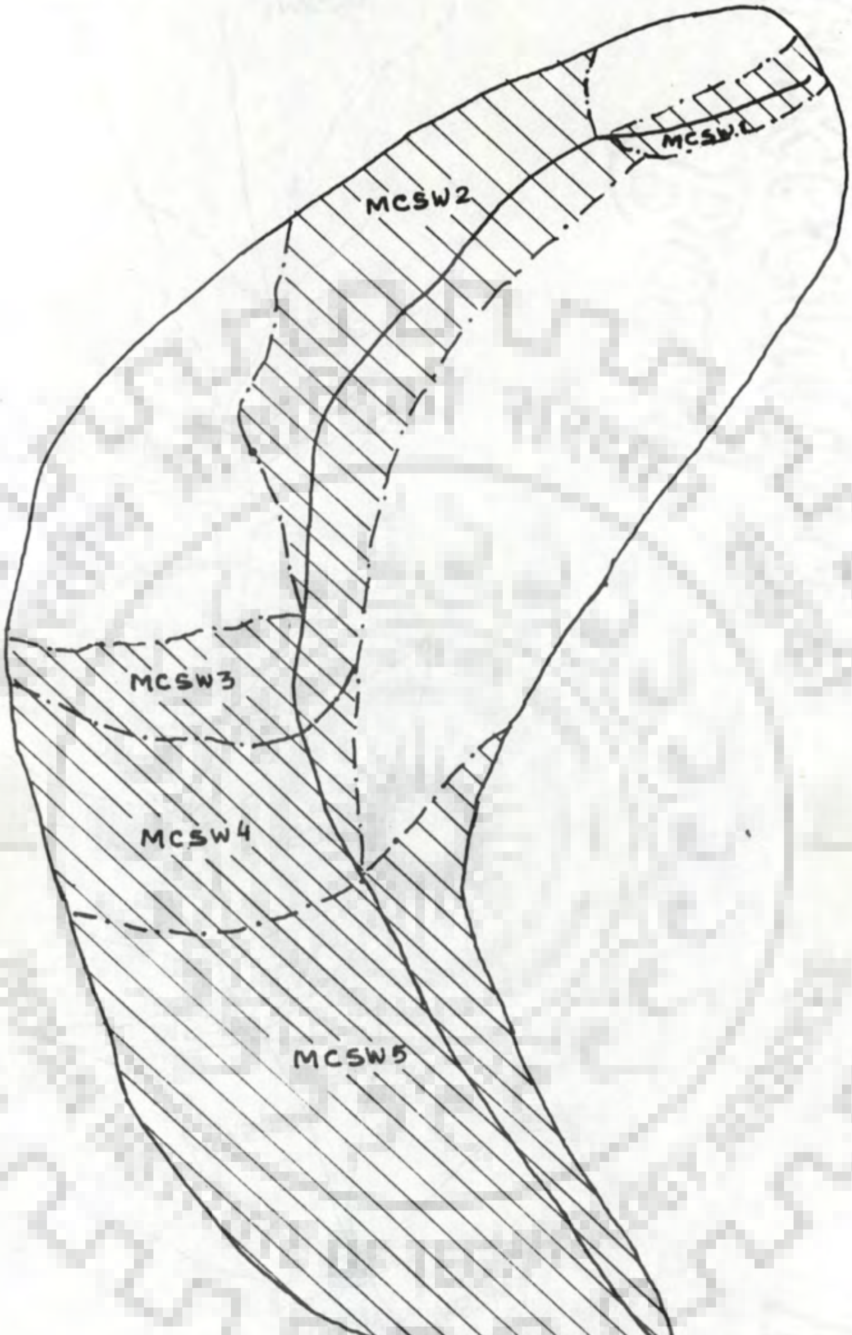


FIG. 5·34(b)-MAIN CHANNEL CATCHMENTS OF JHANDOO-NALA WATERSHED.

parameters are estimated through the watershed characteristics whereas others relating to the internal sub-processes of the watershed (e.g. parameter used in surface and groundwater flow estimations etc.) are indirectly estimated based on related hydrologic information such as historical rainfall and runoff observations (Sorooshian, 1991). Accordingly, the parameters used in the proposed distributed physiographic model need be classified into three broad categories viz., `measured parameters' `computed parameters' and `assigned parameters'. These have been listed in Table 5.16.

The measured parameters for the tributary and main channel subwatersheds of the two test watersheds are given in Table 5.17 and 5.18 under columns 3 to 5. The measured values of infiltration parameters for the two watersheds are given in Table 5.19 as initial values.

In the following sections the methodologies used for the determination for computed parameters have been discussed in detail.

1) **Computation of Kinematic Wave Parameter (α)**

Computation of channel conveyance coefficient (Cr) and measurement of channel slope (Sc) for each subwatershed are required for the determination of kinematic wave parameter (α). Procedure for computation of these is given as under.

a) Computation of Channel Conveyance Coefficient (Cr)

Roughness is a significant and very sensitive parameter for kinematic wave routing. In this physiographic model, the roughness parameter (Cr) has been calculated using the relationships given by the equation 4.48 (section 4.4) and reproduced as under.

Table 5.16 Classification of the Proposed Model Parameters

Measured Parameters	Computed Parameters	Assigned Parameters
a) Areas of main channel and tributary sub-watersheds ($ARMS_i$ and $ARTR_i$)	a) For computing kinematic wave parameter ALP (Coefficient α) i) Channel conveyance coefficient (CR) ii) slope of channel segments	a) Surface supply coefficient (CS/CST)
b) Channel lengths $MCSW_i$ and TSW_i (Li)	b) Initial infiltration rate	b) Groundwater supply coefficient (Cs/CGT)
c) Slope of channel segments (Sc_i)	c) Average width of subwatersheds (i.e. for main channel (BDMS) and tributary (BDTR)	c) Surface supply exponent (GS/GST)
d) Initial infiltration rate (Fo)	d) Manning's roughness coefficient (n_m)	d) Groundwater supply exponent (GG/GGT)
e) Final infiltration rate (F_c)		e) Channel conveyance exponent (m)
f) Infiltration decay constant (PK)		

Table 5.17(a) Computed Physiographic and Flow Parameters of Bhaintan Watershed

Sl. No.	Name of subwatershed	Area of subwatershed (sqm)	Length of channel in the subwatershed (m)	Bed slope of the channel in the subwatershed (%)	Channel conveyance coefficient (Cr)	Value of α kinematic wave parameter (α)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
		[A]	Main Channel Subwatershed			
1	MSW1	252600	540	85.0	0.793	1.25
2	MSW2	54300	140	42.9	1.028	1.33
3	MSW3	49200	205	43.9	1.019	1.32
4	MSW4	74400	276	65.2	0.877	1.28
5	MSW5	24600	149	53.7	0.944	1.30
6	MSW6	88900	213	32.9	1.137	1.35
7	MSW7	30700	137	23.6	1.290	1.39
8	MSW8	62000	350	37.0	1.087	1.35
9	MSW9	0.0	0.0	0.0	0.0	0.0
10	MSW10	35700	156	25.6	1.243	1.39
11	MSW11	22600	123	26.5	1.234	1.39
12	MSW12	63500	305	23.0	1.302	1.39
13	MSW13	7000	95	25.6	1.243	1.39
14	MSW14	10000	91	24.7	1.268	1.38
		[B]	Tributary Subwatersheds			
15	TSW1	109200	650	81.7	0.804	1.2563
16	TSW2	156300	790	60.0	0.905	1.2889
17	TSW3	71100	824	88.1	0.782	1.247
18	TSW4	96200	955	56.4	0.926	1.296
19	TSW5	301300	1046	59.7	0.907	1.2891
20	TSW6	177800	812	81.5	0.805	1.2560
21	TSW7	226400	1048	81.6	0.805	1.2560
22	TSW8	421400	1075	59.3	0.9088	1.2903
23	TSW9	199800	916	64.0	0.8824	1.2824
24	TSW10	29600	310	55.0	0.9352	1.2987

25	TSW7	38500	345	88.0	0.7820	1.2477
26	TSW12	26000	313	84.1	0.796	1.2521
27	TSW13	90900	690	70.5	0.851	1.2714
28	TSW14	0.0	0.0	0.0	0.0	0.0

Table 5.17(b). Computed Physiographic and Flow Parameter of Jhandoo-Nala Watershed.

Sl. No	Name of subwatershed	Area of subwatershed (sqm)	Length of channel in the subwatershed (m)	Bed slope of the channel in the subwatershed (%)	Channel conveyance coefficient (Cr)	Value of α kinematic wave parameter (α)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
		[A]	Main channel subwatersheds			
1	NSW1	3920	128	54.7	0.7330	1.5486
2	NSW2	50900	284	31.6	0.842	1.7062
3	NSW3	17240	84.0	47.6	0.6950	1.6905
4	NSW4	23500	280	37.5	0.7730	1.7061
5	NSW5	7840	72	63.3	0.903	1.2664
		[B]	Tributary Subwatersheds			
6	TSW1	3290	132	60.6	0.705	1.5351
7	TSW2	21510	184	27.2	0.959	1.6403
8	TSW3	19900	456	48.2	0.769	1.5656
9	TSW4	30000	496	46.4	0.780	1.5710
10	TSW5	0.0	0.0	0.0	0.0	0.0

Table 5.18 Initial Infiltration Rates (Fo) Antecedent Precipitation Index (API), Base flow and other storm characteristics for various storm events registered at Jhandoo-Nala Watershed

Sl. No.	Storm event	API (mm)	Baseflow rate at the start of storm (lps)	Max.rain intensity during the storm	Time from the start of storm to the centre of mass of rainfall hyetograph (hr)	Initial infiltration rates (fo) (mm/hr)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	4.7.90	164	12.7	101	0.64	88.0
2	10.8.90	247	27.2	60	0.547	35.0
3	11.8.90	260	38.9	36	1.182	23.0
4	18.8.90	375	27.2	54	1.894	50.0
5	25.8.90	201	9.4	72	0.972	50.0
6	5.7.91	55	1.1	69	2.491	74.0
7	7.8.91	172	12.7	102	1.755	78.0
8	8.8.91	249	64.7	72	0.358	40.0
9	9.8.91	381	64.7	63	0.709	42.0
10	15.8.91	181	6.7	78	2.138	78.0
11	16.8.91	308	69.7	60	1.156	58.0
12	22.7.92	245	47.7	60	1.588	48.0
13	28.7.92	297	19.2	180	0.915	148.0
14	4.8.92	478	36.7	54	0.518	28.8
15	7.7.93	64.0	0.5	82	3.536	90.0
16	15.7.93	198	2.9	59	1.505	68.0
17	17.7.93	212	3.7	75	0.669	72.0
18	22.7.93	287	34.8	57	2.569	52.0
19	2.8.93	215	7.5	90	0.782	82.0
20	23.8.93	149	47.7	72	1.211	50.0
21	24.8.93	268	52.7	75	0.942	56.0
22	25.8.93	416	47.7	104	1.743	128.0
23	29.8.93	375	138.5	75	0.760	50.0

Table 5.19: Source Information Used for Estimation of Parameters and Variables in the Proposed Distributed Physiographic Model.

Sl. No.	Parameters/ Variables	Description	Procedure of Determination	Initial Values adopted	
				Bhaintan Watershed	Jhandoo Nala Watershed
(1)	(2)	(3)	(4)	(5)	(6)
[A] Infiltration Parameters					
1.	FO(fo)	Initial infiltration rate	Field measurement.	90	70
2.	FC(fc)	Final infiltration rate		12	10
3.	PK(k)	Decay constant		0.65	0.60
[B] Parameters for main channel subwatersheds					
Kinematic wave parameter(α) requires estimation of Cr					
4.	CR(Cr)	Channel conveyance coefficient for main channel subwatershed. (It requires estimation of n_m and channel slope (Sc)	Computed with estimated value of n_m and SC(I)	Computed values for each subwatershed are given in table 5.17 & 5.18	
5.	AM(m)	Kinematic wave parameter (Channel conveyance exponent) area	Optimization Adopted from Field and William's(1987) model	1.5	1.5
6.	CS(Cs)	Surface supply coefficient	Optimization	0.4	0.5
7.	GS(γs)	Surface supply exponent	Optimization	0.8	0.75
8.	CG(Cg)	Groundwater supply coefficient	Optimization	40	80
9.	GG(γg)	Groundwater supply exponent	Optimization	0.70	0.66

Sl. No.	Parameters/ Variables	Description	Procedure of Determination	Initial Values adopted	
				Bhaintan Watershed	Jhando Nala-Watershed
(1)	(2)	(3)	(4)	(5)	(6)
	[C] Parameters for tributary subwatersheds				
	Kinematic wave parameter (α_t) requires estimation of Crt				
10	CRT(Crt)	Channel conveyance coefficient for tributary subwatersheds	Computed with estimated value of n_m and SC(I)	Computed values of CRT(I) are given in Table 5.17 & 5.18	
11	AMT(mt)	K.W. exponent for tributary watershed. (channel conveyance exponent)	Adopted from Field and Williams (1987)	1.5	1.5
12	CST(Cst)	Surface supply coefficient for tributary subwatersheds	Optimization	0.7	0.8
13	CGT(Cgt)	Groundwater supply coefficient for tributary subwatershed	Optimization	60.0	100
14	GST(γst)	Surface supply exponent	Optimization	0.7	0.66
15	GGT(γgt)	Groundwater supply exponent	Optimization	0.66	0.6

$$Cr = \frac{Ac^{(5/3-m)}}{n_m \, P^{2/3}} \qquad .... \qquad (5.9)$$

The parameters used in this equation have already been defined under section 4.4. The Manning's roughness coefficient (n_m) for the mountainous channels is estimated by using the following relationship proposed by Jarrett (1984).

$$n_m = 0.32 \, Sc^{(0.38)} R^{(-0.16)} \qquad .... \qquad (5.10)$$

Where R is the hydraulic radius of the channel and Sc is the channel slope of the subwatershed.

b) Computation of α

The kinematic wave parameter α is calculated by using the equation 4.50 in section 4.4 and reproduced below.

$$\alpha = 1/(Cr \, Sc^{1/2})^{1/m} \qquad .... \qquad (5.11)$$

The parameters used in this equation have already been defined under section 4.4.

The values of channel conveyance coefficients (Cr) for all the subwatersheds of the two watersheds were computed by adopting the methodology outlined under section 5.4.2 (a). Computed values are listed in column (6) of Tables 5.17(a) and 5.17(b). The channel slope (Sc) of all the tributary and main channel subwatersheds were measured from contour maps of the two test watersheds. For both the watersheds, the value of channel conveyance exponent (m) was adopted from the model of Field and Williams (1987).

Kinematic wave parameter (α) was computed by using the equation 5.11. The computed values of α for the main channel tributary subwatersheds are given in column (7) of the Tables 5.17(a) and 5.17(b) for Bhaintan and Jhandoo-Nala watersheds respectively.

2) **Computation of Initial Infiltration Rate (fo)**

It may be observed that the initial infiltration rate (fo) varies from storm to storm as shown in Table 5.18. It is characterised by the antecedent moisture conditions, API and baseflow rate before the storm (QBF) and rainfall characteristics viz., total rainfall depth (TTRAIN), maximum rainfall intensity during the storm (IMAX), rain storm duration (RADUR), average rainfall rate (ARATE) and time from beginning of rainstorm to the centre of mass of rainfall hyetograph (TG).

Thus for (fo), the function may be written as:

$$fo = f(API, QBF, TTRAIN, PMAX, RADUR, ARATE, TG) \quad .... \quad (5.12)$$

API values for 23 storm events were calculated (Linsley et al., 1958) and are given in Table 5.18 alongwith other storm characteristics namely, maximum intensity during the storm (mm/hr), time from start to the centre of mass of rainfall hyetograph (hr) and baseflow at the start of storm (lps). Total rainfall depth (mm), average rainfall intensity (mm/hr) and storm duration (hr) for various storms are given in Appendix C4.

Time from start of the storm to the centre of mass of hyetograph area (TG) is calculated from the following relationship.

$$TG = \frac{\sum_{i=1}^{n} (Ii * \Delta t)\ (ti - \Delta t/2)}{TTRAIN} \quad ....(5.13)$$

Where,

I_i = rainfall intensity during i^{th} and $i+1^{th}$ time interval (mm/hr),

t_i = time from beginning of storm to the i^{th} time interval (hr),

Δt = time step (hr) and

n = total number of time steps in the rainstorm.

Multiple linear regression analysis was conducted for establishing a relationship between the initial infiltration rate (fo) and various parameters affecting it. It was found that inclusion or exclusion of the two parameters, namely, API and ARATE did not affect significantly the efficiencies of the relationship. Therefore, in order to reduce the number of independent variables, these two parameters were dropped. Thus, the initial infiltration rate (fo) was computed using the following equation.

$$fo = -14.79 + 0.354 * TTRAIN + 0.786 * PMAX - 160.74\ QBF + 4.03\ TG + 0.624\ RADUR \quad .... \quad (5.14)$$

The parameters used in the equation 5.14 have already been explained in the text (above).

It may be remarked that the baseflow (QBF) parameter was found to be more significant parameter than the API, which happen to be quite arbitrarily related to antecedent precipitation.

The initial values of assigned parameters have been taken up from the works of various researchers and optimized through subjective method (i.e. trial and error method) of parameter fitting based on the good match of volumes. The initial values of 15 model parameters for the two watersheds are given in Table 5.19.

Runoff Synthesis:

Model utilises the following steps, involved in the runoff synthesis of a watershed.

3) Determination of Supply Rates

The proposed model computes surface supply rates (Sg) and groundwater supply rate (Sg) using the relationships given by equations 4.39 and 4.40 respectively. The total supply rate (s) is the sum of Ss and Sg. Thus, the lateral inflow rate to the drainage channel of a subwatershed is the product of average width of subwatershed and its total supply rate per unit area. For the determination of surface and groundwater supply rates, three different infiltration models have been used (viz. the models of Horton, Philip and Modified Horton for variable rainfall infiltration). Result of all these infiltration models have been compared.

4) Establishment of Initial Conditions

Since, the runoff gauging was done only at the outlet of the two watershed therefore the baseflow rates at the confluences of tributary and main channels were established as per procedure outlined under section 4.4.5. The baseflow rates at the confluences were considered proportional to the fraction of total watershed are drained upto that point. Further, main channel subwatersheds which are nearer to the main drainage channel, are assumed to contribute more compared to the tributary subwatersheds as are mentioned in equations 4.68 and 4.69, a weight factor THETA was introduced. The optimized value of this factor has been found to be 0.5 for Jhandoo-Nala and 0.5 for Bhaintan watershed.

The baseflow rates (i.e. the discharge rates just at onset of the storm event) for the two test watersheds are available at the outlet for all the storm events being used for calibration as well as validation of the proposed model. Initial conditions at the confluence were computed with the method discussed above.

5) **Channel flow Routing in Tributary and Main Channel Subwatersheds**

Kinematic wave equation (4.53) is solved using Nonlinear Implicit Finite Difference Scheme (Chow et al. 1988). The Implicit finite difference scheme is unconditionally stable and has been discussed in detail in section 4.4.4. Initial estimate for Q_{i+1}^{j+1} computed using Linear Implicit Finite Difference scheme, as the first approximation to the nonlinear scheme. The initial estimate Q_{i+1}^{j+1} is important for the convergence of iterative scheme.

As a boundary condition, the inflow to the tributary subwatersheds remains zero for all the time steps. During a time step (Δt), flows from all the tributary watersheds are routed to contribute to the flows of main channel subwatersheds. Tributary channels receive lateral inflows from 'total supply' (i.e. the sum of surface and groundwater supply rates). In kinematic wave routing, space step (Δx) is taken equal to the length of channel within the subwatershed. Time step (Δt) has been taken as 60 seconds for both the watersheds. Flows from tributary and main channel subwatersheds are thus routed simultaneously using the concept of continuity. The model computations start at successive time intervals from the upper reaches and progressively proceed downstream towards the watershed outlet. The conceptual configuration developed on the lines of model formulation given in section. 4.4.3 for the two watersheds under consideration are given in Fig. 5.35(a) and 5.35(b).

The eleven storm events registered at Jhandoo-Nala watershed during monsoon months of 1991 and 1992 and all the five storm events registered at the Bhaintan watershed were adopted for the calibration of the model. It was found that when the

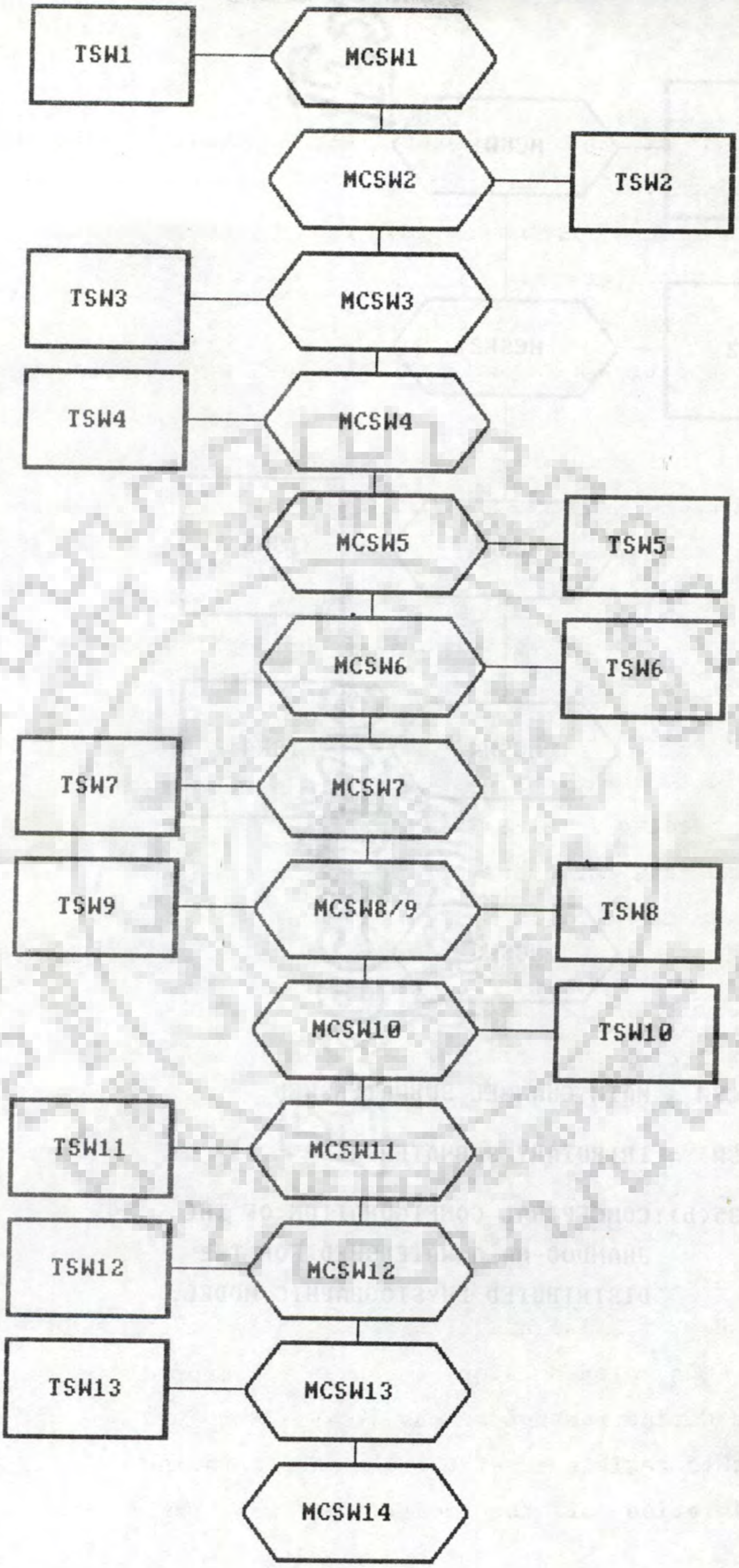
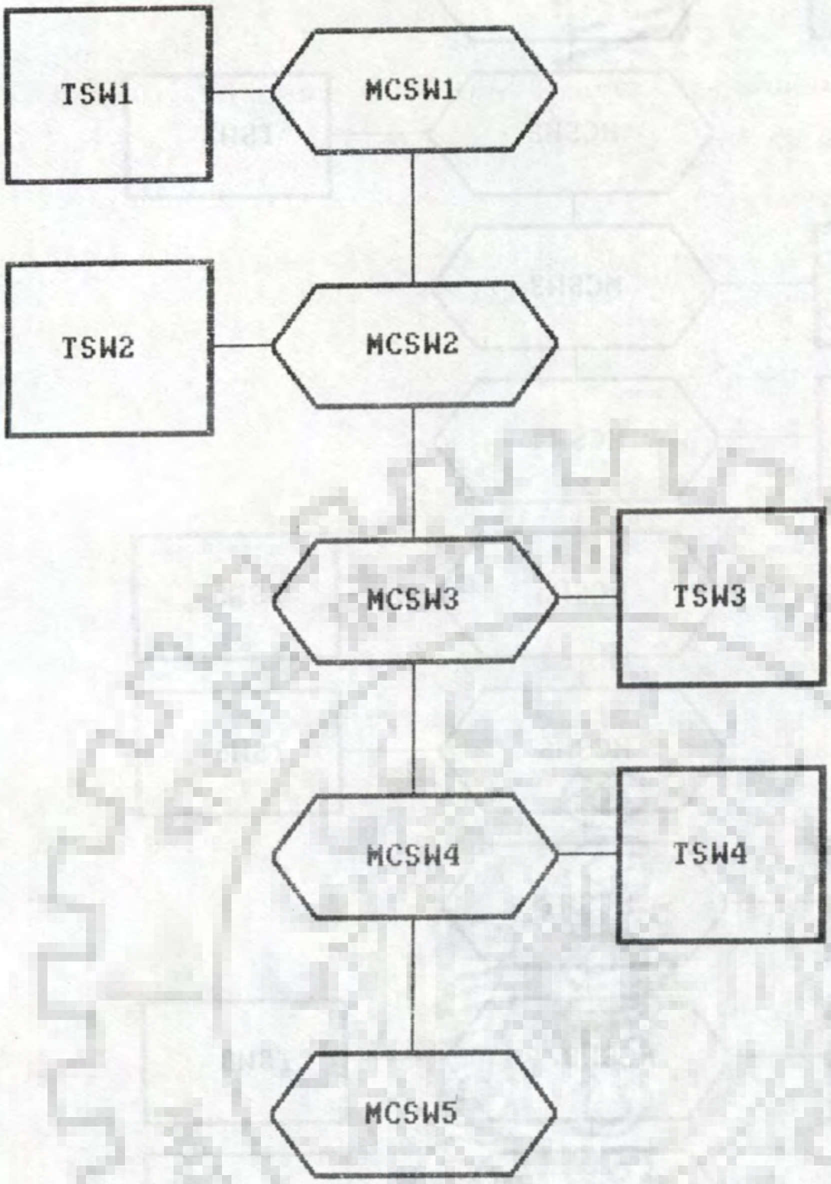


FIG. 5.35(a)-CONCEPTUAL CONFIGURATION OF THE BHAINTAN WATERSHED FOR THE DISTRIBUTED PHYSIOGRAPHIC MODEL.



MCSW = MAIN CHANNEL SUBWATERSHED

TSW = TRIBUTARY SUBWATERSHED

FIG.5.35(b): CONCEPTUAL CONFIGURATION OF THE JHANDOO-NALA WATERSHED FOR THE DISTRIBUTED PHYSIOGRAPHIC MODEL.

differences in the observed and simulated runoff volumes were minimised, the peaks of the observed and computed runoff hydrographs did not match properly. Further, if the differences in peak flow rates of observed and computed hydrographs were minimised the runoff volumes differed. Therefore, in the calibration of this proposed model, the model efficiency (Nash & Sutcliffe, 1970) has been maximised for over all satisfactory match of observed and computed runoff hydrographs. The results of model calibration showing comparisons between observed and computed values of the peak flow rates alongwith the model efficiencies are given in Table 5.20. The visual comparison of observed and computed hydrographs are shown in Fig. 5.36 to 5.38.

It may be seen that the observed peak flow rates match quite satisfactorily with the computed ones and the model efficiencies for various storm events for the two test watersheds are also high i.e. above 76 percent.

The ranges of model parameters (Column (3) and (4)) alongwith their optimum values (Columns (5) and (6)) are given in the Table 5.21 for Jhandoo-Nala and Bhaintan watersheds respectively.

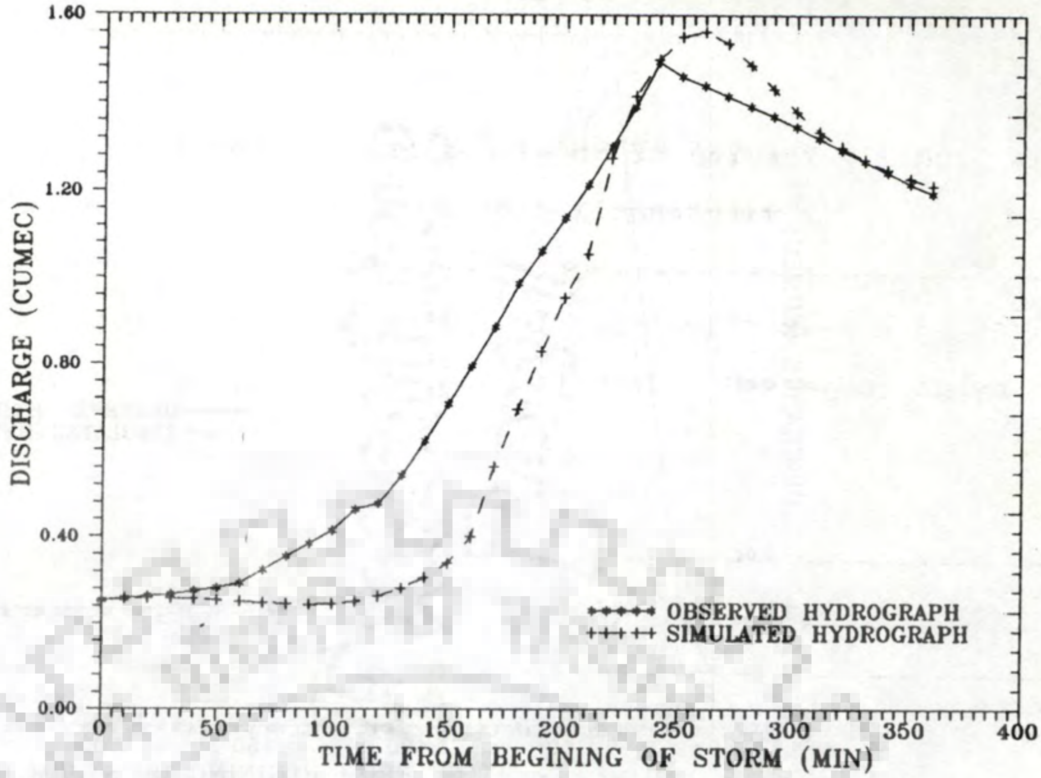
5.4.3 Model Testing

Eleven storm events registered at the Jhandoo-Nala watershed during the monsoon months of 1992 and 1993 were available for the validation of the proposed distributed physiographic model. All the five available storm events registered at Bhaintan watershed and used in calibration were employed for testing optimum values of the parameter for the two watersheds, obtained during calibration (Table 5.21) were used for the simulation of runoff hydrographs for testing the validity of the proposed watershed model.

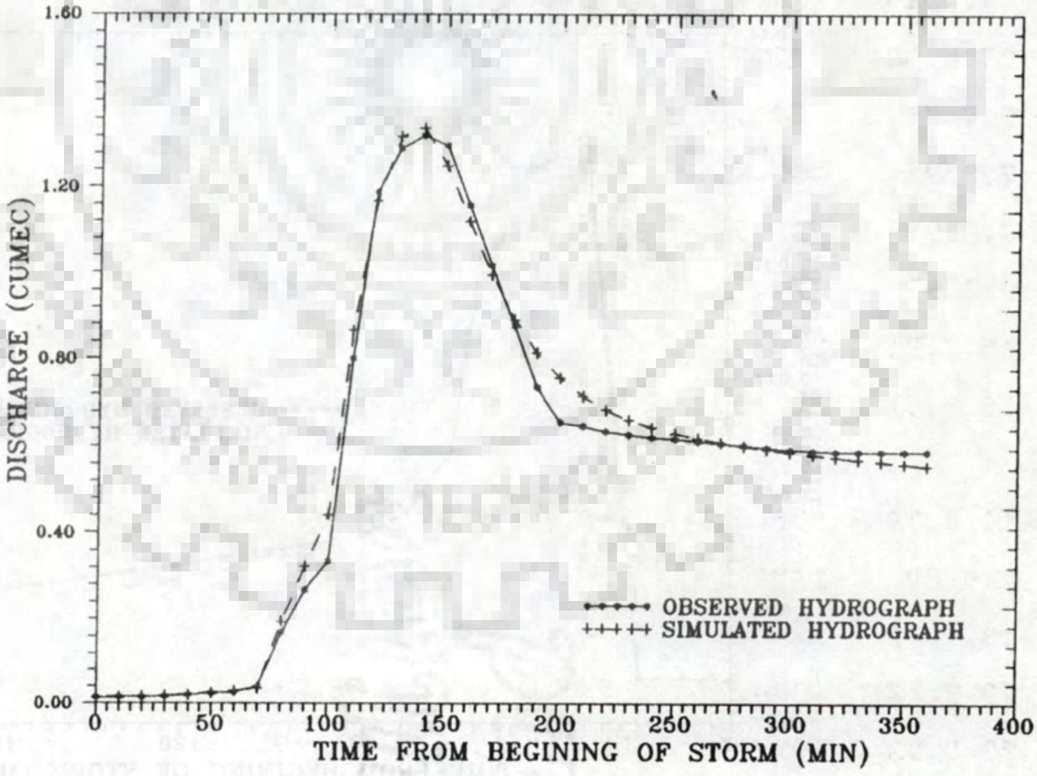
The storm characteristics and the resulting runoff

Table 5.20 Results of Model Calibration for the Distributed Physiographic Model Onto the Two Test Watersheds

Sl. No.	Storm event	Peak Flow Rate (lps) Observed	Computed	Relative percent error in peak flow rate (%)	Relative percent error in total run off volume (%)	Model Effici. (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
			(A) JHANDOO-NALA WATERSHED			
1	4.7.90	150.0	156.1	-4.07	-5.83	85.73
2	10.8.90	122.7	122.9	-0.17	-2.43	94.96
3	11.8.90	126.0	127.2	-0.95	-15.39	91.50
4	18.8.90	176.1	152.7	13.29	-3.10	90.12
5	25.8.90	82.7	78.1	5.61	10.07	95.67
6	5.7.91	90.7	91.0	-0.33	-2.31	93.67
7	7.8.91	293.4	258.0	12.07	-7.09	91.82
8	8.8.91	412.9	392.8	4.94	-1.53	98.04
9	9.8.91	377.7	336.4	10.93	-1.02	95.53
10	15.8.91	248.0	240.5	3.02	1.77	99.04
11	16.8.91	331.5	369.4	-11.43	2.11	83.25
			(B) BHAINTAN WATERSHED			
12	14.8.79	528.6	516.4	2.31	06.36	88.33
13	2.9.80	1494.1	1562.5	-4.58	6.38	87.43
14	13.7.81	3106.0	2944.3	5.21	-10.58	82.41
15	29.7.82	1320.7	1336.8	1.22	-3.81	99.01
16	20.8.92	1029.0	1172.1	13.91	-2.13	76.47

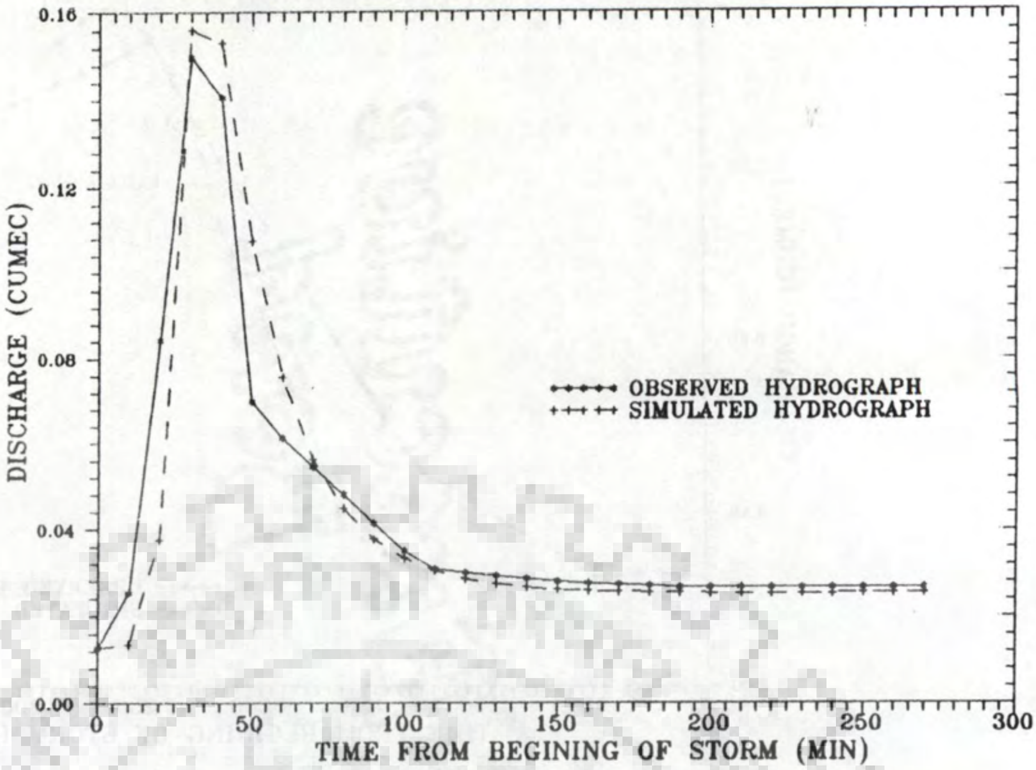


a) STORM EVENT DATED 2-9-1980

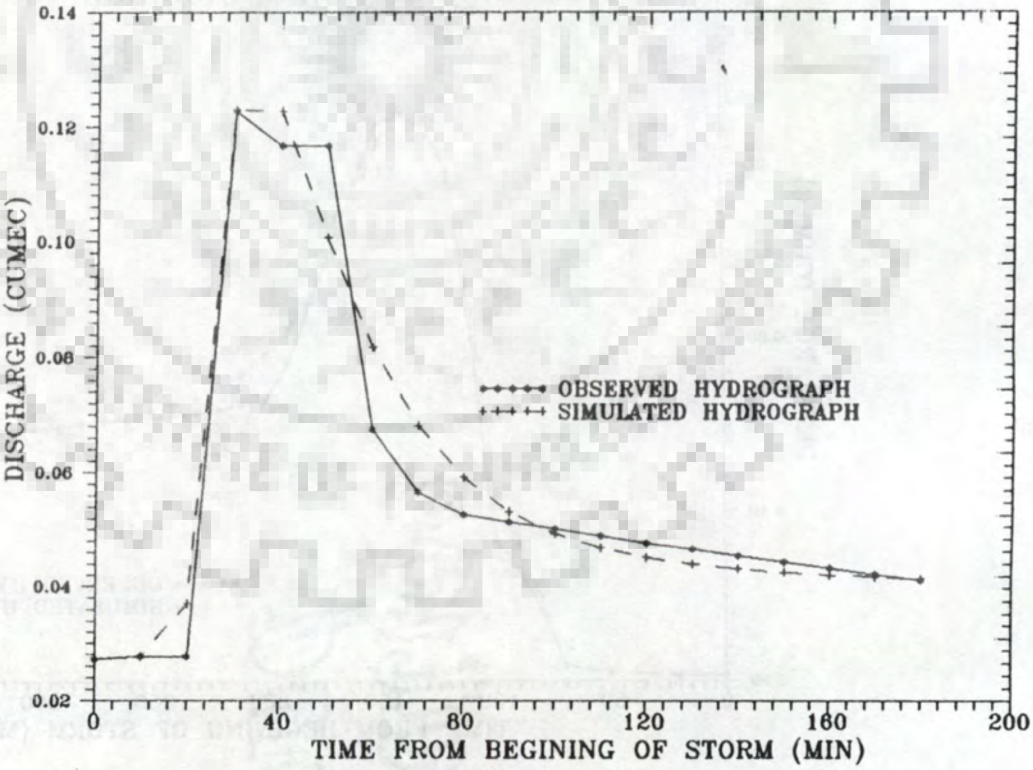


b) STORM EVENT DATED 29-7-1982

FIG.5.36-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHYSIOGRAPHIC MODEL (BHAINTAN WATERSHED).

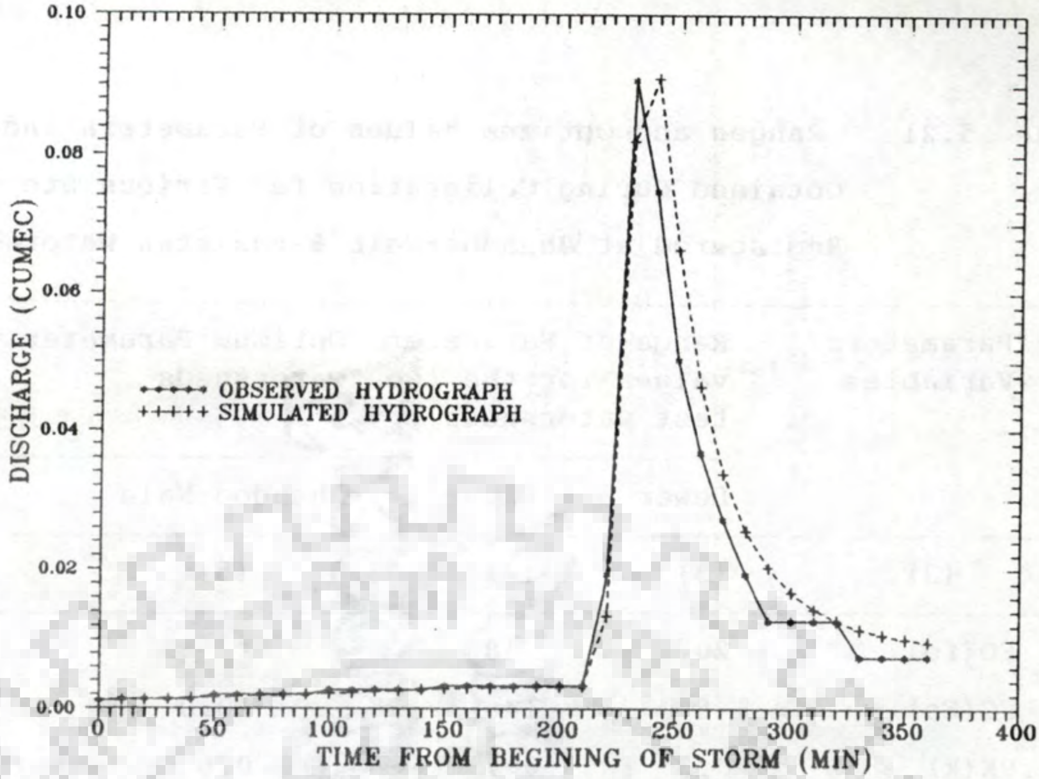


a) STORM EVENT DATED 4-7-1990

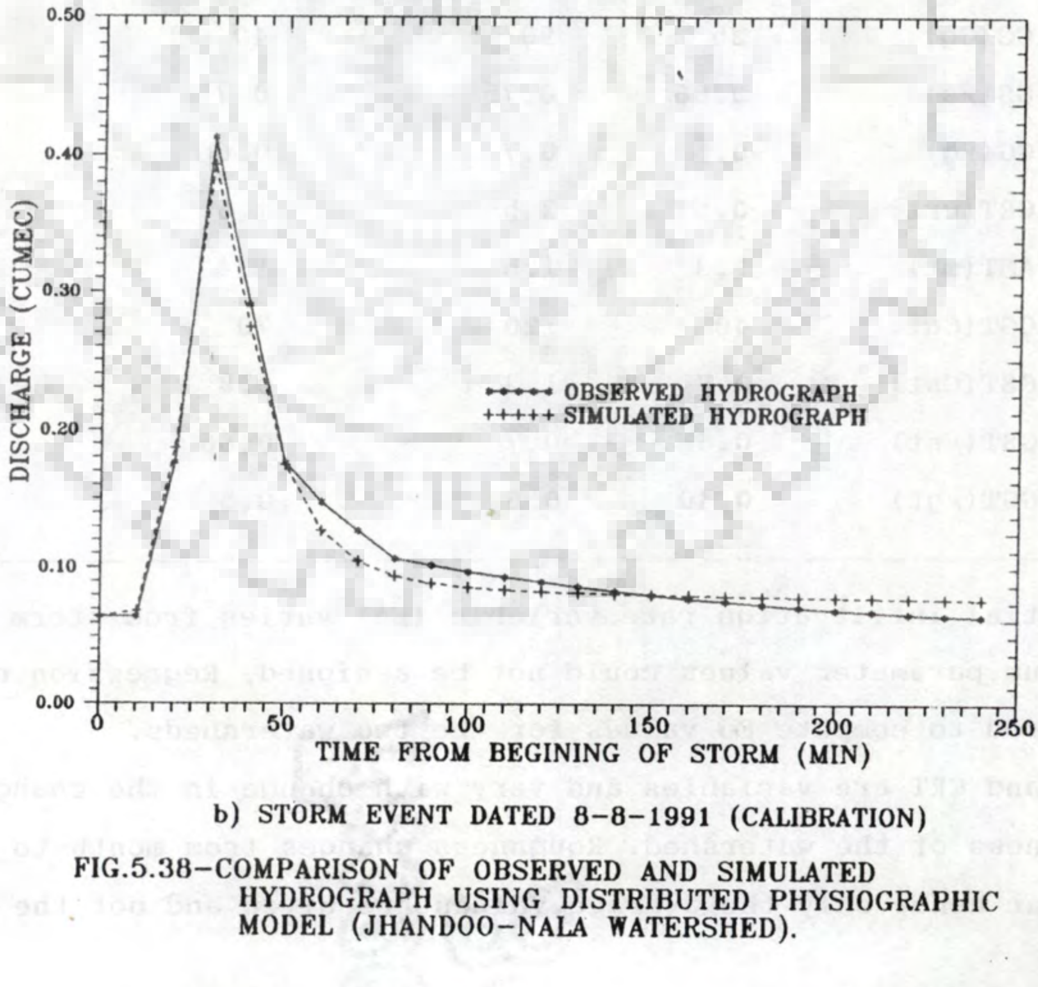


b) STORM EVENT DATED 10-8-1990

FIG.5.37-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHIOGRAPHIC MODEL (JHANDOO-NALA WATERSHED).



a) STORM EVENT DATED 5-7-1991 (CALIBRATION)



b) STORM EVENT DATED 8-8-1991 (CALIBRATION)

FIG.5.38–COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHYSIOGRAPHIC MODEL (JHANDOO-NALA WATERSHED).

Table 5.21 Ranges and Optimum Values of Parameters and Variables Obtained During Calibration for Various Storm Events Registered at Jhandoo-Nala & Bhaintan Watersheds

Sl. No.	Parameters/ Variables	Range of Parameter values for the two test watersheds		Optimum Parameter values for the watersheds	
		Lower	Upper	Jhandoo-Nala	Bhaintan
(1)	(2)	(3)	(4)	(5)	(6)
1	FO(fo)	20	148	*	*
2	FC(Fo)	6	14	10.0	10.0
3	PK(k)	0.3	0.7	0.6	0.5
4	CR(Cr)	0.6	3.0	2.0**	1.6**
5	AM(m)	1.3	1.5	1.4	1.4
6	CS(Cs)	0.3	1.0	0.6	0.4
7	CG(Cg)	25	90	40	25
8	GS(γs)	0.66	0.75	0.7	0.7
9	GG(γg)	0.6	0.7	0.66	0.66
10	CRT(crt)	0.5	2.5	1.6**	1.4**
11	AMT(mt)	1.3	1.5	1.4	1.4
12	CGT(Cgt)	40	120	70	40
13	CST(Cst)	0.7	1.2	0.8	0.5
14	GST(γst)	0.6	0.7	0.66	0.66
15	GGT(γgt)	0.40	0.6	0.5	0.55

* Initial infiltration rate variable (Fo) varies from storm to storm. Optimum parameter values could not be assigned, Regression equation 5.14 is proposed to compute Fo values for the two watersheds.

** CR and CRT are variables and vary with change in the changes in the roughness of the watershed. Roughness changes from month to month and year to year hence only the average values are given and not the optimum one.

alongwith API values as well as the baseflows for the storm events under consideration are included in the table given in Appendix-C4. The data are fed into the formulation described in section 4.4.3. The simulated response were computed using the computer programme given in Appendix-A4. Results of model testing are given in Table 5.22 which shows comparison of observed and simulated peak flow rates, relative per cent error in peak flow rates and runoff volume and model efficiencies (Nash & Sutcliffe, 1970) for various storms of the two watersheds. Visual comparisons of observed and simulated hydrographs are shown in Fig. 5.39 to 5.41.

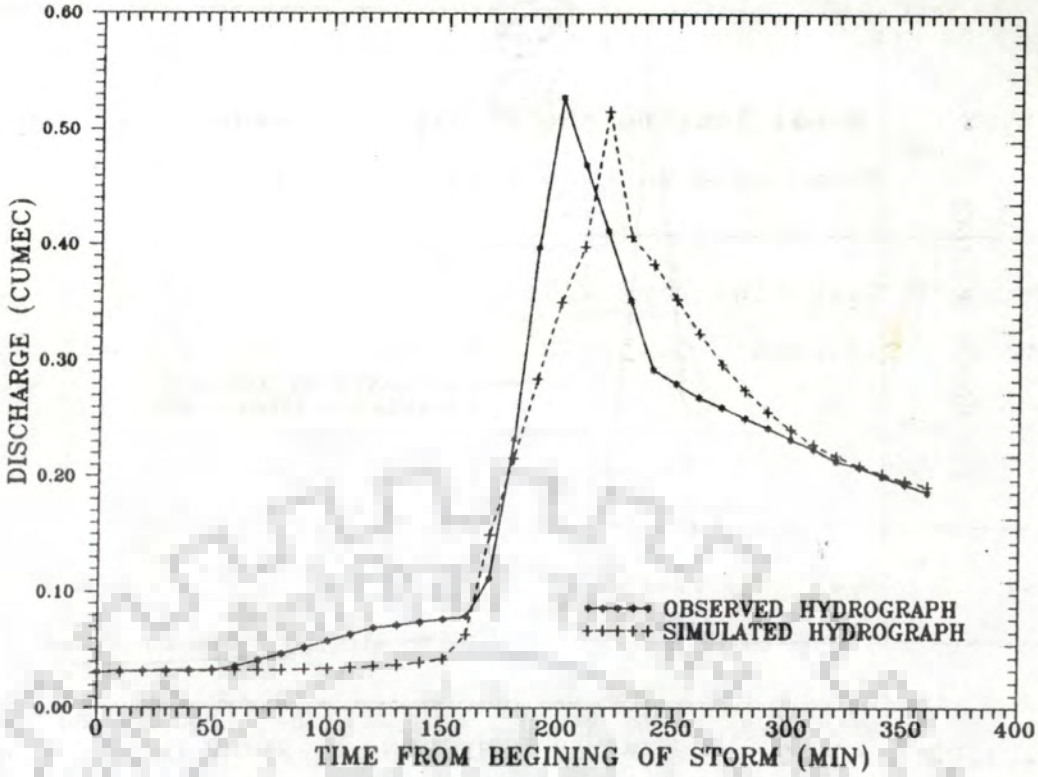
It may be seen that the proposed model has predicted the peak flow rates and flow volumes quite satisfactorily. The model efficiencies vary between 75 percent and 99 percent. In all 14 out of 16 storm events recorded model efficiencies of over 80 percent. Observed and simulated discharge rates for 5 and 25 storms registered at Bhaintan and Jhandoo-Nala watersheds are given in columns (4) and (5) of Appendix-C1 and Appendix-C2 respectively.

Three different infiltration models were used with the Distributed Physiographic model namely, Horton, Philip and Modified Horton (Variable Rainfall Infiltration Model) models. VRIM approach did not yield satisfactory results in the case of Time-area based model because of absence of proper guess of initial infiltration rate. However in Distributed Physiographic model, VRIM helped in simulating peak flows and flood volumes better than Horton and Philip models because of proper estimation of initial infiltration rate using equation 5.14. As an example, comparison of different infiltration models using Distributed Physiographic model, for storm dated 28th July, 1992, registered at Jhandoo-Nala watershed, is shown in Fig. 5.42. Infiltration rates computed using VRIM approach, during various rainfall events

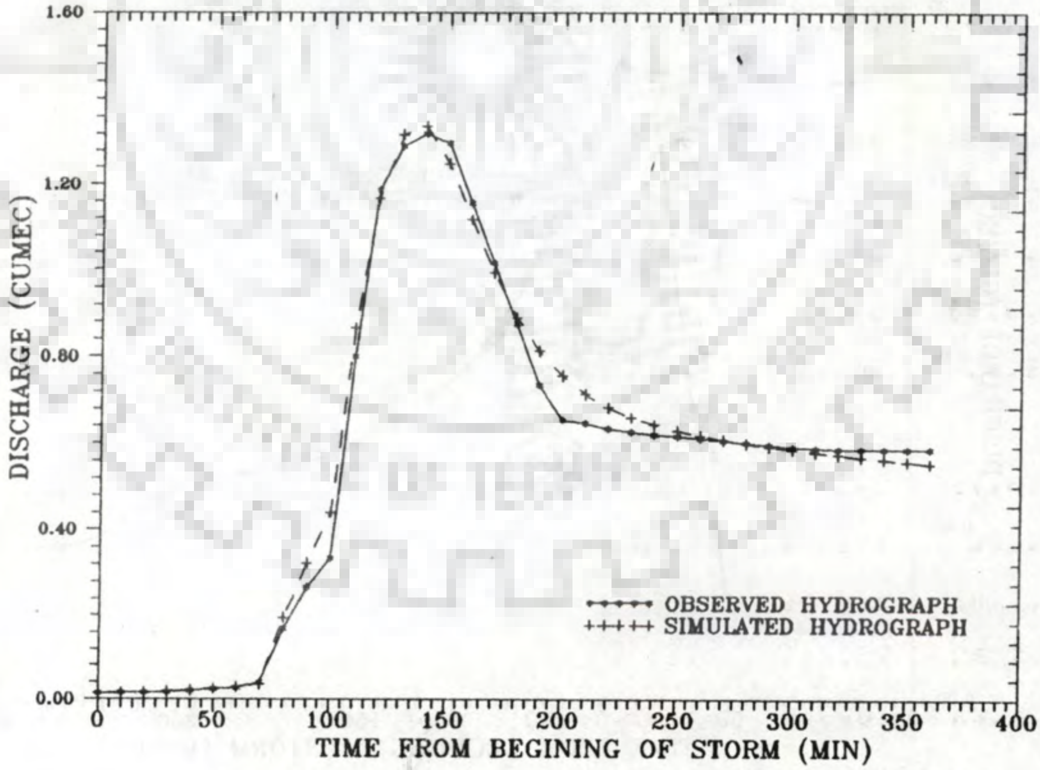
Table 5.22 Model Testing Result for the Distributed Physiographic Model onto the Two Test Watersheds.

Sl. No.	Storm event	Peak Flow Rate (lps) Observed	Peak Flow Rate (lps) Computed	Relative percent error in peak flow rate (%)	Relative percent error in total run off volume (%)	Model Effici. (%) **
(1)	(2)	(3)	(4)	(5)	(6)	(7)
			(A) JHANDOO-NALA WATERSHED			
1	22.7.92	456.7	455.1	0.39	-1.58	98.00
2	28.7.92	195.2	194.6	0.31	-1.42	96.72
3	15.7.93	17.9	14.7	17.88	12.66	92.73
4	17.7.93	165.7	156.1	5.79	0.08	94.98
5	22.7.93	103.5	108.0	-4.35	3.81	87.07
6	2.8.93	52.8	44.1	16.48	0.74	88.97
7	23.8.93	318.2	319.9	-0.53	-2.67	98.87
8	24.8.93	476.2	419.9	11.82	3.12	95.85
9	25.8.93	212.0	214.9	-1.37	-2.70	97.55
10	29.8.93	545.2	544.5	0.13	7.96	94.41
11	2.9.93	366.9	366.3	0.16	2.82	98.47
			(B) BHAINTAN WATERSHED			
12	14.8.79	528.6	510.4	3.44	3.51	85.27
13	2.9.80	1494.1	1543.2	-3.29	-4.37	88.09
14	13.7.81	3106.0	3537.0	-13.88	-10.51	80.17
15	29.7.82	1320.7	1216.3	7.90	5.68	97.28
16	20.8.82	1029.0	1123.7	-9.20	-3.31	74.93

** Nash & Sutcliffe (1970)

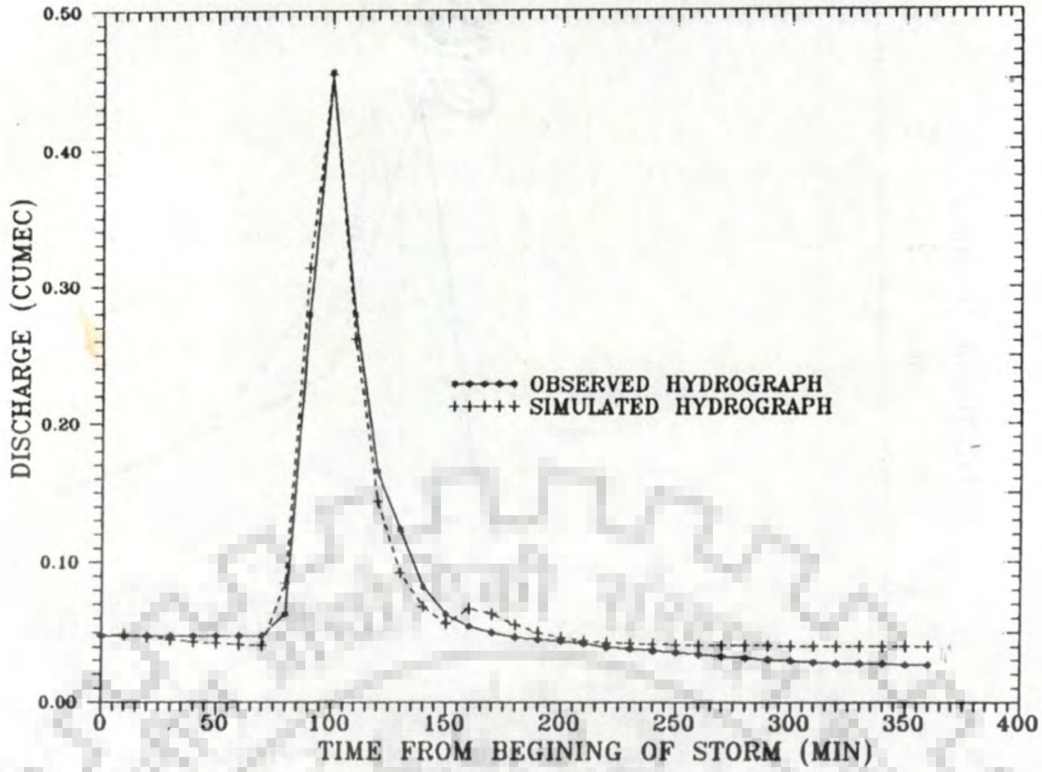


a) STORM EVENT DATED 14-8-1979 (VALIDATION)

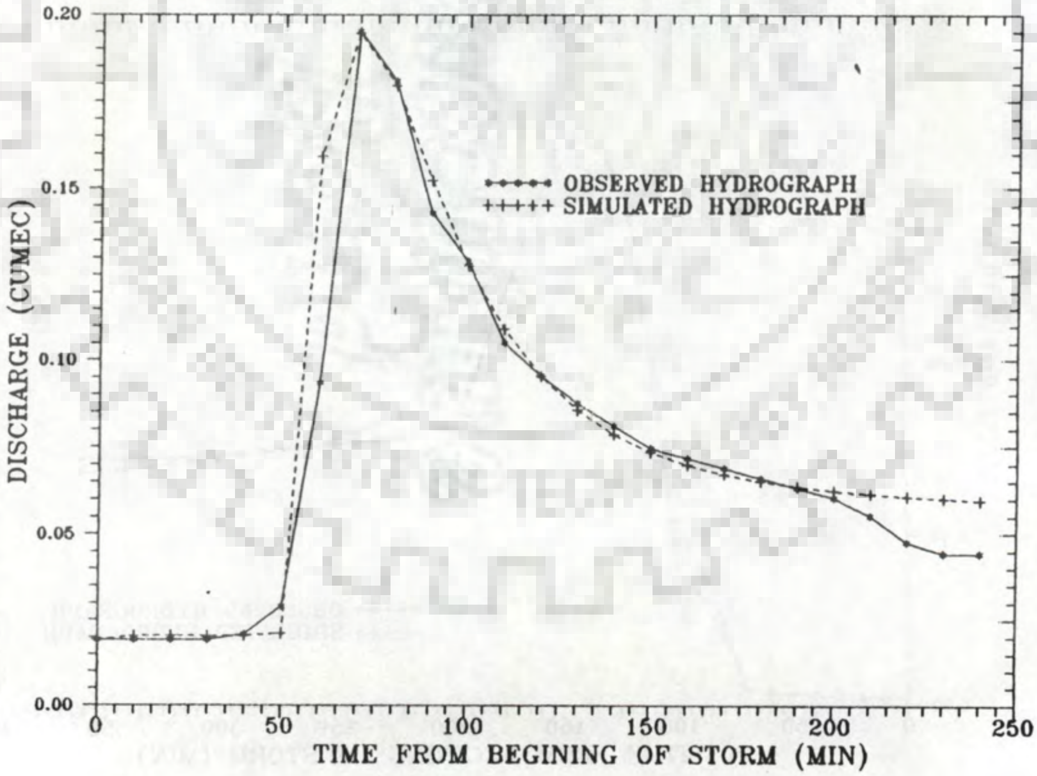


b) STORM EVENT DATED 20-8-1982 (VALIDATION)

FIG.5.39-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHYSIOGRAPHIC MODEL (BHAINTAN WATERSHED).

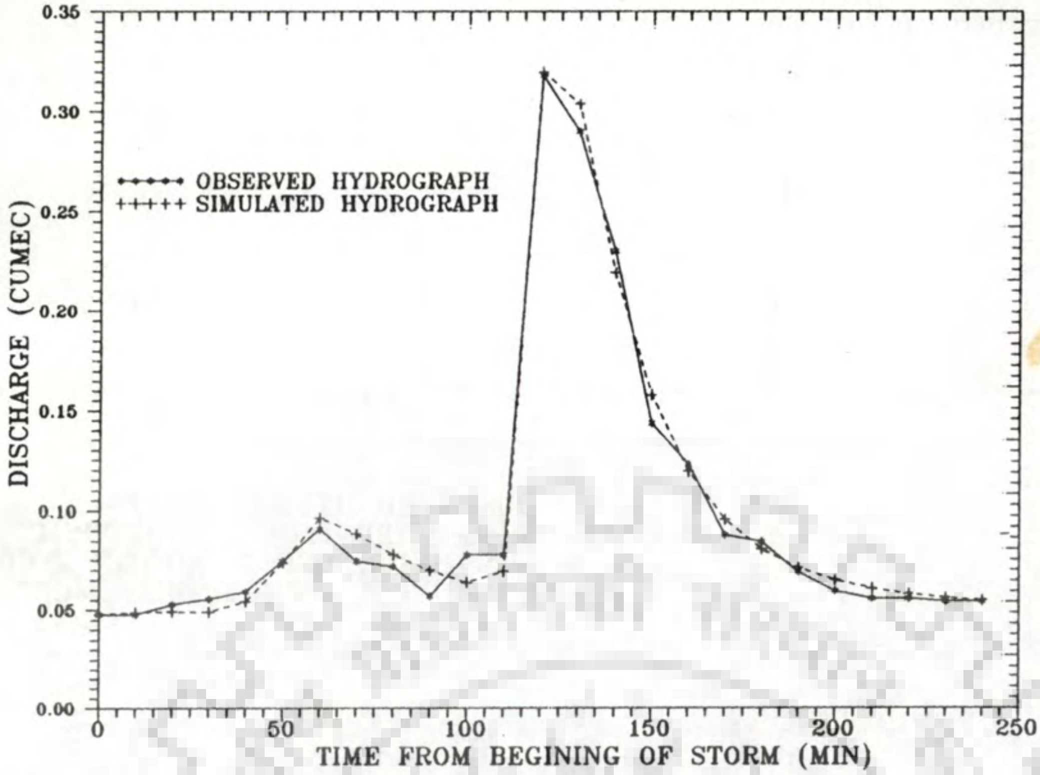


a) STORM EVENT DATED 22-7-1992 (VALIDATION)

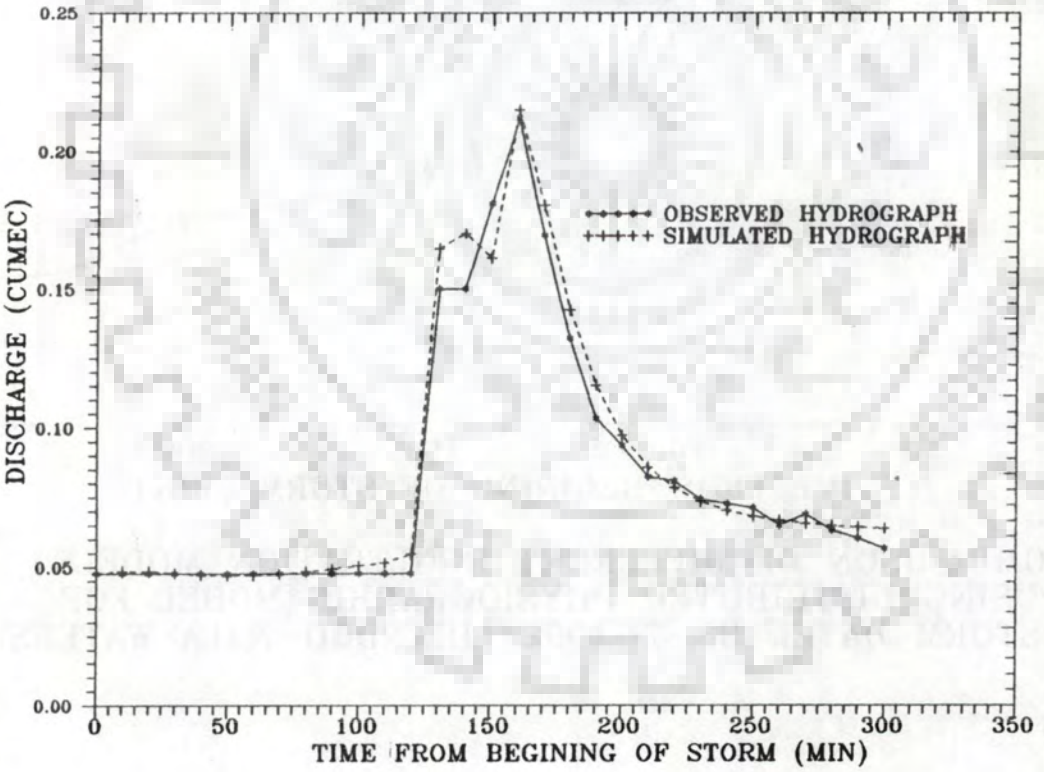


b) STORM EVENT DATED 28-7-1992 (VALIDATION)

FIG.5.40–COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHYSIOGRAPHIC MODEL (JHANDOO-NALA WATERSHED).



a) STORM EVENT DATED 23-8-1993 (VALIDATION)



b) STORM EVENT DATED 25-8-1993 (VALIDATION)

FIG.5.41-COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPH USING DISTRIBUTED PHYSIOGRAPHIC MODEL (JHANDOO-NALA WATERSHED).

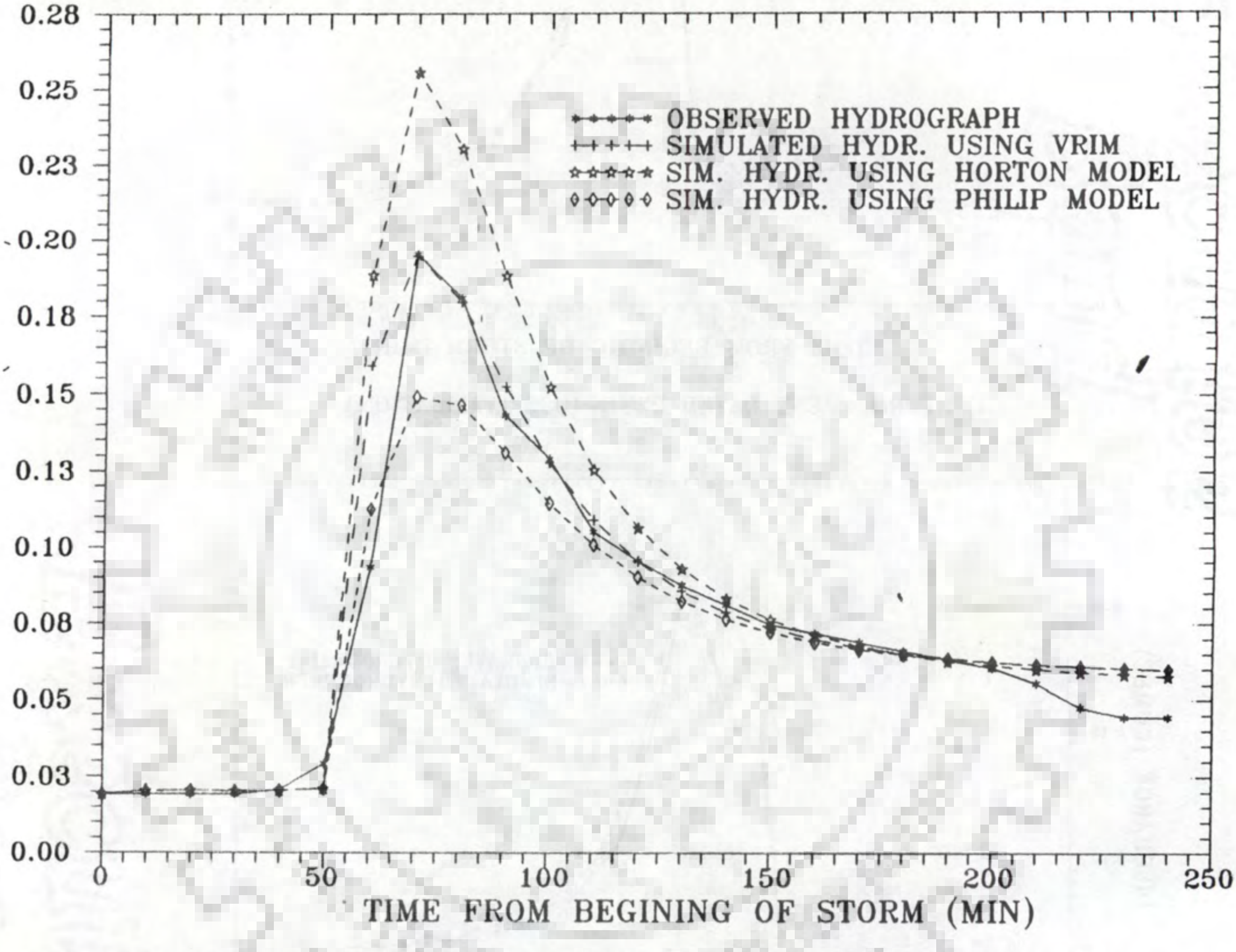


FIG.5.42-COMPARISON OF DIFFERENT INFILTRATION MODELS USING DISTRIBUTED PHYSIOGRAPHIC MODEL FOR STORM DATED 28-7-1992 (JHANDOO-NALA WATERSHED).

registered at two test watersheds, are given in column (3) of Appendix-C1 and Appendix-C2 along with rainfall intensities.

5.4.4 Sensitivity Analysis

There are 15 parameters in the proposed distributed physiographic model which were included in sensitivity analysis (Table 5.17).

Sensitivity analysis of all these parameters was carried out for the storm event registered on 8th August 1991 as was done for the Variable Source Area Model (i.e. section 5.3.2(b)) the results of sensitivity analysis are given in Table 5.23(a) & (b).

The initial infiltration rate parameter fo was found to be most sensitive to flood volume and peak flow rate. It affected change in peak flow rate from -70.9 to 82.2 per cent and flood volume -64.5 to 66.9 per cent for a change in the domain of $\pm$ 30 per cent (Fig. 5.43(a) and 5.44(a)). Surface supply rate exponent parameter γ_s was also observed to be very sensitive to flood volume and peak flow rate. It caused a change of -80.0 to 47.50 per cent and -79.7 to 52.8 per cent in the 'peak flow rate' and 'flood volume' respectively for a variation ranging $\pm$ 30 per cent in parameter values (Fig. 5.43(a) and 5.44(a)).

Channel conveyance coefficient Cr is moderately sensitive as it causes a change in peak flow rate from -23.3 to 16.3 per cent for variation of $\pm$ 30 per cent in its values. However, it was quite insensitive to flood volume. Also the groundwater supply coefficient Cg is insensitive to flood volume as well as to peak flow rate as shown in Fig. 5.43(b) and 5.44(b). Parameters which were found to be moderately sensitive to flood volume and peak flow rate can be seen in Fig. 5.43(a) and 5.44(a).

5.4.5 Concluding Remarks

The average values of channel conveyance coefficient (Cr) for various storm events (25 in number) at Jhandoo-Nala

Table 5.23: Sensitivity Analysis of the Distributed Physiographic Model

a) Sensitivity in Flood Volume

Sl. No.	Parameter	Change in Parameter values (%) -30	-20	-10	+10	+20	+30
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	FO	66.89	44.64	22.08	-22.94	-61.32	-64.50
2	FC	2.41	1.60	0.81	-0.81	-1.60	-2.41
3	PK	- 5.44	-3.60	-1.79	1.76	3.50	5.25
4	AM	0.50	0.33	0.16	-0.19	-0.43	-0.69
5	CS/CST	17.88	11.62	5.63	-5.34	-9.78	-13.99
6	GS/GST	-79.70	-60.44	-32.15	26.76	43.92	52.75
7	GG/GGT	-12.03	- 9.78	-6.08	10.05	26.40	52.16
8	CG/CGT	6.92	4.03	+1.79	-1.45	-2.67	-3.7
9	CR/CRT	-0.60	-0.31	-0.14	0.10	0.17	0.24

b) Sensitivity in Peak Flows

Sl. No.	Parameter	Change in Parameter values (%)					
		-30	-20	-10	+10	+20	+30
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	FO	82.24	54.18	26.45	-26.52	-68.03	-70.85
2	FC	2.98	2.00	0.99	-0.99	- 1.97	-2.96
3	PK	- 6.65	-4.40	-2.19	2.17	4.33	6.48
4	AM/AMT	14.21	8.50	3.76	-2.86	-4.96	-6.43
5	CS/CST	20.45	13.50	6.60	-6.24	-11.59	-16.55
6	GS/GST	-80.0	-65.06	-36.64	29.94	44.78	47.48
7	GG/GGT	-0.82	-0.67	-0.40	0.70	1.85	3.78
8	CG/CGT	0.48	0.26	0.12	-0.09	-0.19	-0.26
9	CR/CRT	-23.27	-14.65	-6.89	6.12	11.52	16.26

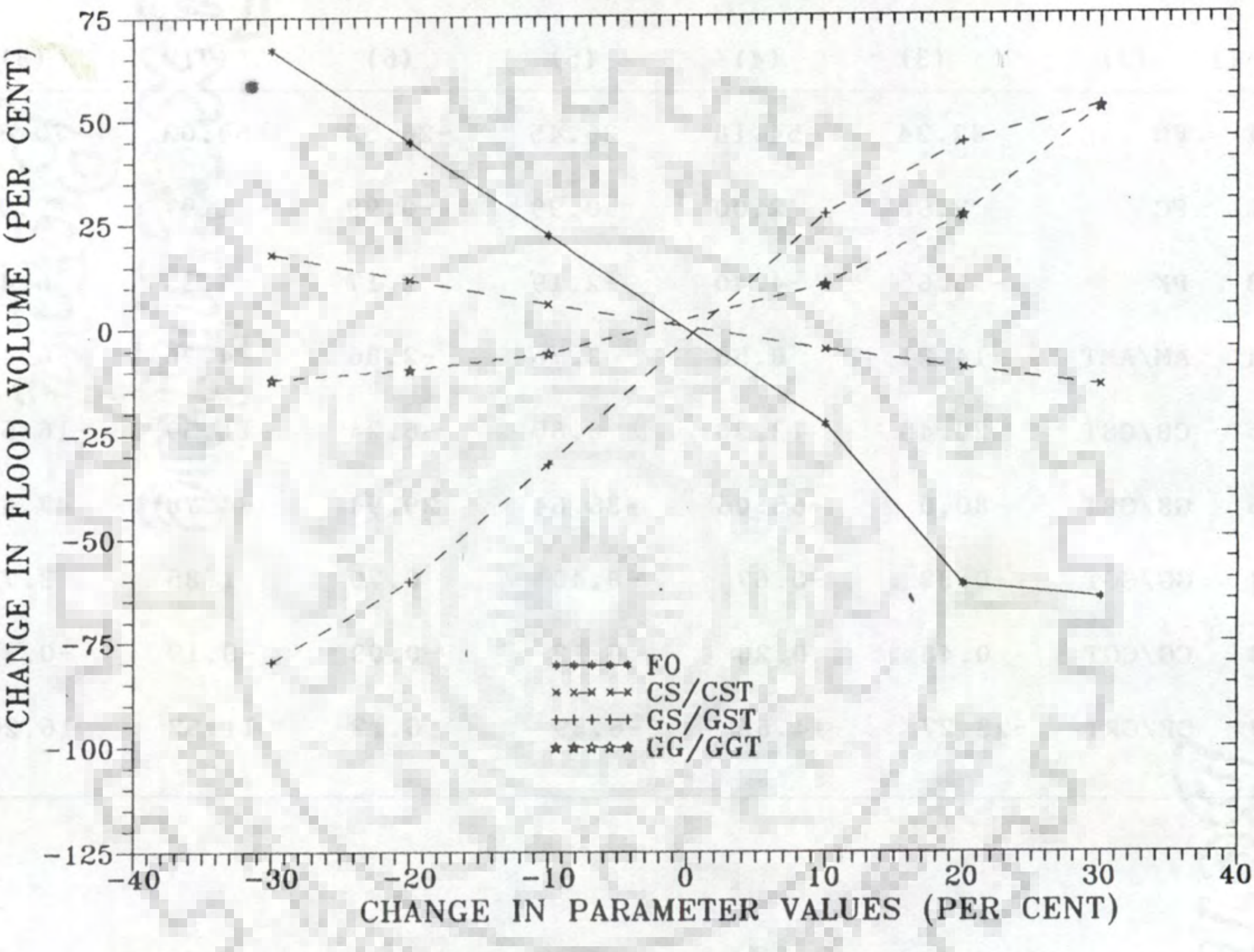


FIG.5.43(a)-SENSITIVITY ANALYSIS OF PARAMETERS FOR DISTRIBUTED PHYSIOGRAPHIC MODEL (FOR FLOOD VOLUME).

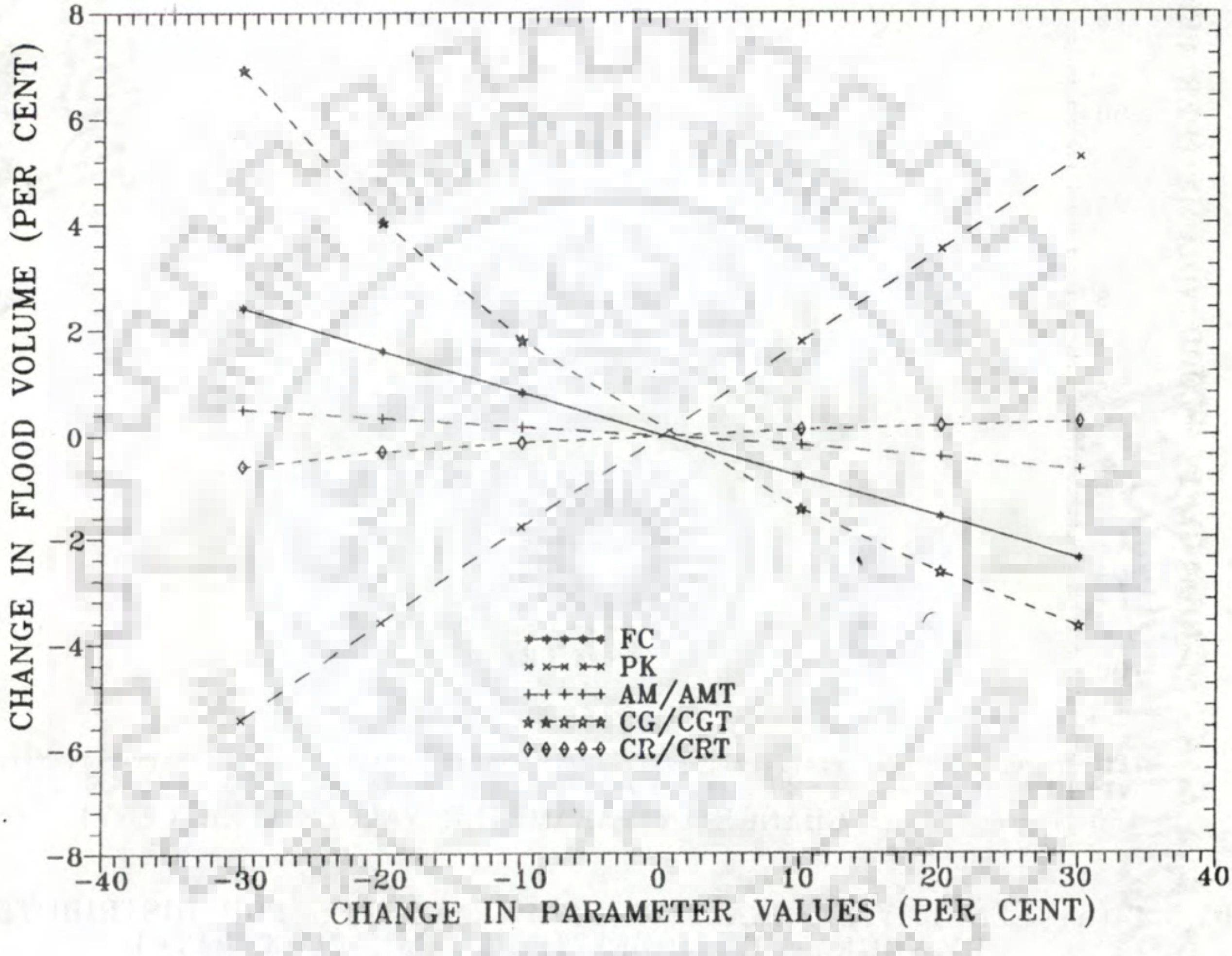


FIG.5.43(b)–SENSITIVITY ANALYSIS OF PARAMETERS FOR DISTRIBUTED PHYSIOGRAPHIC MODEL (FOR FLOOD VOLUME).

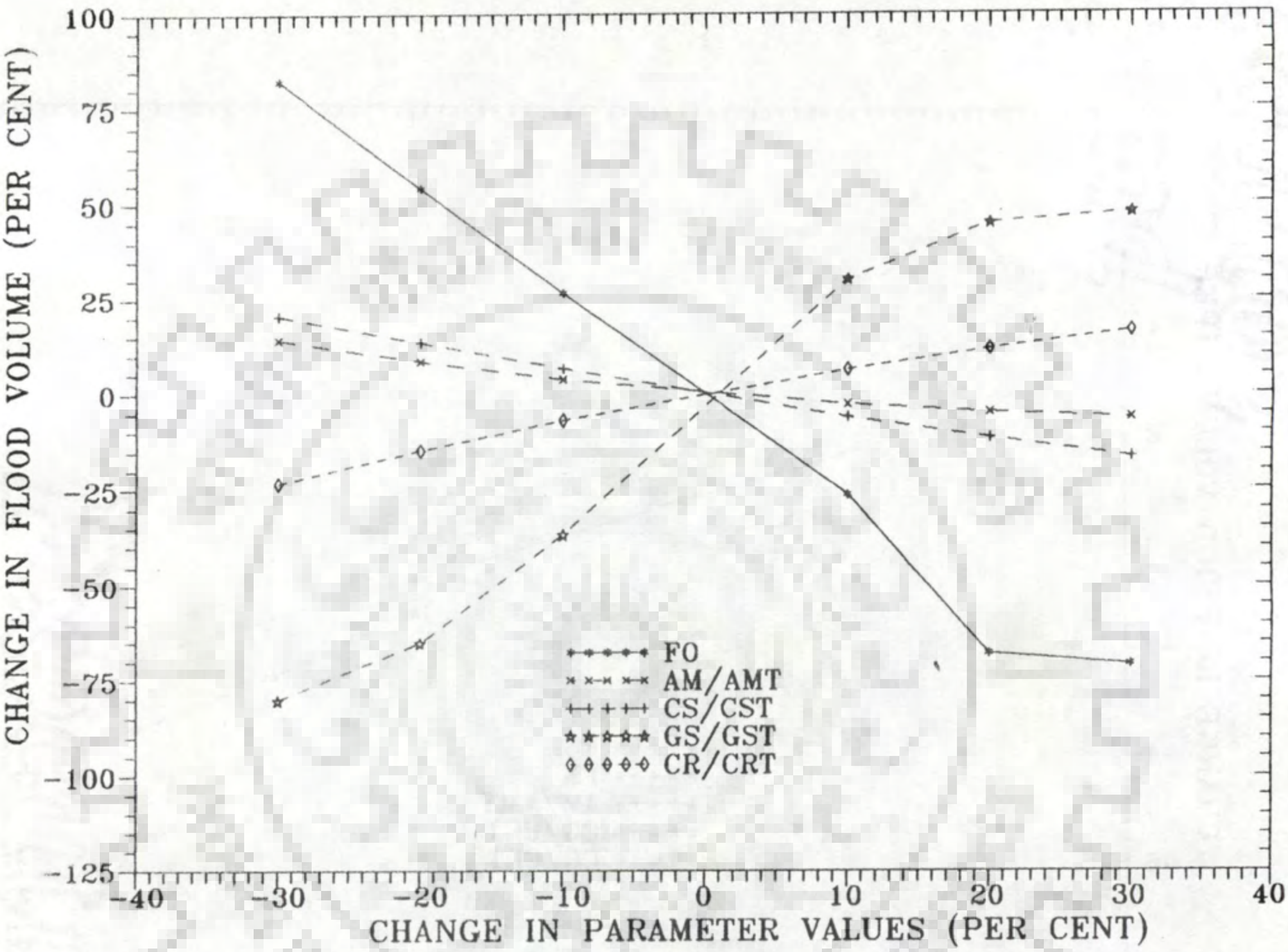


FIG.5.44(a)–SENSITIVITY ANALYSIS OF PARAMETERS FOR DISTRIBUTED PHYSIOGRAPHIC MODEL (FOR PEAK FLOW RATE).

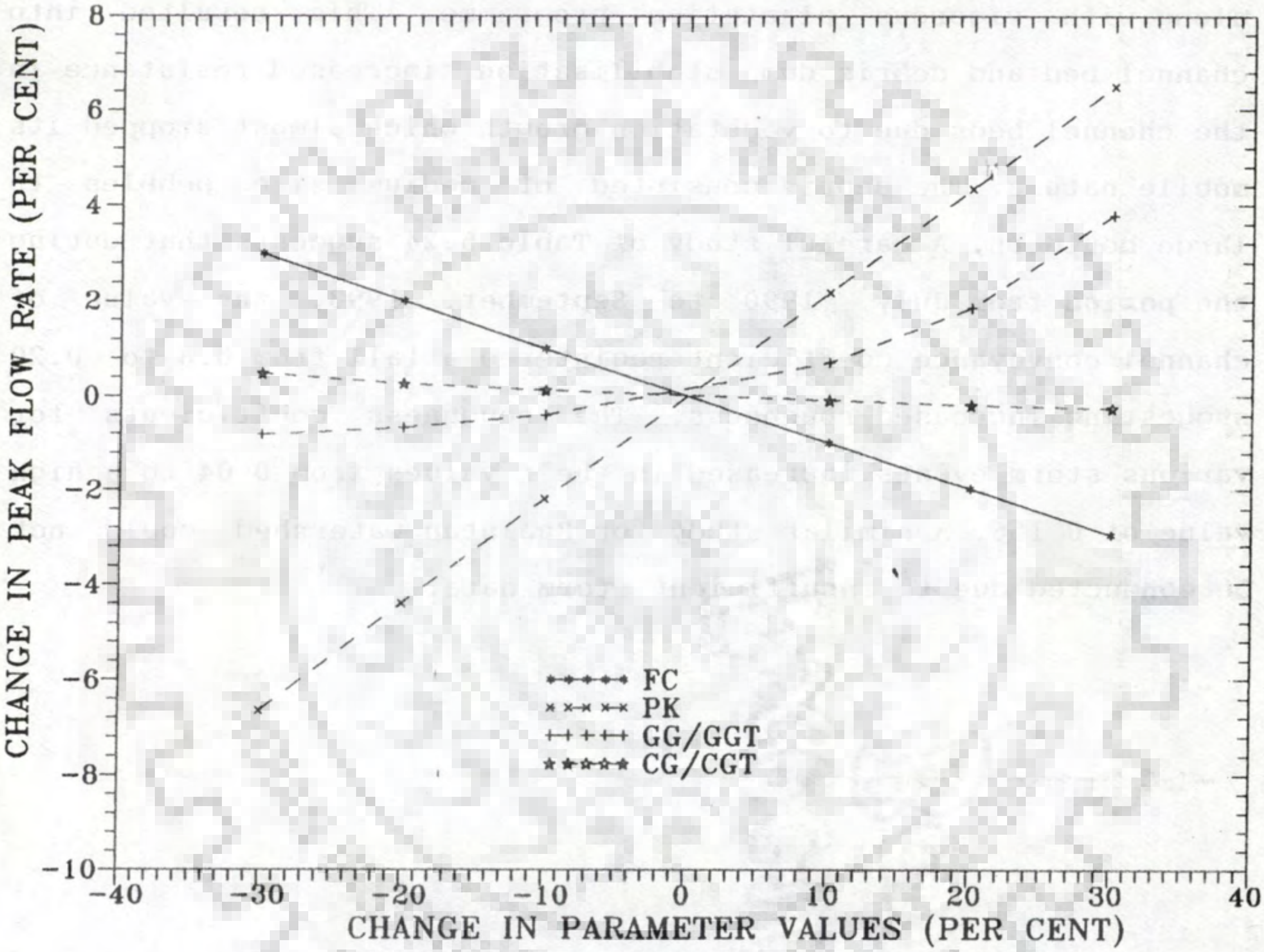


FIG.5.44(b)–SENSITIVITY ANALYSIS OF PARAMETERS FOR DISTRIBUTED PHYSIOGRAPHIC MODEL (FOR PEAK FLOW RATE).

watershed are presented in Table 5.24.

Over this period various efforts were pursued for restoration of the disturbed watershed by the Central Soil & Water Conservation, Research and Training Institute, Dehradun (U.P.), India, through engineering measures like gabion check dams, silt detention dams, loose boulder check dams, crib structures etc. along with vigorous plantation programme. This resulted into channel bed and debris dump stabilisation, increased resistance in the channel beds due to vegetation growth which almost stopped its mobile nature. The debris consisted of medium size pebbles to large boulders. A careful study of Table 5.24 suggests that during the period from July, 1990 to September, 1993, the value of channel conveyance coefficient registered a fall from 0.8 to 0.20 suggesting increased roughness. The roughness coefficients for various storm events increased in their values from 0.04 to a high value of 0.156. A similar study for Bhaintan watershed could not be conducted due to insufficient storm data.

Table 5.24: Average Values of Channel Conveyance Coefficient (Cr) and Channel Roughness Coefficient (nm) for the Various Storm Events Registered at Jhandoo-Nala Watershed

Sl.No.	Storm Event	Average Value of Channel Conveyance Coefficient (Cr)	Average Value of Channel Roughness Coefficient (nm)
1	4.7.90	0.80	0.040
2	10.8.90	0.70	0.047
3	11.8.90	0.70	0.047
4	16.8.90	0.60	0.053
5	18.8.90	0.53	0.058
6	25.8.90	0.42	0.074
7	5.7.91	0.70	0.047
8	7.8.91	0.56	0.056
9	8.8.91	0.56	0.056
10	9.8.91	0.55	0.057
11	15.8.91	0.48	0.065
12	16.8.91	0.48	0.065
13	22.7.92	0.42	0.074
14	28.7.92	0.42	0.074
15	4.8.92	0.37	0.083
16	7.7.93	0.43	0.072
17	15.7.93	0.37	0.083
18	17.7.93	0.33	0.094
19	22.7.93	0.32	0.098
20	2.8.93	0.27	0.118
21	23.8.93	0.22	0.139
22	24.8.93	0.22	0.139
23	25.8.93	0.22	0.140
24	29.8.93	0.20	0.156
25	2.9.93	0.20	0.156

CHAPTER-VI

DISCUSSION OF RESULTS AND CONCLUSIONS

The proposed study was taken up with a view to study some currently used hydrologic models and to modify them so that they can account for the hydrological processes of disturbed, mountainous, small watersheds of the Himalayan region (Chapter-I). The models should have the capabilities of accounting for the impact of soil conservation measures on disturbed mountainous areas. A literature survey was carried out to have an overview of the efforts carried out in this direction. A brief review of these efforts is presented in Chapter-II. The literature review revealed that hydrological studies of small mountainous watersheds have rarely been carried out because of technical (i.e. lack of data) and financial constraints. In fact, the world over mountainous watersheds have not been paid the required attention in comparison to the lowland plain watersheds. India is not an exception.

The hydrologic responses of small watersheds basically depend upon the mechanics of runoff generation which is generally a nonlinear process. The disturbances in a watershed mainly caused by overgrazing, deforestation, road construction and mining etc. do change the behaviour of mountainous area. The various concepts used in defining the complex process have been discussed in Chapter-II. There are three widely accepted mechanism of runoff generation, namely Hortonian overland flow, Variable Source area runoff and Subsurface stormflow. Depending on antecedent conditions and rainfall intensities, infiltration excess and subsurface stormflow runoff may occur in the same watershed or at same location during different storms (Freeze, 1980, Beven, 1986, 1991).

In this thesis, the hydrologic behaviour of one partially disturbed (i.e. Bhaintan watershed) and one highly disturbed watershed (i.e. Jhandoo-Nala watershed) have been studied. Brief descriptions of these watersheds which have undergone soil conservation treatments for nearly 10 years are presented in Chapter-III. The availability of data with reference to physiography, meteorology alongwith hydrological information have been discussed in this chapter.

Three hydrologic modelling approaches using different runoff generation mechanisms, viz. the Hortonian overland flow concept (i.e. for a Time-Area Based Model), the Variable source area concept(i.e.for a variable source Area Model) have been used to study the hydrologic behaviour of disturbed mountainous small watersheds.

Time-Area Based Model which works on the principle of convolution of ``rainfall excess'' on time-areas, may be helpful in high altitude upland mountainous comprising of large impervious areas and devoid of vegetation, where major part of rainfall is converted into runoff. The Time Area based models may prove to be useful tools for runoff simulation of mountainous watersheds if the time of concentration (Tc) can be ascertained properly. Empirical approaches for computation of Tc may not yield the desired results. The rainfall excess computations using the ϕ-index method yield satisfactory results (Figures 5.13 to 5.15) when Tc is computed by using the concepts of S-hydrograph (section 5.2.6). The usefulness of the method lies in its simplicity. However, the proposed model could not account for the disturbance in the watershed (i.e. the effect of soil conservation treatments) because of lumped nature of the rainfall excess function. In disturbed watershed, if exact infiltration rates are available, the rainfall excess function can still be computed more accurately to account for the changes in watershed behaviour.

The Variable Source Area methodology has been modified to develop an event based model to simulate the runoff hydrographs satisfactorily. This can be seen in application of the models for various storm events registered at the two test mountainous watersheds (Tables 5.7, 5.8 and Figures 5.16 to 5.18).

The proposed model requires storm intensity and runoff rates as the main input variables. Some other input variables like watershed area and stream/channel area etc. can easily be measured from the toposheet. The rest of the variables may have to be ascertained through optimization. Thus, the data requirement for the model is not more but estimation of parameters may prove to be time consuming.

The proposed model uses one parameter less than the model suggested by Putty and Rama Prasad (1992) which has been applied onto the watersheds of Western Ghats region (India).

The relationships involving variable source area 'extent', API, rainfall intensities, baseflow, interflow and saturated flows may be of practical help and use in determining different components of runoff as well as volume of runoff from mountainous watersheds.

The two hydrologic models mentioned above, being lumped in nature, could not reveal clearly the effects of soil conservation measures on the hydrologic behaviour of the disturbed watershed. Therefore, a distributed physiographic model was developed by modifying the model of Field and Williams (1987). The model was modified keeping in view the disturbed, mountainous nature of small watersheds under study.

In the proposed Distributed Physiographic model, the watershed is divided into tributary and main channel subwatersheds. The runoff process for each of these subwatersheds is conceptually taken care of with the help of two nonlinear reservoirs. The upper nonlinear reservoir contributes surface runoff which is termed as 'surface supply ' (Ss) and the lower one contributes subsurface runoff (groundwater), which is termed as the 'groundwater supply '(Sg). These contributions form the total supply (S).

As discussed in Chapter-II, the Kinematic Wave Theory based hydrologic models, currently being used for solving the St. Venant's equation, have the capability of taking into account the distributed nature of the watershed physiography. The Kinematic Wave equation (4.53) is solved using nonlinear implicit scheme (Chow, 1988)which is unconditionally stable. The product of total supply rate (per unit area) and width of subwatershed (B) forms the lateral inflow rate (q), which is routed using the Kinematic Wave Theory from the divide (ridge) to the outlet of each subwatershed. Initial and boundary conditions are established depending on the existence of baseflow and stage discharge relationships. There are 15 parameters in the model which were optimized (fitted) using subjective (trial-and-error) method. Sensitivity analysis of the proposed model parameters was carried out and it was observed that the initial infiltration rate (fo) is the most sensitive parameter which varies from storm to storm depending on antecedent moisture conditions of the watershed and storm characteristics. Multiple regression analysis (linear) has been carried out using 25 storm events and an equation (5.14) has been developed for Jhandoo-Nala to compute initial infiltration rate for each storm to be simulated. Optimum values of model parameters obtained are given in Table 5.21 and model calibration results are given in Table 5.22. Peak flow rates and runoff volumes have matched very well as shown in Figures 5.36 to 5.38.

The Distributed Physiographic model was validated with the eleven storm events (i.e. during the monsoon months of 1992 and 1993) and all the five events available for Bhaintan watershed. The proposed model could predict the peak flow rates and volume of runoff with per cent errors in permissible range (Table 5.23).

The proposed model could reveal the impact of soil and water conservation measures through the decrease in values of channel conveyance coefficient (Cr) and increase in the values of channel roughness coefficient from July 1990 to september 1993 (Table 5.24).

Three different infiltration models were used with Distributed Physiographic model namely Horton, Philip and Variable Rainfall Infiltration model (VRIM). As discussed in section 5.2, the VRIM approach did not yield satisfactory results in case of Time-area based model because of absence of proper guess of initial infiltration rates. However, in Distributed Physiographic model VRIM helped in simulating peak flows and flood volumes satisfactorily because of proper estimation of infiltration rate using equation 5.14. The other two infiltration models (i.e. Horton and Philip) did not give desired results.

Concludingly, it may be remarked that a majority of hydrologists dealing with the studies of mountainous catchments, do accept that the runoff generation mechanism is neither purely Hortonian nor totally through 'stormflow' or through 'variable source area'. It may comprise of a combination of all these runoff generating factors on a hillslope.

In future, a hydrologic model for small disturbed mountainous watershed comprising of variable source area concept, overland flow and channel flow routing using Kinematic Wave Theory may be developed. In the proposed model, overland flow routing has not been considered which may be incorporated alongwith topographical effects of hillslope.

APPENDIX-A

Appendix-A1- Programme for Time-area based model.

a) Main Programme:

```
C ************** TIME AREA BASED MODEL FOR RUN-OFF SIMULATION **********
C       *****************************************************************
C       THIS PROGRAMME IS PART OF THE "HYDROLOGICAL STUDIES OF DISTURBED
C       MOUNTAINOUS WATERSHEDS" DEVELOPED BY VIDYA SAGAR KATIYAR RESEARCH
C       SCHOLAR,GUIDED BY DR.B.S.MATHUR,PROFESSOR,DEPARTMENT OF HYDROLOGY
C       UNIVERSITY OF ROORKEE,ROORKEE (INDIA) & DR.M.S.RAMA MOHAN RAO,EX-
C       DIRECTOR, CENTRAL SOIL & WATER CONSERVATION RESEARCH & TRAINING
C       INSTITUTE, DEHRADUN (INDIA).
C ***********************************************************************
C ***************** DEFINITIONS OF PARAMETERS AND VARIABLES ************
C RAINM(J)    = RAINFALL INTENSITY DURING Jth TIME STEP (MM/HR)
C QOBS  (J)   = OBSERVED RUNOFF RATE DURING Jth TIME STEP (CUMEC)
C QSIM  (J)   = SIMULATED RUNOFF RATE DURING Jth TIME STEP (CUMEC)
C RE    (J)   = RAINFALL EXCESS RATE DURING Jth TIME STEP (CUMEC)
C RINFM(J)    = INFILTRATION RATE DURING Jth TIME STEP (MM/HR)
C BORD  (J)   = SUBSURFACE FLOW ORDINATE DURING Jth TIME STEP
C AR    (I)   = AREA OF Ith INTER-ISOCHRONAL STRIP (SQM)
C UH    (J)   = UNIT HYDROGRAPH ORDINATE DURING Jth TIME STEP
C S     (J)   = S-HYDROGRAPH ORDINATE DURING Jth TIME STEP
C QDR   (J)   = DIRECT RUNOFF ORDINATE DURING Jth TIME STEP
C DT          = TIME STEP (SECONDS)
C NDT         = TOTAL NUMBER OF TIME STEPS DURING THE RUNOFF EVENT
C NER         = TOTAL NUMBER OF RAINFALL STEPS DURING THE RAIN EVENT
C NAR         = TOTAL NUMBER OF TIME AREAS IN THE WATERSHED
C CAREA       = TOTAL AREA OF THE WATERSHED (SQM)
C PHIN        = INITIAL VALUE OF PHI-INDEX (MM/HR)
C STEP        = INCREAMENT IN PHI-INDEX FOR COMPUTATION OF PHI-INDEX
C PHIND       = COMPUTED VALUE OF PHI-INDEX FOR THE STORM
C ARATE       = AVERAGE RAINFALL INTENSITY (MM/HR)
C SRUN        = SURFACE RUNOFF DURING THE STORM (PER CENT OF RAINFALL)
C BRUN        = SUBSURFACE RUNOFF DURING THE STORM (PER CENT OF RAINFALL)
C ERR         = ERROR CRITERION
C INFK        = CODE FOR RAINFALL EXCESS COMPUTATION METHOD
C TTRAIN      = TOTAL RAINFALL OF THE STORM (MM)
C EXRAIN      = TOTAL RAINFALL EXCESS OF THE STORM (MM)
C FO          = INITIAL INFILTRATION RATE (MM/HR)
C FC          = FINAL INFILTRATION RATE (MM/HR)
C PK          = INFILTRATION DECAY CONSTANT
C F           = DIFFERENCE BETWEEN OBSERVED & SIMULATED RUNOFF RATE
C FSQ         = SQUIRE OF DIFFERENCE ,, ,, ,, ,, ,, ,, ,, ,, ,, ,,
C RSQ         = COEFFICIENT OF DETERMINATION
```

```
C EFF        = MODEL EFFICIENCY (NASH & SUTCLIFE, 1970)
C ***********************************************************************
      COMMON/AAA/QOBS(1441),QSIM(1441),RAINM(1441),RE(1441),BORD(1441)
      COMMON/BBB/NDT,NER,NAR,CAREA,PHIN,STEP,DT,SRUN,BRUN,KT,ERR
      COMMON/CCC/F,FSQ,RSQ,EFF,PHIND,TEXR,TTRAIN,EXRAIN,KOUNT,ARATE
      COMMON/DDD/FO,FC,PK,INFK,RINFM(1441),OBSQ(100),SIMQ(100),S(1441),
     1UH(1441),QDR(1441),AR(20)
      COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE
C ***********************************************************************
      OPEN(UNIT=1,FILE='TAC3.DAT',STATUS='OLD')
      OPEN(UNIT=2,FILE='TAC3.OUT',STATUS='NEW')
      OPEN(UNIT=3,FILE='MSH.DAT' ,STATUS='OLD')
C ***********************************************************************
      READ(1,*)CAREA,PHIN,STEP,DT,NAR,ERR,FO,FC,PK,INFK,FACT
      WRITE(2,500)
      WRITE(*,500)
 500   FORMAT(5X,'INPUT DATA'/,5X,'==========')
      WRITE(2,9)CAREA,PHIN,STEP,DT,NAR,ERR,FO,FC,PK,INFK,FACT
      WRITE(*,9)CAREA,PHIN,STEP,DT,NAR,ERR,FO,FC,PK,INFK,FACT
  9    FORMAT(2X,'CAREA=',F10.2,2X,'PHIN=',F6.2,2X,'STEP=',F4.2,/2X,
     1'TIME STEP=',F6.2,2X,'NO. OF TIME AREAS=',I3,2X,'ERROR=',F6.4,
     2/2X,'FO =',F6.2,2X,'FC =',F6.2,2X,'PK =',F6.4,2X,'INFK=',I2,2X,
     3'FACT=',F6.4)
      READ(1,*)(AR(I),I=1,NAR)
      READ(3,*)IDATE,IMONTH,IYEAR
      WRITE(2,11)IDATE,IMONTH,IYEAR
      WRITE(*,11)IDATE,IMONTH,IYEAR
 11   FORMAT(5X,'BASE FLOW SEPARATION FOR',2X,I2,2X,I2,2X,I4)
C ***********************************************************************
C     CALCULATION OF NUMBER OF TIME STEPS AND NUMBER OF RAIN EVENTS
C ***********************************************************************
      READ(3,*)RADUR,SIMT
      SIMTS=SIMT*3600.0
      RADURS=RADUR*3600.0
      NDT=SIMTS/DT+1.0
      NER=RADURS/DT+1.0
      WRITE(2,70) NDT,NER
      WRITE(*,70)NDT,NER
 70   FORMAT(2X,'NUMBER OF TIME STEPS=',I5,2X,'NUMBER OF RAIN
     1EVENT=',I5)
      READ(3,*)(QOBS(J),J=1,NDT)
      KT=600./DT
      WRITE(2,*)(QOBS(J),J=1,NDT,KT)
      WRITE(*,*)(QOBS(J),J=1,NDT,KT)
      READ(3,*)(RAINM(J),J=1,NER)
      WRITE(2,*)(RAINM(J),J=1,NER,KT)
      WRITE(*,*)(RAINM(J),J=1,NER,KT)
```

```
C ***********************************************************************
C                  RAINFALL EXCESS COMPUTATION
C ***********************************************************************
C        INFK=1 : PHI-INDEX METHOD FOR EXCESS RAIN ESTIMATION
C        INFK=2 : VARIABLE RAIN INFILTRATION METHOD
         IF(INFK.EQ.2) GO TO 170
          CALL EXR
          GO TO 180
 170       CALL INFILT
 180       WRITE(*,101)
           WRITE(2,101)
 101      FORMAT(5X,'SIMULATION STARTS')
C ***********************************************************************
C      CONVOLUTION OF RAINFALL EXCESS ONTO THE TIME-AREA HISTOGRAM
C ***********************************************************************
         QSIM(1)=0.0
         DO 55 J = 2,NDT+1
         QR=0.0
C          K=NAR
         DO 44 I = 1,NAR
          IF(J.LE.I) GO TO 45
          QR=QR+AR(I)*RE(J-I)
C           K=K-1
  44       CONTINUE
  45       QSIM(J-1)=QR
  55        CONTINUE
          WRITE(*,103)(K,QSIM(K),K=1,NDT)
          WRITE(2,103)(K,QSIM(K),K=1,NDT)
 103      FORMAT(6(I4,F7.4))
         WRITE(2,112)PHIND,TEXR,TTRAIN,EXRAIN,KOUNT
         WRITE(*,112)PHIND,TEXR,TTRAIN,EXRAIN,KOUNT
 112     FORMAT(5X,'PHIND=',F6.2,2X,'TEXR=',F6.3,2X,'TTRAIN=',F6.2,/2X,
     1'EXRAIN=',F6.3,2X,'KOUNT=',I5)
C ***********************************************************************
C COMPUTED HYDROGRAPH & TOTAL FLOOD VOLUME(CUM) DURING THE ROUTING PERIOD
C AND STATISTICAL PARAMETERS FOR GOODNESS OF FIT FOR THE STORM EVENT
C ***********************************************************************
         EXRN=0.0
         QCSUM=0.0
         Q=0.0
         DO 60 J =2,NDT
         Q=Q+QSIM(J)
 60      CONTINUE
         QCSUM=Q*DT
         EXRN =(QCSUM*1000.)/CAREA
         WRITE(2,552)
         WRITE(*,552)
```

```
552      FORMAT(4X,'STEP',5X,'TIME(MINS.)',5X,'OBS. DISCH.',5X,
     1'SIM. DISCH.')
         DO 56 K=1,NDT,KT
          NC= K/KT+1
         QSIM(K) = QSIM(K) + BORD(K)
         SIMQ(NC)=QSIM(K)
         OBSQ(NC)=QOBS(K)
         TIME=(FLOAT(K)-1.0)*DT/60.0
         WRITE(2,555)NC,TIME,OBSQ(NC),SIMQ(NC)
         WRITE(*,555)NC,TIME,OBSQ(NC),SIMQ(NC)
56       CONTINUE
        CALL OBJECT
        WRITE(2,119)F,FSQ,RSQ,EFF
        WRITE(*,119)F,FSQ,RSQ,EFF
        WRITE(2,111)EXRAIN,TTRAIN,SRUN,BRUN,ARATE
        WRITE(*,111)EXRAIN,TTRAIN,SRUN,BRUN,ARATE
        WRITE(2,117)ABSF,SDO,SDS,CVO,CVS,SE
        WRITE(*,117)ABSF,SDO,SDS,CVO,CVS,SE
         WRITE(2,550)QCSUM,EXRN
         WRITE(*,550)QCSUM,EXRN
111     FORMAT(2X,'EXRAIN=',F10.6,2X,'TTRAIN=',F10.4,2X,'SRUN=',F8.6,
     1  2X,'BRUN=',F8.6,/2X,'ARATE=',F10.4)
117     FORMAT(5X,'ABS DIFF.=',F10.4,5X,'SDO=',F10.4,5X,'SDS=',
     1F10.4,/5X,'CVO=',F10.6,5X,'CVS=',F10.6,5X,'SE=',F10.6)
119     FORMAT(5X,'F =',F10.4,4X,'FSQ=',F10.4,4X,'RSQ=',F8.6,4X,'EFF=',
     1F12.6)
550     FORMAT(5X,'FLOOD VOL.(CUM)=',F10.2,5X,'EXRAIN(MM)=',F8.4)
555     FORMAT(4X,I3,5X,F7.2,7X,F9.6,7X,F9.6)
        STOP
        END
```

b) Subroutine EXR

```
C ***********************************************************************
C    PROGRAMME FOR CALCULATION OF EXCESS RAIN BY PHI INDEX METHOD
C ***********************************************************************
        SUBROUTINE EXR
       COMMON/AAA/QOBS(1441),QSIM(1441),RAINM(1441),RE(1441),BORD(1441)
       COMMON/BBB/NDT,NER,NAR,CAREA,PHIN,STEP,DT,SRUN,BRUN,KT,ERR
       COMMON/CCC/F,FSQ,RSQ,EFF,PHIND,TEXR,TTRAIN,EXRAIN,KOUNT,ARATE
       COMMON/DDD/FO,FC,PK,INFK,RINFM(1441),OBSQ(100),SIMQ(100),S(1441),
     1UH(1441),QDR(1441),AR(20)
C ***********************************************************************
       KOUNT =0.0
       TEXR  =0.0
       TOBS  =0.0
       TRAIN =0.0
```

```
      TRUN  =0.0
      EXRAIN=0.0
      TTRAIN=0.0
      DTT   =0.0
      SDT   =0.0
      BORD(1)=QOBS(1)
       DO 10 J=1,NDT
      TRUN=TRUN + ((QOBS(J)*DT*1000.)/CAREA)
      DELQ=QOBS(NDT)-QOBS(1)
      DELX=((J-1)*DELQ)/(NDT-1)
      BORD(J)=QOBS(1)+DELX
      IF(BORD(J).GT.QOBS(J)) BORD(J)=QOBS(J)
      QDR(J)=QOBS(J)-BORD(J)
      TOBS =TOBS+QDR(J)
      IF(TOBS.LE.0.) TOBS=0.0
      TRAIN=TRAIN+RAINM(J)
 10   CONTINUE
      EXRAIN =(TOBS*DT*1000.)/(CAREA)
      TTRAIN =(TRAIN*DT)/3600.
      SRUN=EXRAIN/TTRAIN
      BRUN=(TRUN-EXRAIN)/TTRAIN
C ************************************************************************
C     CALCULATION OF S-HYDROGRAPH ORDINATES FOR THE STORM
C ************************************************************************
      S(1)=0.0
      UH(1)=0.0
      EXRCM=EXRAIN/10.
      DO 160 I=1,NDT
       UH(I)=QDR(I)/EXRCM
       S(I)=S(I-1)+UH(I)
 160  CONTINUE
       WRITE (2,161)
 161   FORMAT(9X,'TIME',9X,'UNIT ORDI',8X,'S-ORDI.',6X,'DRHO')
       WRITE(2,162)
 162   FORMAT(5X,4('-'),15X,24('-'))
       HR=DT/60.
       WRITE(2,163)  (HR*(I-1),UH(I),S(I),QDR(I),I=1,NDT)
 163   FORMAT(5X,F8.4,5X,F10.4,5X,F10.4,9X,F10.4)
       WRITE(2,111)EXRCM,TTRAIN,SRUN,BRUN,ARATE
       WRITE(*,111)EXRCM,TTRAIN,SRUN,BRUN,ARATE
 111  FORMAT(2X,'EXRAIN(CM)=',F10.6,2X,'TTRAIN=',F10.6,2X,'SRUN=',F8.6,
    1  /2X,'BRUN=',F8.6,2X,'ARATE=',F8.4)
       KT=600./DT
 14      DO 15 J=1,NDT,KT
        KOUNT=KOUNT+1
       IF(RAINM(J).LE.PHIN) GO TO 12
       TEXR =TEXR+((RAINM(J)-PHIN)*(KT*DT)/3600.)
```

```
 12     IF(J.EQ.NDT) GO TO 13
 15       CONTINUE
 13     IF(ABS(EXRAIN-TEXR).LE.ERR) GO TO 16
        TEXR=0.0
        PHIN=PHIN+STEP
        J=1
        IF(KOUNT.GT.2000001) GO TO 17
        GO TO 14
 16     PHIND=PHIN
        GO TO 18
 17     WRITE(*,102)
        WRITE(2,102)
102     FORMAT(5X,'CHANGE PHIN OR STEP')
18      DO 20 J=1,NDT
        RE(J)=RAINM(J)-PHIND
        IF(RE(J).LE.0.0) RE(J)=0.0
        RE(J)=RE(J)/(3600.*1000.)
 20      CONTINUE
        WRITE(2,*)(J,RE(J),J=1,NDT)
        WRITE(*,*)(J,RE(J),J=1,NDT,KT)
        WRITE(2,112)PHIND,TEXR,TTRAIN,EXRAIN,KOUNT
        WRITE(*,112)PHIND,TEXR,TTRAIN,EXRAIN,KOUNT
112     FORMAT(5X,'PHIND=',F6.2,2X,'TEXR=',F6.3,2X,'TTRAIN=',F6.2,/2X,
     1'EXRAIN=',F6.3,2X,'KOUNT=',I5)
C        WRITE(2,*)(BORD(J),J=1,NDT,KT)
         RETURN
         END
```

c) Subroutine OBJECT

```
C ***********************************************************************
C THIS SUBROUTINE CALCULATES STATISTICAL PARAMETERS LIKE COEFFICIENT OF
C DETERMINATION, MODEL EFFICIENCY, STANDARD ERROR OF ESTIMATES ETC.
C ***********************************************************************
        SUBROUTINE OBJECT
       COMMON/AAA/QOBS(1441),QSIM(1441),RAINM(1441),RE(1441),BORD(1441)
       COMMON/BBB/NDT,NER,NAR,CAREA,PHIN,STEP,DT,SRUN,BRUN,KT,ERR
       COMMON/CCC/F,FSQ,RSQ,EFF,PHIND,TEXR,TTRAIN,EXRAIN,KOUNT,ARATE
       COMMON/DDD/FO,FC,PK,INFK,RINFM(1441),OBSQ(100),SIMQ(100),S(1441),
     1UH(1441),QDR(1441),AR(20)
       COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE
C ***********************************************************************
C  Computer program for subroutine OBJECT for all the models starts from
C  here.
C ***********************************************************************
       QSUM1 =0.0
       QSUM2 =0.0
```

```
      FSUM1 =0.0
      FSUM2 =0.0
      FSUM3 =0.0
      FSUM4 =0.0
      DIFS1 =0.0
      DIFS2 =0.0
      DIFQO =0.0
      DIFQS =0.0
      F     =0.0
      F1    =0.0
      F2    =0.0
      FSQ   =0.0
      RSQ   =0.0
      EFF   =0.0
      DIFABS=0.0
      FABS  =0.0
      SE    =0.0
      SDO   =0.0
      SDS   =0.0
      CVO   =0.0
      CVS   =0.0
      NT =NDT/KTT+1
      DO 76 J=1,NT
      DIFS1 = OBSQ(J)-SIMQ(J)
      F  = F+DIFS1
      DIFABS=ABS(OBSQ(J)-SIMQ(J))
      ABSF=ABSF+DIFABS
      DIFSQ =DIFS1*DIFS1
      FSQ   =FSQ+DIFSQ
      QSUM1 =QSUM1+OBSQ(J)
      QSUM2 =QSUM2+SIMQ(J)
76    CONTINUE
      QMEANO=QSUM1/(NT-1)
      QMEANS=QSUM2/(NT-1)
      DO 77 J=1,NT
      DIFQO =QMEANO-OBSQ(J)
      DIFQS=QMEANS-SIMQ(J)
      QMULT=DIFQO*DIFQS
      FSUM1=FSUM1+QMULT
      FQO  =DIFQO*DIFQO
      FSUM2=FSUM2+FQO
      FQS  =DIFQS*DIFQS
      FSUM3=FSUM3+FQS
      DIFS2=OBSQ(J)-SIMQ(J)
      FQSX =DIFS2*DIFS2
      FSUM4=FSUM4+FQSX
77    CONTINUE
```

```
      EFF=(FSUM2-FSUM4)/FSUM2
      RSQ=(FSUM1*FSUM1)/(FSUM2*FSUM3)
      SDO=(FSUM2/(NT-1))**.5
      SDS=(FSUM3/(NT-1))**.5
      CVO=SDO/QMEANO
      CVS=SDS/QMEANS
      SE =SDO*((1.-RSQ)**0.5)
      WRITE(2,*)F,FSQ,EFF,RSQ,SDO,SDS,CVO,CVS,SE
        RETURN
        END
```

d) Subroutine INFILT

```
C***********************************************************************
C        INFILTRATION RATE BY MODIFIED HORTON'S EQUATION
C **********************************************************************
       SUBROUTINE INFILT
      COMMON/AAA/QOBS(1441),QSIM(1441),RAINM(1441),RE(1441),BORD(1441)
      COMMON/BBB/NDT,NER,NAR,CAREA,PHIN,STEP,DT,SRUN,BRUN,KT,ERR
      COMMON/CCC/F,FSQ,RSQ,EFF,PHIND,TEXR,TTRAIN,EXRAIN,KOUNT,ARATE
      COMMON/DDD/FO,FC,PK,INFK,RINFM(1441),OBSQ(100),SIMQ(100),S(1441),
    1UH(1441),QDR(1441),AR(20)
       DIMENSION FINT(1441),RR(20),J1(20),J2(20),TP(20),TS(20)
       DIMENSION DELT(20)
C**********************************************************************
      CALL EXR
C**********************************************************************
C  Computer programme for subroutine INFILT used for all the other
C  model starts from here
C***********************************************************************
 18    SDT=0.0
       TSS=0.0
       SUMT=0.0
       SDELT=0.0
       SUMF1=0.0
       SUMF2=0.0
       NP=1
       TSS1=0.0
       DTT =DT/3600.
      DO 5 I=2,NDT
       SDT =SDT+DTT
       IF (NP.GT.1) GO TO 130
       FINT(I)=FC+(FO-FC)*EXP((-1)*PK*SDT)
130    SDT=(I-2)*DTT
       FINT(I)=FC+(FO-FC)*EXP((-1)*PK*(SDT-SDELT))
       IF(FINT(I).LT.RAINM(I).AND.FINT(I-1).GT.RAINM(I-1)) GO TO 140
       IF(FINT(I).GT.RAINM(I).AND.FINT(I-1).LT.RAINM(I-1)) GO TO 63
```

```
      IF(RAINM(I).LT.FINT(I).AND.RAINM(I-1).LT.FINT(I-1)) GO TO 110
      IF(RAINM(I).GT.FINT(I).AND.RAINM(I-1).GT.FINT(I-1)) GO TO 68
        GO TO 110
110   SUMT=SUMT+RAINM(I)*DTT
      RINFM(I)=RAINM(I)
        GO TO 175
140   RR(NP)=RAINM(I)
      J1(NP)= I-2
      IF(NP.GT.1) GO TO 65
45    DO 55 J=2,NER
      TSS=TSS+DTT
      FF1=FC+(FO-FC)*EXP((-1)*PK*TSS)
      SUMF1=SUMF1+FF1*DTT
      IF(SUMF1.LT.SK1) GO TO 55
        GO TO 60
55    CONTINUE
60    TS(NP)=TSS
      TP(NP)=(I-2)*DTT
      DELT(NP)=TP(NP)-TS(NP)
      SDELT=DELT(NP)
        GO TO 68
63    NP =NP+1
      J2(NP)=I-2
      SUMT=0.0
      SUMT=RAINM(I)*DTT
      RINFM(I)=RAINM(I)
        GO TO 175
65    DO 80 K=J2(NP),J1(NP)
      TSS1=SDT+DTT
      FF2=FC+(FO-FC)*EXP((-1)*PK*(TSS1-SDELT))
      SUMF2=SUMF2+FF2*DT
      IF(SUMF2.LT.SUMT) GO TO 80
        GO TO 66
80    CONTINUE
66    TS(NP)=TSS1
      TP(NP)=J1(NP)*DTT
      DELT(NP)=TP(NP)-TS(NP)
      SDELT=SDELT+DELT(NP)
68    FINT(I)=FC+(FO-FC)*EXP((-1)*PK*(SDT-SDELT))
      IF(FINT(I).GT.RAINM(I)) GO TO 41
      RINFM(I)=FINT(I)
       GO TO 175
41    RINFM(I)=RAINM(I)
175   SK1=SUMT
      SK1=SK1+RR(NP)*DTT
5     CONTINUE
C     WRITE(2,131)(I,RINFM(I),I=2,NER)
```

```
131     FORMAT(/,5(I3,2X,F6.2,2X))
        RETURN
        END
```

Appendix-A2- Programme for Variable source area model (Subjective method of optimization)

a) Main programme

```
C ******************  VARIABLE SOURCE AREA BASED MODEL *****************
C PROGRAMME FOR PREDICTING EVENT RUNOFF FROM SMALL WATERSHEDS
C WITH SUBJECTIVE OPTIMIZATION
C THIS MODEL SIMULATES SURFACE & SUBSURFACE STORMFLOW ON STEEPLY
C SLOPING WATERSHEDS
C      ******************************************************************
C      THIS PROGRAMME IS PART OF THE "HYDROLOGICAL STUDIES OF DISTURBED
C      MOUNTAINOUS WATERSHEDS" DEVELOPED BY VIDYA SAGAR KATIYAR RESEARCH
C      SCHOLAR,GUIDED BY DR.B.S.MATHUR,PROFESSOR,DEPARTMENT OF HYDROLOGY
C      UNIVERSITY OF ROORKEE,ROORKEE (INDIA) & DR.M.S.RAMA MOHAN RAO,EX-
C      DIRECTOR, CENTRAL SOIL & WATER CONSERVATION RESEARCH & TRAINING
C      INSTITUTE, DEHRADUN (INDIA).
C ************************************************************************
C CSMAX   = PARAMETER FOR ESTIMATION OF SATURATED AREA
C PCAR    = PARTIAL CONTRIBUTING AREA (FRACTION OF TOTAL AREA ALWAYS
C           CONTRIBUTING TO DIRECT RUNOFF OR STREAM AREA)
C SC      = SOURCE AREA COEFFICIENT
C SAC     = SOURCE AREA EXPONENT
C USZT    = UPPER SOIL ZONE THICKNESS (MM)
C USIN    = ACTUAL SOIL WATER VOLUME (MM)
C SSIN    = ACTUAL GROUND WATER VOLUME (MM)
C PB      = FRACTION OF WATERSHED CONTRIBUTING TO DIRECT RUNOFF
C PA      = PB - PCAR
C KU      = SOIL WATER CONDUCTIVITY EXPONENT
C FU      = SOIL WATER CONDUCTIVITY COEFFICIENT
C K1      = FRACTION OF SOIL ZONE DRAINAGE BECOMING INTERFLOW
C USWP    = WILTING POINT WATER CONTENT(MM)
C USFC    = FIELD CAPACITY WATER CONTENT(MM)
C KS      = GROUND WATER EXPONENT
C FS      = GROUND WATER COEFFICIENT
C K2      = FRACTION OF GW DRAINAGE BECOMING BASEFLOW
C DT      = TIME STEP (SECONDS)
C RAINF   = RAINFALL INTENSITY FOR THE DURATION (MM/HR)
C OBSQ    = OBSERVED DISCHARGE RATE (CUMEC OR LPS)
C QOBS    = OBSERVED DISCHARGE RATE (MM/TIME STEP)
```

```
C SIMQ    = COMPUTED DISCHARGE RATE (,,  ,,  ,,  )
C QSIM    = OBSERVED DISCHARGE RATE (MM/TIME STEP)
C TRUN    = COMPUTED TOTAL DISCHARGE RATE (MM/TIME STEP)
C RUNO1   = SATURATED FLOW OR CHANNEL PRECIPITATION (MM/TIME STEP)
C RUNO2   = OVER LAND FLOW CONTRIBUTION (MM/TIME STEP)
C RUNO3   = INTERFLOW CONTRIBUTION (MM/TIME STEP)
C RUNO4   = BASEFLOW OR GROUNDWATER CONTRIBUTION (MM/TIME STEP)
C QSOIL   = INTERFLOW+BASEFLOW CONTRI. THROUGH SOIL MATRIX (MM/DT)
C CAREA   = CATCHMENT AREA (SQM)
C K3 & K4 = CONSTANTS FOR CALCULATION OF PCAR
C TTRAIN  = TOTAL RAINFALL DURING STORM THE (MM)
C TORUNO  = TOTAL OBSERVED RUNOFF DURING THE STORM (MM)
C TCRUNO  = TOTAL COMPUTED RUNOFF DURING THE STORM (MM)
C RUNPO   = OBSERVED RUNOFF PER CENT OF RAINFALL DURING THE STORM (%)
C RUNPC   = COMPUTED RUNOFF PER CENT OF RAINFALL DURING THE STORM (%)
C FVOL    = FLOOD VOLUME OR EXCESS RAIN VOLUME (CUM)
C ABSF    = SUM OF ABSOLUTE DIFF.BETWEEN OBSERVED & COMPUTED DISCHARGE
C SDO     = STANDARD DEVIATION IN OBSERVED RUNOFF
C SDS     = STANDARD DEVIATION IN SIMULATED RUNOFF
C CVO     = COEFFICIENT OF VARIATION IN OBSERVED RUNOFF
C CVS     = COEFFICIENT OF VARIATION IN COMPUTED RUNOFF
C SE      = STANDARD ERROR OF ESTIMATE
C TDRUN   = TOTAL DIRECT RUNOFF DURING THE STORM (MM)
C TSAT    = TOTAL SATURATED RUNOFF DURING THE STORM (MM)
C TINTER  = TOTAL INTER FLOW DURING THE STORM (MM)
C TGFLOW  = TOTAL GROUNDWATER FLOW DURING THE STORM (MM)
C FACT    = CONVERSION FACTOR FOR RUNOFF IN LPS FROM CUMEC
C DT      = TIME STEP (SECONDS)
C RADUR   = RAINFALL DURATION (HR)
C SIMT    = SIMULATION DURATION (HR)
C METHOD  = CODE FOR CHOOSING METHOD FOR CALCULATING PA
C METHOD  = 1, SLOAN'S METHOD
C METHOD  = 2, PUTTY'S METHOD
C METHOD  = 3, PROPOSED METHOD
C *******************************************************************
        REAL KU,KS,K1,K2,K3,K4
      COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,PA,METHOD
      COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4
      COMMON/PARAM3/RFALL,RUNF,RUNO3,RUNO4,QSL,DRUN,GW,TRUN,CSMAX
      COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
      COMMON/BBB/F,FSQ,RSQ,EFF,NDT,KT,FACT,ABSF,SDO,SDS,CVO,CVS,SE
C *******************************************************************
       OPEN(UNIT=1,FILE='DM3.DAT',STATUS='OLD')
       OPEN(UNIT=2,FILE='DM3.OUT',STATUS='NEW')
       OPEN(UNIT=3,FILE='MSH.DAT',STATUS='OLD')
       OPEN(UNIT=4,FILE='DM3.RES',STATUS='NEW')
C *******************************************************************
```

```
      READ(1,*)CAREA,CSMAX,API,DT,METHOD
      READ(1,*)PCAR,SAC,SC,FACT
      READ(1,*)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
      READ(3,*)IDATE,MONTH,IYEAR
      READ(3,*)RADUR,SIMT
      NDT = ((SIMT*3600.)/DT)+1
      NER = ((RADUR*3600.)/DT)+1
      WRITE(4,*)IDATE,MONTH,IYEAR
      READ(3,*)(OBSQ(I),I=1,NDT)
      READ(3,*)(RAINF(I),I=1,NER)
      KT=600./DT
      DO 9 J=1,NDT
      OBSQ(J)=OBSQ(J)*FACT
9     CONTINUE
      WRITE(4,102)
      WRITE(4,103)(OBSQ(J),J=1,NDT,KT)
      BFLOW=OBSQ(1)
      WRITE(2,111)IYEAR
      WRITE(2,112)IDATE,MONTH,IYEAR
      WRITE(2,113)PCAR,SAC,SC,DT,RADUR,SIMT,CAREA,CSMAX,API,
     1METHOD
      WRITE(*,113)PCAR,SAC,SC,DT,RADUR,SIMT,CAREA,CSMAX,API,
     1METHOD
      WRITE(2,114)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
      WRITE(*,114)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
C ****************** OBSERVED DISCHARGE IN MM *******************
      SIMQ(1)=(BFLOW*DT)/CAREA
      OBSQ(1)=SIMQ(1)
      QOBS(1)=BFLOW
      QCOMP(1)=QOBS(1)
      TTRAIN=0.0
      TORUNO=0.0
      TCRUNO=0.0
      FVOL  =0.0
      WRITE(2,110)
      WRITE(*,110)
      TDRUN =0.0
      TSAT  =0.0
      TINTER=0.0
      TGFLOW=0.0
      DO 70 J=2,NDT
      OBSQ(J)=(OBSQ(J)*DT)/CAREA
      PRAIN=RAINF(J)
      CALL WATER(PRAIN)
      SIMQ(J)=TRUN
      QCOMP(J)=(SIMQ(J)*CAREA)/(DT)
      QOBS(J) =(OBSQ(J)*CAREA)/(DT)
```

```
      FRAIN=PRAIN*DT/3600.
      WRITE(2,117)J,FRAIN,DRUN,RUNF,QSL,PA,RUNO3,RUNO4
      WRITE(*,117)J,FRAIN,DRUN,RUNF,QSL,PA,RUNO3,RUNO4
      TDRUN=TDRUN+DRUN
      TSAT =TSAT+RUNF
      TINTER=TINTER+RUNO3
      TGFLOW=TGFLOW+RUNO4
      TTRAIN=TTRAIN+FRAIN
      TORUNO=TORUNO+OBSQ(J)
      TCRUNO=TCRUNO+SIMQ(J)
      FVOL=FVOL+((QCOMP(J)-QCOMP(1))/1000.)*DT
70    CONTINUE
      WRITE(4,104)
      WRITE(4,103)(OBSQ(J),J=1,NDT,KT)
      WRITE(2,115)
      WRITE(2,116)(J,RAINF(J),OBSQ(J),SIMQ(J),QOBS(J),QCOMP(J),
     1J=1,NDT,KT)
      WRITE(*,116)(J,RAINF(J),OBSQ(J),SIMQ(J),QOBS(J),QCOMP(J),
     1J=1,NDT,KT)
      RUNPC=(TCRUNO*100.)/TTRAIN
      RUNPO=(TORUNO*100.)/TTRAIN
      WRITE(2,118)TTRAIN,TORUNO,TCRUNO,RUNPO,RUNPC,FVOL
      WRITE(*,118)TTRAIN,TORUNO,TCRUNO,RUNPO,RUNPC,FVOL
      WRITE(2,121)TDRUN,TSAT,TINTER,TGFLOW
      WRITE(*,121)TDRUN,TSAT,TINTER,TGFLOW
      CALL OBJECT
      WRITE(2,119)F,FSQ,RSQ,EFF
      WRITE(*,119)F,FSQ,RSQ,EFF
      WRITE(2,120)ABSF,SDO,SDS,CVO,CVS,SE
      WRITE(*,120)ABSF,SDO,SDS,CVO,CVS,SE
102   FORMAT(5X,'OBSERVED RUN OFF IN LPS ')
103   FORMAT(2X,6(F10.4))
104   FORMAT(5X,'OBSERVED RUN OFF IN MM ')
110    FORMAT(3X,'J',4X,'FRAIN',4X,'DRUN1',5X,'RUNF1',5X,'QSL0',6X,
     1 ' PA ',6X,'INTER',6X,'GFLOW')
111    FORMAT(5X,'SIMULATION OF EVENT RUNOFF FOR =',I5)
112    FORMAT(5X,'SIMULATION RUN FOR =',I3,I3,I5)
113    FORMAT(2X,'PCAR=',F6.4,2X,'SAC=',F5.2,2X,'SC=',
     1F6.4,/2X,'DT=',F5.1,2X,'RADUR=',F5.1,2X,'SIMT=',F6.2,2X,
     2'CAREA=',F8.0,/2X,'CSMAX=',F5.0,2X,'API=',F5.0,2X,'METHOD=',I2)
114   FORMAT(2X,'USZT=',F6.1,2X,'USFC=',F6.2,2X,
     1'USWP=',F6.2,/2X,'USIN=',F6.2,2X,'SSIN=',F6.2,2X,'FU=',E15.1,2X,
     2'KU=',F6.2,/2X,'FS=',F6.4,2X,'KS=',F6.3,2X,'K1=',F5.4,2X,'K2=',
     3 F6.4,2X,'K3=',F6.4,2X,'K4=',F6.4)
115   FORMAT(7X,'J',5X,'RAIN(MM)',3X,'OBSQ(MM)',5X,'SIMQ(MM)',5X,
     1'QOBS(LPS)',2X,'QCOMP(LPS)')
116   FORMAT(5X,I4,3X,F6.2,3X,F10.4,3X,F10.4,3X,F10.4,3X,F10.4)
```

```
117     FORMAT(2X,I3,2X,F5.2,6(2X,F8.4))
118     FORMAT(5X,'TTRAIN=',F8.2,5X,'TORUNO=',F8.4,5X,'TCRUNO=',F8.4,
     1/5X,'RUNPO=',F6.2,5X,'RUNPC=',F6.2,5X,'FVOLUME =',F10.2)
119     FORMAT(2X,'F =',F12.6,2X,'FSQ=',F12.6,2X,'RSQ=',F8.6,2X,'EFF=',
     1F8.6)
120     FORMAT(5X,'ABS DIFF.=',F10.4,5X,'SDO=',F10.4,5X,'SDS=',
     1F10.4,/5X,'CVO=',F10.6,5X,'CVS=',F10.6,5X,'SE=',F10.6)
121     FORMAT(5X,'TDRUN=',F8.4,2X,'TSAT=',F8.4,2X,'TINTER=',F8.4,2X,
     1'TGFLOW=',F8.4)
        STOP
        END
```

b) Subroutine WATER

```
C ***************************************************************************
C THIS SUBROUTINE COMPUTES DIFFERENT COMPONENTS OF RUNOFF RATES
C ***************************************************************************
      SUBROUTINE WATER(RAINP)
      COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,PA,METHOD
      COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4
      COMMON/PARAM3/RFALL,RUNF,RUNO3,RUNO4,QSL,DRUN,GW,TRUN,CSMAX
      COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
      REAL KU,KS,K1,K2,K3,K4
      TRUN=0.0
      DRUN=0.0
      RUNO1=0.0
      RUNO2=0.0
      QSL=0.0
      RUNO3=0.0
      RUNO4=0.0
      GW=0.0
      PPT=0.0
      RUNF=0.0
      PPT=RAINP
      PPT=(PPT*DT)/3600.
C******* WETTING CYCLE INTERCEPTION ***************************************
      AINC=0.2
      PPT=PPT*AINC
      DO 50 I=1,5
      IF(PPT.LE.0.0) GO TO 40
C ********** PARTIAL AREA RUNOFF ******************************************
      IF(METHOD.GT.1) GO TO 45
      PA=SC*EXP(SAC*USIN/USZT)
      GO TO 47
45    IF(METHOD.GT.2) GO TO 46
      PA=SC*EXP(SAC*(K3*USIN+K4*SSIN)/CSMAX)
      GO TO 47
```

```
46      PA=SC*EXP(SAC*(K3*USIN+K4*SSIN)/USZT)
47       PB=PA+PCAR
        PB=AMIN1(PB,1.0)
        PA=PB-PCAR
        RUNO1=RUNO1+PA*PPT
        RUNO2=RUNO2+PCAR*PPT
C ********* WETTING CYCLE UPPER SOIL ZONE ****************************
        USIN = USIN+PPT*(1.0-PB)
C ********* DRAINAGE CYCLE *******************************************
C        GO TO 41
40      FFU = 0.0
        IF(METHOD.GE.1) GO TO 48
        IF(USIN.LE.USWP) GO TO 42
        FFU=FU*((USIN/USZT)**KU)*AINC
         GO TO 42
        IF(USIN.LE.USFC) GO TO 42
48      FFU =FU*(((USIN-USFC)/USZT)**KU)*AINC
42      IF(USIN.LE.FFU) FFU=USIN
        RUNO3 = RUNO3+FFU*K1
        RFALL = FFU*(1.0-K1)
        USIN = USIN-FFU
        IF(K1.EQ.1.0) GO TO 50
        SSIN = SSIN+RFALL
        FFS = 0.0
        IF(METHOD.GE.1) GO TO 49
        IF(SSIN.LE.USWP) GO TO 43
        FFS=FS*(SSIN**KS)*AINC
         GO TO 43
        IF(SSIN.LE.USFC) GO TO 43
49      FFS = FS*((SSIN-USFC)**KS)*AINC
43      IF(SSIN.LE.FFS) FFS=SSIN
        RUNO4 = RUNO4+FFS*K2
        GW=GW+FFS*(1.-K2)
        SSIN = SSIN-FFS
50      CONTINUE
C *********** SUMMARY AND ACCOUNTING ********************************
        DRUN = RUNO2
        RUNF = RUNO1
        QSL = RUNO3+RUNO4
        TRUN =RUNF+QSL+DRUN
C       WRITE(2,*)PPT,USIN,SSIN,PA
        RETURN
        END
```

c) **Subroutine OBJECT**

```
C ************************************************************************
C THIS SUBROUTINE CALCULATES STATISTICAL PARAMETERS FOR DETERMINING
C GOODNESS OF FIT CRITERIA
C ************************************************************************
      SUBROUTINE OBJECT
     COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
     COMMON/BBB/F,FSQ,RSQ,EFF,NDT,KT,FACT,ABSF,SDO,SDS,CVO,CVS,SE
C ************************************************************************
  Computer programme of this subroutine is given in Appendix-A1(c)
C ************************************************************************
```

Appendix-A3- Programme for Variable source area event based model (Objective method of optimization)

a) **Main programme**

```
C ************************************************************************
C PROGRAMME FOR VARIABLE SOURCE AREA EVENT BASED MODEL USING
C ROSENBROCK'S OPTIMIZATION TECHNIQUE
C ***********************************
C       THIS PROGRAMME IS PART OF THE "HYDROLOGICAL STUDIES OF DISTURBED
C       MOUNTAINOUS WATERSHEDS" DEVELOPED BY VIDYA SAGAR KATIYAR RESEARCH
C       SCHOLAR,GUIDED BY DR.B.S.MATHUR,PROFESSOR,DEPARTMENT OF HYDROLOGY
C       UNIVERSITY OF ROORKEE,ROORKEE (INDIA) & DR.M.S.RAMA MOHAN RAO,EX-
C       DIRECTOR, CENTRAL SOIL & WATER CONSERVATION RESEARCH & TRAINING
C       INSTITUTE, DEHRADUN (INDIA).
C ************************************************************************
C  THE PARAMETERS HAVE BEEN DEFINED IN APPENDIX-A2(a)
C ************************************************************************
C       DIMENSION X(12),E(12)
        REAL KU,KS,K1,K2,K3,K4,LC
        INTEGER R,C
      COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,GRUT,IRUN,CSMAX,TTRAIN
      COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4,KOUN
      COMMON/PARAM3/FINTER(721),GFLOW(721),RFALL(721),BFLOW,METHOD
      COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
      COMMON/CCC/RUNF(721),DRUN(721),QSL(721),TRUN(721),GW(721),TORUNO
      COMMON/BBB/F,FSQ,RSQ,EFF,NDT,CAREA,FACT1,FACT2,X(12),E(12),TCRUNO
      COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE,KT,PA(721)
C ************************************************************************
       OPEN(UNIT=1,FILE='DM4.DAT',STATUS='OLD')
       OPEN(UNIT=2,FILE='DM4.OUT',STATUS='NEW')
```

```
      OPEN(UNIT=3,FILE='MSH.DAT',STATUS='OLD')
C *****************************************************************
      READ(1,*)CAREA,CSMAX,API,DT,PCAR,SAC,SC,METHOD
      READ(1,*)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
      READ(3,*)IDATE,MONTH,IYEAR
      READ(3,*)RADUR,SIMT
      NDT = ((SIMT*3600.)/DT)+1
      NER = ((RADUR*3600.)/DT)+1
      READ(3,*)(OBSQ(I),I=1,NDT)
      READ(3,*)(RAINF(I),I=1,NER)
      KT=600./DT
      WRITE(2,111)IYEAR
      WRITE(*,111)IYEAR
      WRITE(2,112)IDATE,MONTH,IYEAR
      WRITE(*,112)IDATE,MONTH,IYEAR
      WRITE(2,113)PCAR,SAC,SC,DT,RADUR,SIMT,CAREA,CSMAX,API,
     1METHOD
      WRITE(*,113)PCAR,SAC,SC,DT,RADUR,SIMT,CAREA,CSMAX,API,
     1METHOD
      WRITE(2,114)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
      WRITE(*,114)USZT,USFC,USWP,USIN,SSIN,FU,KU,FS,KS,K1,K2,K3,K4
C ....ENTRY VARIABLES TO ROSEN ..........................................
      M=-1
      READ(1,*)IRUN,NP,NC,NPR,NSTEP,LOOPY,FACT1,FACT2
      WRITE(2,105)IRUN,NP,NC,NPR,NSTEP,LOOPY,FACT1,FACT2
      WRITE(*,105)IRUN,NP,NC,NPR,NSTEP,LOOPY,FACT1,FACT2
C ***************** OBSERVED DISCHARGE IN MM/TIME STEP ******************
      BFLOW=OBSQ(1)*1000
      SIMQ(1)=(BFLOW*DT)/CAREA
      OBSQ(1)=SIMQ(1)
      QOBS(1)=BFLOW
      QCOMP(1)=BFLOW
      KOUN=0
C ...........................................................................
      READ(1,*)(X(J),J=1,NP)
      WRITE(2,106)
      WRITE(2,*)(X(J),J=1,NP)
      IF(IRUN.GT.0) GO TO 11
      READ(1,*)(E(J),J=1,NP)
      WRITE(2,107)
C ...........................................................................
   11 DO 70 J=2,NDT
      OBSQ(J)=(OBSQ(J)*DT*1000)/CAREA
      OBSQ(J)=(OBSQ(J-1)+OBSQ(J))*.5
      QOBS(J) =(OBSQ(J)*CAREA)/(DT)
   70 CONTINUE
      WRITE(2,104)
```

```
      WRITE(4,103)(OBSQ(J),J=1,NDT,KT)
      WRITE(2,*)(E(J),J=1,NP)
      READ(1,108)ERROF
      IF(IRUN.GT.0) GO TO 12
      CALL ROSEN (M,NP,NC,LOOPY,NPR,NSTEP,ERROF)
      WRITE(*,109)
      WRITE(2,109)
   12 CALL WATBA (OF)
      WRITE(2,*)(X(J),J=1,NP)
      WRITE(*,*)(X(J),J=1,NP)
      TTRAIN=0.0
      TORUNO=0.0
      TCRUNO=0.0
      SRATE =0.0
      TDRUN =0.0
      TSAT  =0.0
      TINTER=0.0
      TGFLOW=0.0
      DO 80 K=1,NDT
      FRAIN=RAINF(K)*DT/3600.
C     WRITE(2,117)K,FRAIN,DRUN,RUNF,QSL,PA,RUNO3,RUNO4
C     WRITE(*,117)K,FRAIN,DRUN,RUNF,QSL,PA,RUNO3,RUNO4
      TTRAIN=TTRAIN+FRAIN
      SRATE =SRATE +RAINF(K)
      TORUNO=TORUNO+OBSQ(K)
      TCRUNO=TCRUNO+SIMQ(K)
      TDRUN=TDRUN+DRUN(K)
      TSAT =TSAT+RUNF(K)
      TINTER=TINTER+FINTER(K)
      TGFLOW=TGFLOW+GFLOW(K)
      FVOL=FVOL+((QCOMP(K)-QCOMP(1))/1000.)*DT
   80 CONTINUE
      ARATE=SRATE/(NDT-1)
      WRITE(2,110)
      WRITE(*,110)
      WRITE(2,116)(J,RUNF(J),DRUN(J),PA(J),FINTER(J),GFLOW(J),
     1J=1,NDT,KT)
      WRITE(*,116)(J,RUNF(J),DRUN(J),PA(J),FINTER(J),GFLOW(J),
     1J=1,NDT,KT)
      WRITE(2,115)
      WRITE(2,116)(J,RAINF(J),OBSQ(J),SIMQ(J),QOBS(J),QCOMP(J),
     1J=1,NDT,KT)
      WRITE(*,116)(J,RAINF(J),OBSQ(J),SIMQ(J),QOBS(J),QCOMP(J),
     1J=1,NDT,KT)
      RUNPC=(TCRUNO*100.)/TTRAIN
      RUNPO=(TORUNO*100.)/TTRAIN
      WRITE(2,118)TTRAIN,TORUNO,TCRUNO,RUNPO,RUNPC,ARATE
```

```
      WRITE(*,118)TTRAIN,TORUNO,TCRUNO,RUNPO,RUNPC,ARATE
      CALL OBJECT
      WRITE(2,119)F,FSQ,RSQ,EFF
      WRITE(*,119)F,FSQ,RSQ,EFF
      WRITE(2,120)ABSF,SDO,SDS,CVO,CVS,SE
      WRITE(*,120)ABSF,SDO,SDS,CVO,CVS,SE
      WRITE(2,121)TDRUN,TSAT,TINTER,TGFLOW,FVOL
      WRITE(*,121)TDRUN,TSAT,TINTER,TGFLOW,FVOL
C ************************** FORMAT STATEMENTS *************************
 103  FORMAT(2X,6(F10.4))
 104  FORMAT(5X,'OBSERVED RUN OFF IN MM')
 105  FORMAT(2X,'IRUN=',I2,5X,'NP=',I2,5X,'NC=',I2,5X,'NPR=',I2,5X,/,
     12X,'NSTEP=',I2,5X,'LOOPY=',I3,5X,'FACT1=',F7.4,5X,'FACT2=',F7.4)
 106  FORMAT(5X,' VECTOR OF PARAMETERS TO BE OPTIMISED ')
 107  FORMAT(5X,' INITIAL STEP SIZE IN RELATION TO X ')
 108  FORMAT(F10.8)
 109  FORMAT(2X,'ROSEN COMPLETE ')
 110  FORMAT(7X,'J',8X,'RUNF',9X,'DRUN',9X,'PA',9X,'FINTER',7X,
     1 'GFLOW')
 111  FORMAT(5X,'SIMULATION OF DAILY RUNOFF FOR =',I5)
 112  FORMAT(5X,'SIMULATION RUN FOR =',I3,I3,I5)
 113  FORMAT(2X,'PCAR=',F6.4,2X,'SAC=',F5.2,2X,'SC=',
     1F6.4,2X,'DT=',F5.1,2X,'RADUR=',F5.1,/2X,'SIMT=',F6.2,2X,
     2'CAREA=',F8.0,2X,'CSMAX=',F5.0,2X,'API=',F5.0,2X,'METHOD=',I2)
 114  FORMAT(2X,'USZT=',F6.1,2X,'USFC=',F6.2,2X,
     1'USWP=',F6.2,/2X,'USIN=',F6.2,2X,'SSIN=',F6.2,2X,'FU=',E15.1,2X,
     2'KU=',F6.2,/2X,'FS=',F6.4,2X,'KS=',F6.3,2X,'K1=',F5.4,2X,'K2=',
     3 F6.4,2X,'K3=',F6.4,2X,'K4=',F6.4)
 115  FORMAT(7X,'J',8X,'RAIN(MM)',4X,'OBSQ(MM)',5X,'SIMQ(MM)',5X,
     1'QOBS(LPS)',2X,'QCOMP(LPS)')
 116  FORMAT(4X,I4,3X,F10.6,3X,F9.6,3X,F9.8,3X,F10.4,3X,F10.4)
C117  FORMAT(2X,I3,2X,F5.2,6(2X,F8.4))
 118  FORMAT(5X,'TTRAIN=',F8.2,5X,'TORUNO=',F8.2,5X,'TCRUNO=',F8.2,
     1/,5X,'RUNPO=',F8.2,5X,'RUNPC=',F8.2,5X,'ARATE=',F8.2)
 119  FORMAT(5X,'F =',F10.4,5X,'FSQ=',F12.4,5X,'RSQ=',F8.6,5X,'EFF=',
     1F8.6)
 120  FORMAT(5X,'ABS DIFF.=',F10.4,5X,'SDO=',F10.4,5X,'SDS=',
     1F10.4,/5X,'CVO=',F10.6,5X,'CVS=',F10.6,5X,'SE=',F10.6)
 121  FORMAT(5X,'TDRUN=',F8.4,2X,'TSAT=',F8.4,2X,'TINTER=',F8.4,/2X,
     1'TGFLOW=',F8.4,5X,'FVOLUME=',F12.4)
      STOP
      END
```

b) Subroutine OBJECT

```
C ***********************************************************************
C THIS SUBROUTINE COMPUTES STATISTICAL PARAMETERS FOR DETERMINING
C GOODNESS OF FIT BETWEEN OBSERVED AND COMPUTED HYDROGRAPHS
C ***********************************************************************
        SUBROUTINE OBJECT
       COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
       COMMON/CCC/RUNF(721),DRUN(721),QSL(721),TRUN(721),GW(721),TORUNO
       COMMON/BBB/F,FSQ,RSQ,EFF,NDT,CAREA,FACT1,FACT2,X(12),E(12),TCRUNO
       COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE,KT,PA(721)
C ***********************************************************************
C  Computer programme for this subroutine is given in Appendix-A1(c)
C ***********************************************************************
```

c) Subroutine ROSEN

```
       SUBROUTINE ROSEN (M,NP,NC,LOOPY,NPR,NSTEP,DELY)
C .......................................................................
C  SUBROUTINE FOR NONLINEAR OPTIMIZATION (ROSENBROCK TECHNIQUE)
C  M=1 (MAXIMIZATION)                    M=-1 (MINIMIZATION)
C  NP   =NO. OF VARIABLES TO BE OPTIMIZED NC=NO. OF CONSTRAINTS
C  LOOPY=MAXIMUM NO. OF STEPS IN THE OPTIMIZATION
C  NPR  =PROGRAM PRINTS THE RESULTS EVERY NPR STEPS IN THE OPTIMIZATION
C  DELY =ACCEPTABLE RELATIVE ERROR IN THE MINIMIZATION OF THE OBJ. FUN.
C  X(.) =VECTOR OF PARAMETERS TO BE OPTIMIZED
C  FR   =VALUE OF THE OBJECTIVE FUNCTION
C  NEEDED SUBROUTINES ......... RESTR AND WATER
C .......................................................................
      COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,GRUT,IRUN,CSMAX,TTRAIN
      COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4,KOUN
      COMMON/PARAM3/FINTER(721),GFLOW(721),RFALL(721),BFLOW,METHOD
      COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
      COMMON/CCC/RUNF(721),DRUN(721),QSL(721),TRUN(721),GW(721),TORUNO
      COMMON/BBB/F,FSQ,RSQ,EFF,NDT,CAREA,FACT1,FACT2,X(12),E(12),TCRUNO
      COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE,KT,PA(721)
      DIMENSION AL(12),B(12,12),D(12),EINT(12),H(12),PH(12),SA(12),
     1V(12,12),VV(12,12)
       INTEGER R,C
       REAL LC
       WRITE(2,111)
111    FORMAT(1H1,10X,41H   PROCEDURE      -HILLCLIMB OF ROSENBROCK)
       LAP=NPR-1
       LOOP=0
       ISW =0
       INIT=0
       KOUNT=0
```

```
      TERM=0.0
      FR  =0.0
C1.....IT CALLS SUBROUTINE OF CONSTRAINTS
      DO 40 K=1,NC
      CALL RESTR(K,LC,UC,XC)
      IF(K.GT.5) GO TO 39
      AL(K)=(UC-LC)*FACT1
      GO TO 40
   39 AL(K)=(UC-LC)*FACT2
   40 CONTINUE
C1 ..............................................................
      DO 60 I=1,NP
      DO 60 J=1,NP
      V(I,J)=0.0
      IF(I-J) 60,61,60
   61 V(I,J)=1.0
   60 CONTINUE
      DO 65 KK=1,NP
      EINT(KK)=E(KK)
   65 CONTINUE
 1000 DO 70 J=1,NP
      IF(NSTEP.EQ.0) E(J)=EINT(J)
      SA(J)=2.0
      D(J) =0.0
   70 CONTINUE
      FBEST=FR
   80 I=1
      IF(INIT.EQ.0) GO TO 120
   90 DO 110 K=1,NP
      X(K)=X(K)+E(I)*V(I,K)
  110 CONTINUE
      DO 50 K=1,NC
      H(K)=F0
   50 CONTINUE
  120 KOUNT=KOUNT+1
C2..IT CALLS SUBROUTINE OF WATER BALANCE..........................
      CALL WATBA(FR)
C2 ..............................................................
      IF(KOUNT.GT.1501) GO TO 122
      FR=M*FR
      IF(ISW.EQ.0) F0=FR
      ISW=1
C     IF(FR.EQ.0) GO TO 119
      ERROR=ABS((FBEST-FR)/FR)-DELY
      IF(ERROR) 122,122,125
  122 TERM=1.0
      GO TO 450
```

```
 125   J=1
C3 ....IT CALLS SUBROUTINE OF CONSTRAINTS ...............
 130   CALL RESTR (J,LC,UC,XC)
C3 ..................................................................
       IF(XC.LE.LC) GO TO 420
       IF(XC.GE.UC) GO TO 420
       IF(FR.LT.F0) GO TO 420
       IF(XC.LT.LC+AL(J)) GO TO 140
       IF(XC.GT.UC-AL(J)) GO TO 140
       H(J)=F0
       GO TO 210
 140   BW=AL(J)
       IF(XC.LE.LC.OR.UC.LE.XC) GO TO 150
       IF(LC.LT.XC.AND.XC.LT.LC+BW) GO TO 160
       IF(UC-BW.LT.XC.AND.XC.LT.UC) GO TO 170
       PH(J)=1.0
       GO TO 210
 150   PH(J)=0.0
       GO TO 190
 160   PW=(LC+BW-XC)/BW
       GO TO 180
 170   PW=(XC-UC+BW)/BW
 180   PH(J)=1.0-3.0*PW+4.0*PW*PW-2.0*PW*PW*PW
 190   FR=H(J)+(FR-H(J))*PH(J)
 210   IF(J.EQ.NC) GO TO 220
       J=J+1
       GO TO 130
 220   INIT=1
       IF(FR.LT.F0) GO TO 420
       D(I)=D(I)+E(I)
       E(I)=3.0*E(I)
       F0=FR
       IF(SA(I).GE.1.5) SA(I)=1.0
 230  DO 240 JJ=1,NP
       IF(SA(JJ).GE.0.5) GO TO 440
 240  CONTINUE
      DO 250 R=1,NP
       DO 250 C=1,NP
       VV(C,R) = 0.0
 250  CONTINUE
      DO 260 R=1,NP
       KR = R
        DO 260 C=1,NP
         DO 265 K=KR,NP
          VV(R,C)=D(K)*V(K,C)+VV(R,C)
 265   CONTINUE
       B(R,C)=VV(R,C)
```

```
 260   CONTINUE
        BMAG = 0.0
       DO 280 C=1,NP
        BMAG = BMAG+B(1,C)*B(1,C)
 280   CONTINUE
        BMAG = SQRT(BMAG)
       DO 310 C=1,NP
       V(1,C)=B(1,C)/BMAG
 310   CONTINUE
       DO 390 R=2,NP
        IR = R-1
        DO 390 C=1,NP
         SUMVM = 0.0
         DO 320 KK=1,IR
          SUMAV = 0.0
          DO 330 KJ=1,NP
           SUMAV=SUMAV+VV(R,KJ)*V(KK,KJ)
 330     CONTINUE
         SUMVM=SUMVM+SUMAV*V(KK,C)
 320     CONTINUE
        B(NP,C)= VV(R,C)-SUMVM
 390   CONTINUE
      DO 340 R=2,NP
       BBMAG = 0.0
        DO 350 K=1,NP
         BBMAG = BBMAG+B(R,K)*B(R,K)
 350   CONTINUE
        BBMAG = SQRT(BBMAG)
       DO 340 C=1,NP
        V(R,C)= B(R,C)/BBMAG
 340   CONTINUE
       LOOP= LOOP+1
       LAP= LAP +1
       IF(LAP.EQ.NPR) GO TO 450
        GO TO 1000
 420   IF(INIT.EQ.0) GO TO 450
      DO 430 IX=1,NP
       X(IX) = X(IX)-E(I)*V(I,IX)
C      WRITE(2,421)INIT
C      WRITE(*,421)INIT
 421   FORMAT(5X,'INIT=',I2)
 430  CONTINUE
       E(I) = -0.5*E(I)
       IF(SA(I).LT.1.5) SA(I)=0.0
        GO TO 230
 440   IF(I.EQ.NP) GO TO 80
       I = I+1
```

```
          GO TO 90
 450     WRITE(2,003)
 003     FORMAT(/,2X,4HLOOP,5X,5HSTAGE,8X,8HFUNCTION,9X,8HPROGRESS,6X,
    1    16HLATERAL PROGRESS,8X,5HFBEST,12X,5HERROR)
         WRITE(2,004)LOOP,LAP,F0,BMAG,BBMAG,FBEST,ERROR
 004     FORMAT(1H0,I5,5X,I5,5E18.8)
         WRITE(2,014)KOUNT
 014     FORMAT(/,2X,33HNUMBER OF FUNCTION EVALUATIONS=   ,I8)
         WRITE(2,005)
 005     FORMAT(/,2X,'VALUES OF FUNCTION AT THIS STAGE',2X'(MODEL
    1    PARAMETERS)')
        DO 501 JM=1,NP
         WRITE(2,006)JM,X(JM)
 501    CONTINUE
 006     FORMAT(/2X,2HX(,I2,4H) =,E14.6)
         LAP = 0
         IF(INIT.EQ.0) GO TO 470
         IF(TERM.EQ.1.0) GO TO 480
         IF(LOOP.GE.LOOPY) GO TO 480
           GO TO 1000
 470     WRITE(2,007)
 007     FORMAT(///,2X,' THE STARTING POINT APPEARS TO BE VIOLATING
    1THE CONSTRAINTS')
 480      RETURN
          END
```

d) Subroutine RESTR

```
C ***************************************************************************
C ......THIS SUBROUTINE DEFINES THE CONSTRAINTS OF THE PARAMETERS ....
       SUBROUTINE RESTR (J,LC,UC,XC)
       COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,GRUT,IRUN,CSMAX,TTRAIN
       COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4,KOUN
       COMMON/PARAM3/FINTER(721),GFLOW(721),RFALL(721),BFLOW,METHOD
       COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
       COMMON/CCC/RUNF(721),DRUN(721),QSL(721),TRUN(721),GW(721),TORUNO
       COMMON/BBB/F,FSQ,RSQ,EFF,NDT,CAREA,FACT1,FACT2,X(12),E(12),TCRUNO
       COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE,KT,PA(721)
       REAL LC
       LC=0.0
       UC=1.0
       GO TO (1,1,1,1,1,1,1,1,1,1,2,2),J
 1      XC=X(J)
       GO TO 3
 2     LC=0.333
       UC=1.0
       XC=X(J)
```

```
 3      RETURN
        END
```

e) Subroutine WATBA

```
C ***********************************************************************
C THIS SUBROUTINE COMPUTES COMPONENTS OF RUNOFF USING VARIABLE SOURCE
C AREA CONCEPT
      SUBROUTINE WATBA (OF)
      COMMON/PARAM1/USIN,SSIN,USFC,PCAR,DT,GRUT,IRUN,CSMAX,TTRAIN
      COMMON/PARAM2/USZT,USWP,FU,KU,FS,KS,K1,K2,SAC,SC,K3,K4,KOUN
      COMMON/PARAM3/FINTER(721),GFLOW(721),RFALL(721),BFLOW,METHOD
      COMMON/AAA/OBSQ(721),SIMQ(721),QOBS(721),QCOMP(721),RAINF(721)
      COMMON/CCC/RUNF(721),DRUN(721),QSL(721),TRUN(721),GW(721),TORUNO
      COMMON/BBB/F,FSQ,RSQ,EFF,NDT,CAREA,FACT1,FACT2,X(12),E(12),TCRUNO
      COMMON/EEE/ABSF,SDO,SDS,CVO,CVS,SE,KT,PA(721)
       REAL KU,KS,K1,K2,K3,K4,LC
       INTEGER R,C
C .......................................................................
C       BFLOW=OBSQ(1)*1000
C       SIMQ(1)=(BFLOW*DT)/CAREA
        OBSQ(1)=SIMQ(1)
C       QOBS(1)=BFLOW
C       QCOMP(1)=BFLOW
        SUMSKA=0.0
        DIFF  =0.0
        OF    =0.0
        TTRAIN=0.0
        TORUNO=0.0
        TCRUNO=0.0
        FRAIN =0.0
        PA(1)=0.0
C .......................................................................
        K1     =X(1)
        K2     =X(2)
        K3     =X(3)
        K4     =X(4)
        KU     =X(5)*40.
        FU     =X(6)*3.E+7
        KS     =X(7)
        FS     =X(8)
        SAC    =X(9)*20.
        SC     =X(10)
        USIN   =X(11)*600.
        SSIN   =X(12)*600.
C        IF(METHOD.EQ.1) GO TO 6
C        USIN =USZT*K3
```

```
C        SSIN =USZT*K4
  6      FUSIN=USIN
         FSSIN=SSIN
C ..........................................................................
       DO 75 J=2,NDT
       RUNO1=0.0
       RUNO2=0.0
       RUNO3=0.0
       RUNO4=0.0
       PPT=0.0
       PRAIN     =RAINF(J)
       SIMQ(J)   =0.0
       QCOMP(J)  =0.0
       FINTER(J)=0.0
       GFLOW(J)  =0.0
       RFALL(J)  =0.0
       TRUN(J)   =0.0
       DRUN(J)   =0.0
       QSL(J)    =0.0
       GW(J)     =0.0
       RUNF(J)   =0.0
       PA(J)     =0.0
       PPT=PRAIN
       PPT=(PPT*DT)/3600.
C******* WETTING CYCLE INTERCEPTION ***********************************
       AINC=0.2
       PPT=PPT*AINC
       DO 50 I=1,5
       IF(PPT.LE.0.0) GO TO 40
C ********** PARTIAL AREA RUNOFF ***************************************
       IF(METHOD.EQ.2) GO TO 7
       PA(J)=SC*EXP(SAC*(K3*FUSIN+K4*FSSIN)/CSMAX)
         GO TO 8
  7    PA(J)=SC*EXP(SAC*(K3*FUSIN+K4*FSSIN)/USZT)
  8    PB=PA(J)+PCAR
       PB=AMIN1(PB,1.0)
       PA(J)=PB-PCAR
       RUNO1=RUNO1+PA(J)*PPT
       RUNO2=RUNO2+PCAR*PPT
C ********* WETTING CYCLE UPPER SOIL ZONE ****************************
       FUSIN = FUSIN+PPT*(1.0-PB)
C ********* DRAINAGE CYCLE ********************************************
C        GO TO 41
 40    FFU = 0.0
       IF(FUSIN.LE.USFC) GO TO 42
       FFU =FU*(((FUSIN-USFC)/USZT)**KU)*AINC
 42    IF(FUSIN.LE.FFU) FFU=FUSIN
```

```
      RUNO3 = RUNO3+FFU*K1
      RFALL(J) = FFU*(1.0-K1)
      FUSIN = FUSIN-FFU
      IF(K1.EQ.1.0) GO TO 50
      FSSIN = FSSIN+RFALL(J)
      FFS = 0.0
      IF(FSSIN.LE.USFC) GO TO 43
      FFS = FS*((FSSIN-USFC)**KS)*AINC
43    IF(FSSIN.LE.FFS) FFS=FSSIN
      RUNO4 = RUNO4+FFS*K2
      GW(J)=GW(J)+FFS*(1.-K2)
      FSSIN = FSSIN-FFS
50    CONTINUE
C *********** SUMMARY AND ACCOUNTING ***********************************
      DRUN(J) = RUNO2
      RUNF(J) = RUNO1
      QSL(J) = RUNO3+RUNO4
      FINTER(J)=RUNO3
      GFLOW (J)=RUNO4
      TRUN(J) =RUNF(J)+QSL(J)+DRUN(J)
      SIMQ(J)=TRUN(J)
      SIMQ(J)=(SIMQ(J-1)+SIMQ(J))*.5
      QCOMP(J)=(SIMQ(J)*CAREA)/(DT)
      DIFF    =ABS(OBSQ(J)-SIMQ(J))
      FRAIN=RAINF(J)*DT/3600.
      OF = OF+DIFF
      SUMSKA=SUMSKA+(OBSQ(J)-SIMQ(J))**2
      TORUNO=TORUNO+OBSQ(J)
      TCRUNO=TCRUNO+SIMQ(J)
75    CONTINUE
      KOUN=KOUN+1
      GRUT=SUMSKA
      WRITE(2,*)KOUN,GRUT,OF,TORUNO,TCRUNO
      WRITE(*,*)KOUN,GRUT,OF,TORUNO,TCRUNO
      RETURN
      END
```

Appendix-A4- Programme for Distributed physiographic model.

a) Main Programme

```
C        ******************************************************
C          *ONE DIMENSIONAL DISTRIBUTED PHYSIOGRAPHIC MODEL*
C        (WATERSHED DISTRIBUTED INTO TRIBUTARY & MAIN CHANNEL
C         SUB-WATERSHEDS)
C        ******************************************************
C       THIS PROGRAMME IS PART OF THE "HYDROLOGICAL STUDIES OF DISTURBED
C       MOUNTAINOUS WATERSHEDS" DEVELOPED BY VIDYA SAGAR KATIYAR RESEARCH
C       SCHOLAR,GUIDED BY DR.B.S.MATHUR,PROFESSOR,DEPARTMENT OF HYDROLOGY
C       UNIVERSITY OF ROORKEE,ROORKEE (INDIA) & DR.M.S.RAMA MOHAN RAO,EX-
C       DIRECTOR, CENTRAL SOIL & WATER CONSERVATION RESEARCH & TRAINING
C       INSTITUTE, DEHRADUN (INDIA).
C        ****************************************************************
C        COMMON VARIABLES
C        DT   = TIME STEP (SECONDS)
C        RADUR= RAINFALL DURATION (HOURS)
C        SIMT = SIMULATION TIME (HOURS)
C        QBF  = BASEFLOW AT OUTLET (M**3/SEC)
C        ARWS = TOTAL WATERSHED AREA (M**2)
C        BETA = WEIGHTING FACTOR IN THE NUMERICAL SCHEME
C        THETA= WEIGHTING FACTOR IN BASEFLOW CONTRIBUTIONS
C        FACT = FACTOR FOR CHANGING CHANNEL CONVEYANCE COEFFICIENT
C        RAINM= RAINFALL RATE (M/SEC)
C        RINFM= INFILTRATION RATE (M/SEC)
C        WSB  = WATERSHED WIDTH (M)
C           FOR TRIBUTARY CATCHMENTS
C        NTR  = NUMBER OF TRIBUTARIES
C        ARTR = AREA OF TRIBUTARY CATCHMENT (M**2)
C        DXT  = SPACE STEP FOR TRIBUTARY (M)/TRIBUTARY LENGTH
C        SLOPT= SLOPE OF TRIBUTARY (M/M)
C        CRT  = CHANNEL CONVEYANCE COFFICIENT
C        AMT  = CHANNEL CONVEYANCE EXPONENT
C        CST  = SURFACE SUPPLY COFFICIENT
C        CGT  = GROUND  SUPPLY COFFICIENT
C        GST  = SURFACE SUPPLY EXPONENT
C        GGT  = GROUND  SUPPLY EXPONENT
C        ALPT = ALPHA FOR TRIBUTARY
C        BDTR = WIDTH OF TRIBUTARY CATCHMENT (M)
C        SST  = SURFACE STORAGE CONTRIBUTION
C        GCT  = GROUND  STORAGE CONTRIBUTION
C        TST  = TOTAL STORAGE CONTRIBUTION
C        QTR  = DISCHARGE RATE OF TRIBUTARY
C           FOR MAIN STREAM SUBCATCHMENTS
C        NDX  = NO. OF MAIN-STREAM SUBCATCHMENTS
```

```
C        ARMS = AREA OF M.S. SUBCATCHMENTS
C        DX   = SPACE STEP FOR MAIN-STREAM
C        SLOPE= SLOPE OF M.S. CHANNEL
C        CR   = CHANNEL CONVEYANCE COFFICIENT FOR M.S.
C        AM   = CHANNEL CONVEYANCE EXPONENT  FOR M.S.
C        CS   = SURFACE SUPPLY COEFFICIENT   FOR M.S.
C        CG   = GROUND  SUPPLY COEFFICIENT   FOR M.S.
C        GS   = SURFACE SUPPLY EXPONENT      FOR M.S.
C        GG   = GROUND  SUPPLY EXPONENT      FOR M.S.
C        ALPM = ALPHA FOR MAIN-STREAM
C        BDMS = WIDTH OF M.S. SUBCATCHMENT
C        SSM  = SURFACE STORAGE CONTRIBUTION FOR M.S.
C        GCM  = GROUND  STORAGE CONTRIBUTION FOR M.S.
C        TSM  = TOTAL   STORAGE CONTRIBUTION FOR M.S.
C        QMS  = DISCHARGE RATE OF MAIN-STREAM
C        INFK = 1, INFILTRATION DATA GIVEN
C        INFK = 2, USING HORTON'S EQUATION
C        INFK = 3, USING PHILIP'S EQUATION
C        INFK = 4, USING VARIABLE RAINFALL INFILTRATION MODEL
C*********************************************************************
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
     1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
      DIMENSION ALPT(15),ALPM(15),CR(15),CRT(15),AM(15)
      DIMENSION AMT(15),SLOPE(15),SLOPT(15),WSB(15)
      DIMENSION EFRUF(15),LIS(15),ELIS(15),DFQ2(35)
      DIMENSION AQTR(35),AQMS(35),FQ1(35),FQ2(35),DFQ1(35)
      COMMON/DDD/SST(15,722),SSM(15,722),GCM(15,722),GCT(15,722),
     1TSM(15,722),TST(15,722),PQTR(15,722),QMS(20,722),GAMM(15),GAMT(15)
C*********************************************************************
      OPEN(UNIT=1,FILE='SD3.DAT',STATUS='OLD')
      OPEN(UNIT=2,FILE='SD3.OUT',STATUS='NEW')
      OPEN(UNIT=3,FILE='MSH.DAT',STATUS='OLD')
C*********************************************************************
      READ(1,*)ARWS,DT,BETA,NTR,NDX,THETA,SORP,PHI,FO,FC,PK,INFK,FACT
      WRITE(2,10)
   10 FORMAT(2X,20(1H0'*'),2X,'INPUT DATA',2X,20(1H0'*'))
      WRITE(2,20)ARWS,DT,BETA,NTR,NDX,THETA,SORP,PHI,FO,FC,PK,INFK,FACT
      WRITE(*,20)ARWS,DT,BETA,NTR,NDX,THETA,SORP,PHI,FO,FC,PK,INFK,FACT
   20 FORMAT(/5X,'CATCHMENT AREA=',F10.2,5X,'TIME STEP=',F8.2,/5X,
     1'BETA=',F4.2,5X,'NO. OF TRIBUT.=',I4,5X,'NO. OF M.S. SUB.=',
     2I4,/5X,'THETA=',F6.2,5X,'SORPT.=',F8.2,5X,'PHI=',F8.2,/5X,'FO=',
     3F8.3,5X,'FC=',F8.3,5X,'PK=',F6.4,/5X,'INFK=',I2,5X,'FACT=',F6.4)
C*********************************************************************
```

```
C     DATA INPUT OF MAIN CHANNEL SUBWATERSHEDS
          READ(1,*)(ARMS(I),I=1,NDX)
          WRITE(2,30)(ARMS(I),I=1,NDX)
          READ(1,*)(DX(I),I=1,NDX)
          WRITE(2,30)(DX(I),I=1,NDX)
          READ(1,*)(SLOPE(I),I=1,NDX)
          WRITE(2,30)(SLOPE(I),I=1,NDX)
          READ(1,*)(CR(I),I=1,NDX)
          WRITE(2,30)(CR(I),I=1,NDX)
          READ(1,*)(AM(I),I=1,NDX)
          WRITE(2,30)(AM(I),I=1,NDX)
          READ(1,*)(CS(I),I=1,NDX)
          WRITE(2,30)(CS(I),I=1,NDX)
          READ(1,*)(CG(I),I=1,NDX)
          WRITE(2,30)(CG(I),I=1,NDX)
          WRITE(*,*)(CR(I),I=1,NDX)
          READ(1,*)(GS(I),I=1,NDX)
          WRITE(2,30)(GS(I),I=1,NDX)
          READ(1,*)(GG(I),I=1,NDX)
          WRITE(2,30)(GG(I),I=1,NDX)
C   DATA INPUT OF TRIBUTARY SUBWATERSHEDS
          READ(1,*)(ARTR(I),I=1,NTR)
          WRITE(2,30)(ARTR(I),I=1,NTR)
          READ(1,*)(DXT(I),I=1,NTR)
          WRITE(2,30)(DXT(I),I=1,NTR)
          READ(1,*)(SLOPT(I),I=1,NTR)
          WRITE(2,30)(SLOPT(I),I=1,NTR)
          READ(1,*)(CRT(I),I=1,NTR)
          WRITE(2,30)(CRT(I),I=1,NTR)
          READ(1,*)(AMT(I),I=1,NTR)
          WRITE(2,30)(AMT(I),I=1,NTR)
          READ(1,*)(CST(I),I=1,NTR)
          WRITE(2,30)(CST(I),I=1,NTR)
          READ(1,*)(CGT(I),I=1,NTR)
          WRITE(2,30)(CGT(I),I=1,NTR)
          READ(1,*)(GST(I),I=1,NTR)
          WRITE(2,30)(GST(I),I=1,NTR)
          READ(1,*)(GGT(I),I=1,NTR)
          WRITE(2,30)(GGT(I),I=1,NTR)
          READ(1,*)(EFRUF(I),I=1,NTR)
          WRITE(2,30)(EFRUF(I),I=1,NTR)
          WRITE(*,*)(EFRUF(I),I=1,NTR)
   30     FORMAT(/,2X,6F12.5)
C ***************************************************************************
C CALCULATION OF TIME STEPS & NUMBER OF RAIN EVENTS
          READ(3,*)IDATE,IMONTH,IYEAR
          WRITE(2,122)IDATE,IMONTH,IYEAR
```

```
      READ(3,*)RADUR,SIMT
      SIMTS=SIMT*3600.0
      RADURS=RADUR*3600.0
      NDT    =SIMTS/DT+1
      NER    =RADURS/DT+1
      WRITE(2,40)NDT,NER
      WRITE(*,40)NDT,NER
      KTT=600./DT
      READ(3,*)(QOBS(J),J=1,NDT)
C     WRITE(2,*)(QOBS(J),J=1,NDT,KTT)
  40  FORMAT(2X,'NO. OF TIME STEPS=',I5,5X,'NO. OF RAIN EVENTS=',I5)
 122  FORMAT(/,2X,'SIMULATION FOR',2X,I3,2X,I3,2X,I4)
C *******************************************************************
C    COMPUTATION OF INITIAL INFILTRATION RATE
      READ(3,*)(RAINM(J),J=1,NER)
      WRITE(2,*)(J,RAINM(J),J=1,NER,KTT)
      WRITE(*,*)(J,RAINM(J),J=1,NER,KTT)
      READ(3,*)PMAX
      TRM   =0.0
      RM    =0.0
      TG    =0.0
      SDT   =0.0
      TTRAIN=0.0
      SRATE =0.0
      DTT   =DT/3600.
     DO 225 M=1,NER
      SDT=SDT+DTT
      RM=RAINM(M)*DTT*(SDT-(.5*DTT))
      TRM=TRM+RM
      TTRAIN=TTRAIN+RAINM(M)*DTT
      SRATE=SRATE+RAINM(M)
 225 CONTINUE
      TG=TRM/TTRAIN
C     ARATE=TTRAIN/RADUR
      ARATE=(SRATE/(NER-1))
      WRITE(2,171)ARATE,PMAX
 171  FORMAT(5X,'AV. RAIN RATE =',F6.2,5X,'MAX. INTENSITY=',F7.2)
      QBF=QOBS(1)
      FO=-14.7895+.354*TTRAIN+.786*PMAX-160.74*QBF+4.029*TG+.624*RADUR
C *******************************************************************
C    COMPUTATION OF INFILTRATION RATES
      RINFM(1)=0.0
      SDT    =0.0
      IF(INFK.EQ.1) GO TO 651
      IF(INFK.EQ.2) GO TO 652
      IF(INFK.EQ.3) GO TO 653
      IF(INFK.EQ.4) GO TO 654
```

```
 651     READ(1,*)(RINFM(J),J=1,NDT)
          GO TO 655
 652    DO 101 J=2,NDT
         SDT =SDT+DTT
         RINFM(J)=FC+(FO-FC)*EXP((-1)*PK*SDT)
 101    CONTINUE
           GO TO 655
 653    DO 102 J=2,NDT
         SDT =SDT+DTT
         RINFM(J)=(.5*SORP/(SDT**.5))+PHI
 102    CONTINUE
           GO TO 655
 654     CALL INFILT
 655    DO 100 J=2,NER
         RAINM(J)=RAINM(J)/(1000.*3600.)
         RINFM(J)=RINFM(J)/(1000.*3600.)
 100    CONTINUE
C        WRITE(2,*)(J,RAINM(J),J=1,NER,KTT)
C        WRITE(2,*)(J,RINFM(J),J=1,NER,KTT)
C        WRITE(*,*)(J,RAINM(J),J=1,NER,KTT)
C        WRITE(*,*)(J,RINFM(J),J=1,NER,KTT)
C************************************************************************
         WRITE(2,12)
 12      FORMAT(2X,'GAMM(I)                BDMS(I)           ALPM(I)          G
     1AMT(I)          BDTR(I)       ALPT(I)')
        DO 300 I=2,NDX
         CR(I)=CR(I)*FACT
         IF(DX(I).EQ.0) GO TO 250
         GAMM(I)=1./AM(I)
         BDMS(I)=ARMS(I)/DX(I)
         ALPM(I)=1./((CR(I)*SLOPE(I)**0.5)**GAMM(I))
           GO TO 260
 250     GAMM(I)=0.0
         BDMS(I)=0.0
         ALPM(I)=0.0
 260     IF(DXT(I).EQ.0) GO TO 270
         CRT(I)=CRT(I)*FACT
         GAMT(I)=1./AMT(I)
         BDTR(I)=ARTR(I)/DXT(I)
         ALPT(I)=1./((CRT(I)*SLOPT(I)**0.5)**GAMT(I))
           GO TO 280
 270     GAMT(I)=0.0
         BDTR(I)=0.0
         ALPT(I)=0.0
 280     WRITE(2,*)GAMM(I),BDMS(I),ALPM(I),GAMT(I),BDTR(I),ALPT(I)
         WRITE(*,*)GAMM(I),BDMS(I),ALPM(I),GAMT(I),BDTR(I),ALPT(I)
 300    CONTINUE
```

```
C***************************************************************************
C       INITIAL CONDITIONS
        WRITE(2,13)
 13     FORMAT(2X,'BASE FLOW AT DIFFERENT PTS. INITIALLY')
        K=NDX-1
        QTS(1,1)     = 0.0
        QMS(1,1)     = 0.0
        QTR(1,2,1)   = 0.0
        QTR(NDX,2,1)= 0.0
        QMS(NDX,1)   = QBF
       DO 400 I=1,NDX-1
C       QMS(K,1)=QMS(K+1,1)-(QMS(NDX,1)*WSB(K+1)*DX(K+1)/ARWS)
        QMS(K,1)=QMS(K+1,1)-(QMS(NDX,1)*(ARMS(K+1)+ARTR(K+1))/ARWS)
        IF(QMS(K,1).LE.0.0) QMS(K,1)=0.0
        IF(K.EQ.10) QMS(K,1)=QMS(K+1,1)
        QTS(NDX,1)=QMS(NDX,1)-QMS(NDX-1,1)
        KT=K+1
        QTR(KT,2,1)=(ARTR(KT)*QBF/ARWS)*THETA
C       QTS(KT,1)=ARMS(KT)*QBF/ARWS
        QTS(KT,1)=(QMS(KT,1)-QMS(KT-1,1)-QTR(KT,2,1))
        IF(QTS(KT,1).LE.0.0) QTS(KT,1)=0.0
        IF(KT.EQ.10)QTS(KT,1)=QTS(KT,1)-QTR(KT+1,2,1)
        WRITE(2,*)KT,QMS(KT,1),QTS(KT,1),QTR(KT,2,1)
        WRITE(*,*)KT,QMS(KT,1),QTS(KT,1),QTR(KT,2,1)
          K=K-1
 400   CONTINUE
C***************************************************************************
C       BOUNDARY CONDITIONS
        I=1
        DO 500 J=1,NDT
        QOBS(J)=QOBS(J)
        DO 500 N=1,NTR
        QTR(N,1,J)=0.0
        QMS(I,J)=0.0
        PQTR(N,1)=QTR(N,2,1)
 500    CONTINUE
C***************************************************************************
C       SURFACE STORAGE CONTRIBUTIONS
        WRITE(2,14)
 14     FORMAT(2X,'SURFACE & SUBSUR. CONTRIBUTIONS')
        DO 600 J=1,NDT
        DO 600 I=2,NDX
        RR=RAINM(J+1)
        RI=RINFM(J+1)
        SSM(I,1)=0.0
        SST(I,1)=0.0
        SRAT=RAINM(J)+RAINM(J+1)
```

```
      SINF =RINFM(J)+RINFM(J+1)
      IF(RR.GT.RI) GO TO 350
      SSM(I,J+1)=0.0
      SST(I,J+1)=0.0
      IF(RAINM(J+1).LE.RINFM(J+1)) RINFM(J+1)=RAINM(J+1)
      GO TO 360
 350  CSBM =2*CS(I)*(BDMS(I)**GS(I))/DT
      AS1=CSBM
      IF(AS1.LE.0.0) GO TO 355
      RHS1=AS1*SSM(I,J)**GS(I)-SSM(I,J)+SRAT-SINF
      ASSM=SSM(I,J)
      IF(ASSM.LE.0.0) ASSM=.5*(SRAT-SINF)
         EP1=1.0E-8
      CALL SOLUSN(AS1,RHS1,ASSM,GS(I),SSM(I,J+1),EP1)
      GO TO 356
 355  SSM(I,J+1)=0.0
 356  CSBT =2*CST(I)*(BDTR(I)**GST(I))/DT
      AS2  =CSBT
      IF(AS2.LE.0.0) GO TO 357
      RHS2 =AS2*SST(I,J)**GST(I)-SST(I,J)+SRAT-SINF
      ASST=SST(I,J)
      IF(ASST.LE.0.0) ASST=.5*(SRAT-SINF)
      EP2=1.0E-8
      CALL SOLUSN(AS2,RHS2,ASST,GST(I),SST(I,J+1),EP2)
      GO TO 360
 357  SST(I,J+1)=0.0
C ***********************************************************
C     GROUND WATER CONTRIBUTIONS
 360  IF(ARMS(I).EQ.0.0)  GO TO 361
      GCM(I,1)=QTS(I,1)/ARMS(I)
      CGBM =2*CG(I)*(BDMS(I)**GG(I))/DT
      IF(RR.LE.RI) SINF=SRAT
      AG1  =CGBM
      IF(AG1.LE.0.0) GO TO 361
      RHS3=AG1*(GCM(I,J)**GG(I))-GCM(I,J)+SINF
      AGCM=GCM(I,J)
      EP3=1.0E-9
      CALL SOLUSN(AG1,RHS3,AGCM,GG(I),GCM(I,J+1),EP3)
      GO TO 362
 361  GCM(I,J+1)=0.0
 362  IF(ARTR(I).EQ.0.0)  GO TO 363
      GCT(I,1)=QTR(I,2,1)/ARTR(I)
      CGBT =2.*CGT(I)*(BDTR(I)**GGT(I))/DT
      AG2  =CGBT
      IF(AG2.LE.0.0) GO TO 363
      IF(RR.LE.RI) SINF=SRAT
      RHS4=AG2*(GCT(I,J)**GGT(I))-GCT(I,J)+SINF
```

```
      AGCT=GCT(I,J)
      EP4=1.E-9
      CALL SOLUSN(AG2,RHS4,AGCT,GGT(I),GCT(I,J+1),EP4)
        GO TO 364
363   GCT(I,J+1)=0.0
364   TSM(I,J+1)=SSM(I,J+1)+GCM(I,J+1)
      TST(I,J+1)=SST(I,J+1)+GCT(I,J+1)
       M=J+1
600     CONTINUE
C     WRITE(2,*)((M,I,SSM(I,M),SST(I,M),GCM(I,M),GCT(I,M),I=2,
C    1NDX),M=1,NDT,KTT)
      WRITE(*,*)((M,I,SSM(I,M),SST(I,M),GCM(I,M),GCT(I,M),I=2,
     1NDX),M=1,NDT,KTT)
C***********************************************************************
C     TRIBUTARIES ROUTING
      WRITE(2,16)
16    FORMAT(2X,'TRIBUTARIES CONTRIBUTIONS')
      I=1
      DO 700 J=1,NDT
      DO 700 N=2,NTR
      PQTR(1,J)=0.0
      QMS(1,J)=0.0
      QTR(N,1,J+1)=0.0
      QTR(1,I+1,J+1)=0.0
      QTR(NTR,I+1,1)=0.0
      PQTR(NTR,J+1)=0.0
      IF(DXT(N).EQ.0.0) QTR(N,I+1,J+1)=0.0
      IF(DXT(N).EQ.0.0) GOTO 370
      DTX1=DT/DXT(N)
      PREQ2=QTR(N,I+1,J)
      PREQ3=QTR(N,I,J+1)
      AVERQ=(PREQ2+PREQ3)
      IF(AVERQ.LE.0.0) QTR(N,I+1,J+1)=0.0
      IF(AVERQ.LE.0.0) GO TO 370
      AVS1=1./AVERQ
      GAM1=1.-GAMT(N)
      PKU1=AVS1**GAM1
      SSC1=DT*BDTR(N)*.5*(TST(N,J)+TST(N,J+1))
      CUMR1=(DTX1*PREQ3)+(ALPT(N)*GAMT(N)*PREQ2*PKU1)+SSC1
      DENM1=DTX1+ALPT(N)*GAMT(N)*PKU1
      AQTR(1)=(CUMR1)/(DENM1)
      EPS1=1.0E-6
      RHS1=DTX1*PREQ3+ALPT(N)*(PREQ2**GAMT(N))+SSC1
       K=1
      FQ1(K)=DTX1*AQTR(K)+ALPT(N)*(AQTR(K)**GAMT(N))-RHS1
22    RTQA=1./AQTR(K)
      DFQ1(K)=DTX1+ALPT(N)*GAMT(N)*(RTQA**GAM1)
```

```
      AQTR(K+1)=AQTR(K)-(FQ1(K)/DFQ1(K))
      FQ1(K+1)=DTX1*AQTR(K+1)+ALPT(N)*(AQTR(K+1)**GAMT(N))-RHS1
      IF(FQ1(K+1).LE.EPS1) RQTR=AQTR(K+1)
      IF(FQ1(K+1).LE.EPS1) GO TO 23
      K=K+1
      IF(K.EQ.35) GO TO 24
      GO TO 22
 23   QTR(N,I+1,J+1)=RQTR
      GO TO 370
 24   WRITE(2,151)
      WRITE(*,151)
 151  FORMAT(2X,'SCHEME DOES NOT CONVERGE')
 370  PQTR(N,J+1)=QTR(N,I+1,J+1)
        M=J+1
C     WRITE(2,*)N,M,PQTR(N,M),SSM(N,M),SST(N,M),GCM(N,M),GCT(N,M)
C     WRITE(*,*)N,M,PQTR(N,M),SSM(N,M),SST(N,M),GCM(N,M),GCT(N,M)
 700  CONTINUE
C     WRITE(2,*)((J,I,PQTR(I,J),I=1,NDX),J=1,NDT,KTT)
C     WRITE(*,*)((J,I,PQTR(I,J),I=1,NDX),J=1,NDT,KTT)
      WRITE(*,19)
 19   FORMAT(/,2X,'TRIBUTARIES ROUTING OVER ')
C*****************************************************
C     MAIN STREAM ROUTING
      WRITE(2,17)
 17   FORMAT(2X,'MAIN STREAM ROUTING')
      TORD=0.0
      TORUNO=0.0
      TCRUNO=0.0
      DO 900 J=1,NDT
      DO 800 N=1,NDX-1
      QMS(NDX,1)=QBF
      QMS(1,J+1)=0.0
      PQTR(1,J+1)=0.0
      PQTR(NTR,J+1)=0.0
C     IF(DX(N).LE.0.0) DTX2=0.0
C     IF(DX(N).LE.0.0.AND.N.EQ.1) GO TO 369
      IF(DX(N+1).LE.0.0) GO TO 371
      DTX2=DT/DX(N+1)
      PRSQ3=QMS(N,J+1)+PQTR(N,J+1)
      PRSQ2=QMS(N+1,J)
      AVMSQ=.5*(PRSQ2+PRSQ3)
      IF(AVMSQ.LE.0.0) WRITE(*,258)
 258  FORMAT(10X,'VS KATIYAR')
      SSC2=DT*.5*(TSM(N+1,J)+TSM(N+1,J+1))*BDMS(N+1)
      AVS2=1./AVMSQ
      GAM2=1.-GAMM(N+1)
      PKU2=AVS2**GAM2
```

```
      CUMR2=DTX2*PRSQ3+ALPM(N+1)*GAMM(N+1)*PRSQ2*PKU2+SSC2
      DENM2=DTX2+ALPM(N+1)*GAMM(N+1)*PKU2
      AQMS(1)=(CUMR2)/(DENM2)
      K=1
      EPS2=1.0E-4
      RHS2=DTX2*PRSQ3+ALPM(N+1)*(PRSQ2**GAMM(N+1))+SSC2
      FQ2(K)=DTX2*AQMS(K)+ALPM(N+1)*(AQMS(K)**GAMM(N+1))-RHS2
 25   SMQA=1./AQMS(K)
      DFQ2(K)=DTX2+ALPM(N+1)*GAMM(N+1)*(SMQA**GAM2)
      AQMS(K+1)=AQMS(K)-(FQ2(K)/DFQ2(K))
      FQ2(K+1)=DTX2*AQMS(K+1)+ALPM(N+1)*AQMS(K+1)**GAMM(N+1)-RHS2
      IF(FQ2(K+1).LE.EPS2) RQMS=AQMS(K+1)
      IF(FQ2(K+1).LE.EPS2) GO TO 26
      K=K+1
      IF(K.EQ.35) GO TO 27
      GO TO 25
 26   QMS(N+1,J+1)=RQMS
      GO TO 372
 27   WRITE(2,112)
      WRITE(*,112)
 112  FORMAT(5X,'SCHEME DOES NOT WORK')
 257  FORMAT(4X,F12.8,4X,F12.8)
      GO TO 372
 371  QMS(N+1,J+1)=QMS(N,J+1)+PQTR(N+1,J+1)
 372       L=N+1
           M=J+1
C     WRITE(2,*)L,M,QMS(L,M)
Ç     WRITE(*,*)L,M,QMS(L,M)
 800  CONTINUE
      QXSS=QMS(NDX,M)-QBF
      TORUNO=TORUNO+QOBS(J)
      TCRUNO=TCRUNO+QMS(NDX,J)
      TORD=TORD+QXSS
      OUTVOL=TORD*DT
      RE=(OUTVOL*1000.)/(ARWS)
 900  CONTINUE
      TORUNO=TORUNO*1000.*(DT/ARWS)
      TCRUNO=TCRUNO*1000.*(DT/ARWS)
 115  FORMAT(2X,'TOT ORDI.=',F12.4,2X,'FLOW VOL.=',F15.4,2X,
     1 /'EXCESS RAIN=',F8.3,5X,'ARATE=',F8.4)
      WRITE(2,115)TORD,OUTVOL,RE,ARATE
      WRITE(*,*)TORD,OUTVOL,RE,ARATE
C     WRITE(2,114)((J,I,QMS(I,J),I=2,NDX),J=2,NDT,KTT)
C     WRITE(2,113)(M,QMS(NDX,M),M=1,NDT,KTT)
 113  FORMAT(6(2X,I3,5X,F10.6))
 114  FORMAT(2X,6(2X,I3,2X,I3,3X,F10.6))
      NT=NDT/10+1
```

```
      DO 74 J=1,NT
       OBSQ(J)=0.0
       SIMQ(J)=0.0
       RAIN(J)=0.0
       RINFIL(J)=0.0
 74   CONTINUE
      DO 75 J=1,NDT,KTT
       NC = J/10+1
       OBSQ(NC)=QOBS(J)
       SIMQ(NC)=QMS(NDX,J)
       RAIN(NC)=RAINM(J)*(1000.*3600.)
       RINFIL(NC)=RINFM(J)*(1000.*3600.)
       MC=(NC-1)*10
       WRITE(2,116)MC,RAIN(NC),RINFIL(NC),OBSQ(NC),SIMQ(NC)
       WRITE(*,116)MC,RAIN(NC),RINFIL(NC),OBSQ(NC),SIMQ(NC)
 75   CONTINUE
       CALL OBJECT
       WRITE(2,117)F,FSQ,RSQ,EFF,TTRAIN,TG,PMAX,FO
       WRITE(*,117)F,FSQ,RSQ,EFF,TTRAIN,TG,PMAX,FO
       WRITE(2,118)ABSF,SDO,SDS,CVO,CVS,SE,TORUNO,TCRUNO
       WRITE(*,118)ABSF,SDO,SDS,CVO,CVS,SE,TORUNO,TCRUNO
 116   FORMAT(2X,I5,5X,F6.2,5X,F6.2,5X,F6.4,5X,F6.4)
 117   FORMAT(5X,'F=',F10.6,5X,'FSQ=',F10.6,5X,'RSQ=',F10.6,5X,
     1'EFF=',F10.6,/5X,'TTRAIN=',F9.4,5X,'TG =',F6.4,5X,'PMAX=',F9.2,
     25X,'FO=',F7.2)
 118   FORMAT(5X,'ABS DIFF.=',F10.4,5X,'SDO=',F10.4,5X,'SDS=',
     1F10.4,/5X,'CVO=',F10.6,5X,'CVS=',F10.6,5X,'SE=',F10.6,/5X,
     2'TORUNO=',F10.4,5X,'TCRUNO=',F10.4)
        STOP
        END
```

b) Subroutine SOLUSN

```
C***********************************************************************
C   THIS SUBROUTINE SOLVES NONLINEAR EQUATIONS
       SUBROUTINE SOLUSN (AS,RHS,QAS,GAM,X,EPS)
       COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
     1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
       COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
       COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
       COMMON/DDD/SST(15,722),SSM(15,722),GCM(15,722),GCT(15,722),
     1TSM(15,722),TST(15,722),PQTR(15,722),QMS(20,722),GAMM(15),GAMT(15)
       DIMENSION FQ(300),DFQ(300),ASQ(300),SAM(300)
       K=1
       ASQ(K)=QAS
```

```
      FQ(K)=AS*(ASQ(K)**GAM)+ASQ(K)-RHS
      IF(ASQ(K).LE.0.0) GO TO 35
      GAM3=1.-GAM
 30   SAM(K)=1./ASQ(K)
      DFQ(K)=AS*GAM*(SAM(K)**GAM3)+1.
      ASQ(K+1)=ABS(ASQ(K)-(FQ(K)/DFQ(K)))
      FQ(K+1)=AS*(ASQ(K+1)**GAM)+ASQ(K+1)-RHS
      IF(FQ(K+1).LE.EPS) RQS=ASQ(K+1)
      IF(FQ(K+1).LE.EPS) GO TO 31
       K=K+1
      IF(K.EQ.300) GO TO 32
       GO TO 30
 31   X=RQS
      GO TO 36
 32   WRITE(2,312)
      WRITE(*,312)
312   FORMAT(5X,'SCHEME DOES NOT WORK ')
 35   X=0.0
 36    RETURN
       END
```

c) Subroutine OBJECT

```
C************************************************************************
C  THIS SUBROUTINE COMPUTES STATISTICAL PARAMETERS FOR FINDING
C  OUT GOODNESS OF FIT BETWEEN OBSERVED & SIMULATED HYDROGRAPHS
C  **************************
      SUBROUTINE OBJECT
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
    1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
   1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
   2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
C ***********************************************************************
C Computer programme for this subroutine is given in Appendix-A1(c)
C ***********************************************************************
```

d) Subroutine INFILT

```
C***********************************************************************
C  INFILTRATION RATE BY MODIFIED HORTON'S EQUATION
      SUBROUTINE INFILT
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
    1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
```

```
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
        DIMENSION FINT(722),RR(20),J1(20),J2(20),TP(20),TS(20)
        DIMENSION DELT(20)
C***********************************************************************
C  Computer programme for this subroutine is given in Appendix-A1(d)
C***********************************************************************
C       INITIAL CONDITIONS
        WRITE(2,13)
 13     FORMAT(2X,'BASE FLOW AT DIFFERENT PTS. INITIALLY')
        K=NDX-1
        QTS(1,1)     = 0.0
        QMS(1,1)     = 0.0
        QTR(1,2,1)   = 0.0
        QTR(NDX,2,1)= 0.0
        QMS(NDX,1)   = QBF
       DO 400 I=1,NDX-1
C       QMS(K,1)=QMS(K+1,1)-(QMS(NDX,1)*WSB(K+1)*DX(K+1)/ARWS)
        QMS(K,1)=QMS(K+1,1)-(QMS(NDX,1)*(ARMS(K+1)+ARTR(K+1))/ARWS)
        IF(QMS(K,1).LE.0.0) QMS(K,1)=0.0
        IF(K.EQ.10) QMS(K,1)=QMS(K+1,1)
        QTS(NDX,1)=QMS(NDX,1)-QMS(NDX-1,1)
        KT=K+1
        QTR(KT,2,1)=(ARTR(KT)*QBF/ARWS)*THETA
C       QTS(KT,1)=ARMS(KT)*QBF/ARWS
        QTS(KT,1)=(QMS(KT,1)-QMS(KT-1,1)-QTR(KT,2,1))
        IF(QTS(KT,1).LE.0.0) QTS(KT,1)=0.0
        IF(KT.EQ.10)QTS(KT,1)=QTS(KT,1)-QTR(KT+1,2,1)
        WRITE(2,*)KT,QMS(KT,1),QTS(KT,1),QTR(KT,2,1)
        WRITE(*,*)KT,QMS(KT,1),QTS(KT,1),QTR(KT,2,1)
          K=K-1
  400  CONTINUE
C***********************************************************************
C       BOUNDARY CONDITIONS
        I=1
        DO 500 J=1,NDT
        QOBS(J)=QOBS(J)
        DO 500 N=1,NTR
        QTR(N,1,J)=0.0
        QMS(I,J)=0.0
        PQTR(N,1)=QTR(N,2,1)
  500   CONTINUE
C***********************************************************************
C       SURFACE STORAGE CONTRIBUTIONS
        WRITE(2,14)
 14     FORMAT(2X,'SURFACE & SUBSUR. CONTRIBUTIONS')
        DO 600 J=1,NDT
```

```
      DO 600 I=2,NDX
      RR=RAINM(J+1)
      RI=RINFM(J+1)
      SSM(I,1)=0.0
      SST(I,1)=0.0
      SRAT=RAINM(J)+RAINM(J+1)
      SINF =RINFM(J)+RINFM(J+1)
      IF(RR.GT.RI) GO TO 350
      SSM(I,J+1)=0.0
      SST(I,J+1)=0.0
      IF(RAINM(J+1).LE.RINFM(J+1)) RINFM(J+1)=RAINM(J+1)
      GO TO 360
 350  CSBM =2*CS(I)*(BDMS(I)**GS(I))/DT
      AS1=CSBM
      IF(AS1.LE.0.0) GO TO 355
      RHS1=AS1*SSM(I,J)**GS(I)-SSM(I,J)+SRAT-SINF
      ASSM=SSM(I,J)
      IF(ASSM.LE.0.0) ASSM=.5*(SRAT-SINF)
         EP1=1.0E-8
      CALL SOLUSN(AS1,RHS1,ASSM,GS(I),SSM(I,J+1),EP1)
      GO TO 356
 355  SSM(I,J+1)=0.0
 356  CSBT =2*CST(I)*(BDTR(I)**GST(I))/DT
      AS2  =CSBT
      IF(AS2.LE.0.0) GO TO 357
      RHS2 =AS2*SST(I,J)**GST(I)-SST(I,J)+SRAT-SINF
      ASST=SST(I,J)
      IF(ASST.LE.0.0) ASST=.5*(SRAT-SINF)
      EP2=1.0E-8
      CALL SOLUSN(AS2,RHS2,ASST,GST(I),SST(I,J+1),EP2)
      GO TO 360
 357  SST(I,J+1)=0.0
C ******************************************************************
C     GROUND WATER CONTRIBUTIONS
 360  IF(ARMS(I).EQ.0.0)  GO TO 361
      GCM(I,1)=QTS(I,1)/ARMS(I)
      CGBM =2*CG(I)*(BDMS(I)**GG(I))/DT
      IF(RR.LE.RI) SINF=SRAT
      AG1  =CGBM
      IF(AG1.LE.0.0) GO TO 361
      RHS3=AG1*(GCM(I,J)**GG(I))-GCM(I,J)+SINF
      AGCM=GCM(I,J)
      EP3=1.0E-9
      CALL SOLUSN(AG1,RHS3,AGCM,GG(I),GCM(I,J+1),EP3)
      GO TO 362
 361  GCM(I,J+1)=0.0
 362  IF(ARTR(I).EQ.0.0)  GO TO 363
```

```
      GCT(I,1)=QTR(I,2,1)/ARTR(I)
      CGBT =2.*CGT(I)*(BDTR(I)**GGT(I))/DT
      AG2  =CGBT
      IF(AG2.LE.0.0) GO TO 363
      IF(RR.LE.RI) SINF=SRAT
      RHS4=AG2*(GCT(I,J)**GGT(I))-GCT(I,J)+SINF
      AGCT=GCT(I,J)
      EP4=1.E-9
      CALL SOLUSN(AG2,RHS4,AGCT,GGT(I),GCT(I,J+1),EP4)
        GO TO 364
 363  GCT(I,J+1)=0.0
 364  TSM(I,J+1)=SSM(I,J+1)+GCM(I,J+1)
      TST(I,J+1)=SST(I,J+1)+GCT(I,J+1)
       M=J+1
 600    CONTINUE
C     WRITE(2,*)((M,I,SSM(I,M),SST(I,M),GCM(I,M),GCT(I,M),I=2,
C    1NDX),M=1,NDT,KTT)
      WRITE(*,*)((M,I,SSM(I,M),SST(I,M),GCM(I,M),GCT(I,M),I=2,
     1NDX),M=1,NDT,KTT)
C***********************************************************************
C     TRIBUTARIES ROUTING
      WRITE(2,16)
 16   FORMAT(2X,'TRIBUTARIES CONTRIBUTIONS')
      I=1
      DO 700 J=1,NDT
      DO 700 N=2,NTR
      PQTR(1,J)=0.0
      QMS(1,J)=0.0
      QTR(N,1,J+1)=0.0
      QTR(1,I+1,J+1)=0.0
      QTR(NTR,I+1,1)=0.0
      PQTR(NTR,J+1)=0.0
      IF(DXT(N).EQ.0.0) QTR(N,I+1,J+1)=0.0
      IF(DXT(N).EQ.0.0) GOTO 370
      DTX1=DT/DXT(N)
      PREQ2=QTR(N,I+1,J)
      PREQ3=QTR(N,I,J+1)
      AVERQ=(PREQ2+PREQ3)
      IF(AVERQ.LE.0.0) QTR(N,I+1,J+1)=0.0
      IF(AVERQ.LE.0.0) GO TO 370
      AVS1=1./AVERQ
      GAM1=1.-GAMT(N)
      PKU1=AVS1**GAM1
      SSC1=DT*BDTR(N)*.5*(TST(N,J)+TST(N,J+1))
      CUMR1=(DTX1*PREQ3)+(ALPT(N)*GAMT(N)*PREQ2*PKU1)+SSC1
      DENM1=DTX1+ALPT(N)*GAMT(N)*PKU1
      AQTR(1)=(CUMR1)/(DENM1)
```

```
      EPS1=1.0E-6
      RHS1=DTX1*PREQ3+ALPT(N)*(PREQ2**GAMT(N))+SSC1
       K=1
      FQ1(K)=DTX1*AQTR(K)+ALPT(N)*(AQTR(K)**GAMT(N))-RHS1
 22   RTQA=1./AQTR(K)
      DFQ1(K)=DTX1+ALPT(N)*GAMT(N)*(RTQA**GAM1)
      AQTR(K+1)=AQTR(K)-(FQ1(K)/DFQ1(K))
      FQ1(K+1)=DTX1*AQTR(K+1)+ALPT(N)*(AQTR(K+1)**GAMT(N))-RHS1
      IF(FQ1(K+1).LE.EPS1) RQTR=AQTR(K+1)
      IF(FQ1(K+1).LE.EPS1) GO TO 23
      K=K+1
      IF(K.EQ.35) GO TO 24
      GO TO 22
 23   QTR(N,I+1,J+1)=RQTR
      GO TO 370
 24   WRITE(2,151)
      WRITE(*,151)
 151  FORMAT(2X,'SCHEME DOES NOT CONVERGE')
 370  PQTR(N,J+1)=QTR(N,I+1,J+1)
        M=J+1
C     WRITE(2,*)N,M,PQTR(N,M),SSM(N,M),SST(N,M),GCM(N,M),GCT(N,M)
C     WRITE(*,*)N,M,PQTR(N,M),SSM(N,M),SST(N,M),GCM(N,M),GCT(N,M)
 700  CONTINUE
C     WRITE(2,*)((J,I,PQTR(I,J),I=1,NDX),J=1,NDT,KTT)
C     WRITE(*,*)((J,I,PQTR(I,J),I=1,NDX),J=1,NDT,KTT)
      WRITE(*,19)
 19   FORMAT(/,2X,'TRIBUTARIES ROUTING OVER ')
C***********************************************************
C     MAIN STREAM ROUTING
      WRITE(2,17)
 17   FORMAT(2X,'MAIN STREAM ROUTING')
      TORD=0.0
      TORUNO=0.0
      TCRUNO=0.0
      DO 900 J=1,NDT
      DO 800 N=1,NDX-1
      QMS(NDX,1)=QBF
      QMS(1,J+1)=0.0
      PQTR(1,J+1)=0.0
      PQTR(NTR,J+1)=0.0
C     IF(DX(N).LE.0.0) DTX2=0.0
C     IF(DX(N).LE.0.0.AND.N.EQ.1) GO TO 369
      IF(DX(N+1).LE.0.0) GO TO 371
      DTX2=DT/DX(N+1)
      PRSQ3=QMS(N,J+1)+PQTR(N,J+1)
      PRSQ2=QMS(N+1,J)
      AVMSQ=.5*(PRSQ2+PRSQ3)
```

```
      IF(AVMSQ.LE.0.0) WRITE(*,258)
258   FORMAT(10X,'VS KATIYAR')
      SSC2=DT*.5*(TSM(N+1,J)+TSM(N+1,J+1))*BDMS(N+1)
      AVS2=1./AVMSQ
      GAM2=1.-GAMM(N+1)
      PKU2=AVS2**GAM2
      CUMR2=DTX2*PRSQ3+ALPM(N+1)*GAMM(N+1)*PRSQ2*PKU2+SSC2
      DENM2=DTX2+ALPM(N+1)*GAMM(N+1)*PKU2
      AQMS(1)=(CUMR2)/(DENM2)
      K=1
      EPS2=1.0E-4
      RHS2=DTX2*PRSQ3+ALPM(N+1)*(PRSQ2**GAMM(N+1))+SSC2
      FQ2(K)=DTX2*AQMS(K)+ALPM(N+1)*(AQMS(K)**GAMM(N+1))-RHS2
25    SMQA=1./AQMS(K)
      DFQ2(K)=DTX2+ALPM(N+1)*GAMM(N+1)*(SMQA**GAM2)
      AQMS(K+1)=AQMS(K)-(FQ2(K)/DFQ2(K))
      FQ2(K+1)=DTX2*AQMS(K+1)+ALPM(N+1)*AQMS(K+1)**GAMM(N+1)-RHS2
      IF(FQ2(K+1).LE.EPS2) RQMS=AQMS(K+1)
      IF(FQ2(K+1).LE.EPS2) GO TO 26
      K=K+1
      IF(K.EQ.35) GO TO 27
      GO TO 25
26    QMS(N+1,J+1)=RQMS
      GO TO 372
27    WRITE(2,112)
      WRITE(*,112)
112   FORMAT(5X,'SCHEME DOES NOT WORK')
257   FORMAT(4X,F12.8,4X,F12.8)
       GO TO 372
371   QMS(N+1,J+1)=QMS(N,J+1)+PQTR(N+1,J+1)
372        L=N+1
           M=J+1
C     WRITE(2,*)L,M,QMS(L,M)
C     WRITE(*,*)L,M,QMS(L,M)
800   CONTINUE
      QXSS=QMS(NDX,M)-QBF
      TORUNO=TORUNO+QOBS(J)
      TCRUNO=TCRUNO+QMS(NDX,J)
      TORD=TORD+QXSS
      OUTVOL=TORD*DT
      RE=(OUTVOL*1000.)/(ARWS)
900   CONTINUE
      TORUNO=TORUNO*1000.*(DT/ARWS)
      TCRUNO=TCRUNO*1000.*(DT/ARWS)
115   FORMAT(2X,'TOT ORDI.=',F12.4,2X,'FLOW VOL.=',F15.4,2X,
    1 /'EXCESS RAIN=',F8.3,5X,'ARATE=',F8.4)
      WRITE(2,115)TORD,OUTVOL,RE,ARATE
```

```
      WRITE(*,*)TORD,OUTVOL,RE,ARATE
C     WRITE(2,114)((J,I,QMS(I,J),I=2,NDX),J=2,NDT,KTT)
C     WRITE(2,113)(M,QMS(NDX,M),M=1,NDT,KTT)
 113  FORMAT(6(2X,I3,5X,F10.6))
 114  FORMAT(2X,6(2X,I3,2X,I3,3X,F10.6))
      NT=NDT/10+1
      DO 74 J=1,NT
      OBSQ(J)=0.0
      SIMQ(J)=0.0
      RAIN(J)=0.0
      RINFIL(J)=0.0
 74   CONTINUE
      DO 75 J=1,NDT,KTT
      NC = J/10+1
      OBSQ(NC)=QOBS(J)
      SIMQ(NC)=QMS(NDX,J)
      RAIN(NC)=RAINM(J)*(1000.*3600.)
      RINFIL(NC)=RINFM(J)*(1000.*3600.)
      MC=(NC-1)*10
      WRITE(2,116)MC,RAIN(NC),RINFIL(NC),OBSQ(NC),SIMQ(NC)
      WRITE(*,116)MC,RAIN(NC),RINFIL(NC),OBSQ(NC),SIMQ(NC)
 75   CONTINUE
      CALL OBJECT
      WRITE(2,117)F,FSQ,RSQ,EFF,TTRAIN,TG,PMAX,FO
      WRITE(*,117)F,FSQ,RSQ,EFF,TTRAIN,TG,PMAX,FO
      WRITE(2,118)ABSF,SDO,SDS,CVO,CVS,SE,TORUNO,TCRUNO
      WRITE(*,118)ABSF,SDO,SDS,CVO,CVS,SE,TORUNO,TCRUNO
 116  FORMAT(2X,I5,5X,F6.2,5X,F6.2,5X,F6.4,5X,F6.4)
 117  FORMAT(5X,'F=',F10.6,5X,'FSQ=',F10.6,5X,'RSQ=',F10.6,5X,
     1'EFF=',F10.6,/5X,'TTRAIN=',F9.4,5X,'TG =',F6.4,5X,'PMAX=',F9.2,
     25X,'FO=',F7.2)
 118  FORMAT(5X,'ABS DIFF.=',F10.4,5X,'SDO=',F10.4,5X,'SDS=',
     1F10.4,/5X,'CVO=',F10.6,5X,'CVS=',F10.6,5X,'SE=',F10.6,/5X,
     2'TORUNO=',F10.4,5X,'TCRUNO=',F10.4)
      STOP
      END
```

b) Subroutine SOLUSN

```
C***********************************************************************
C   THIS SUBROUTINE SOLVES NONLINEAR EQUATIONS
      SUBROUTINE SOLUSN (AS,RHS,QAS,GAM,X,EPS)
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
     1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
```

```
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
      COMMON/DDD/SST(15,722),SSM(15,722),GCM(15,722),GCT(15,722),
     1TSM(15,722),TST(15,722),PQTR(15,722),QMS(20,722),GAMM(15),GAMT(15)
      DIMENSION FQ(300),DFQ(300),ASQ(300),SAM(300)
      K=1
      ASQ(K)=QAS
      FQ(K)=AS*(ASQ(K)**GAM)+ASQ(K)-RHS
      IF(ASQ(K).LE.0.0) GO TO 35
      GAM3=1.-GAM
   30 SAM(K)=1./ASQ(K)
      DFQ(K)=AS*GAM*(SAM(K)**GAM3)+1.
      ASQ(K+1)=ABS(ASQ(K)-(FQ(K)/DFQ(K)))
      FQ(K+1)=AS*(ASQ(K+1)**GAM)+ASQ(K+1)-RHS
      IF(FQ(K+1).LE.EPS) RQS=ASQ(K+1)
      IF(FQ(K+1).LE.EPS) GO TO 31
       K=K+1
      IF(K.EQ.300) GO TO 32
       GO TO 30
   31 X=RQS
      GO TO 36
   32 WRITE(2,312)
      WRITE(*,312)
  312 FORMAT(5X,'SCHEME DOES NOT WORK ')
   35 X=0.0
   36  RETURN
       END
```

c) Subroutine OBJECT

```
C***************************************************************************
C  THIS SUBROUTINE COMPUTES STATISTICAL PARAMETERS FOR FINDING
C  OUT GOODNESS OF FIT BETWEEN OBSERVED & SIMULATED HYDROGRAPHS
C  *************************
      SUBROUTINE OBJECT
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
     1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
C **************************************************************************
C Computer programme for this subroutine is given in Appendix-A1(c)
C **************************************************************************
```

d) Subroutine INFILT

```
C***************************************************************************
```

```
C  INFILTRATION RATE BY MODIFIED HORTON'S EQUATION
      SUBROUTINE INFILT
      COMMON/AAA/NER,DT,NDT,NDX,FO,FC,PK,ARWS,QBF,F,FSQ,RSQ,EFF,PHI,
     1SORP,INFK,ARATE,KTT,ABSF,SDO,SDS,CVO,CVS,SE
      COMMON/BBB/QOBS(722),OBSQ(100),SIMQ(100),RAIN(100),RINFIL(100)
      COMMON/CCC/RAINM(722),RINFM(722),CS(15),CG(15),DX(15),DXT(15),
     1GS(15),GG(15),CST(15),CGT(15),GST(15),GGT(15),BDMS(15),
     2BDTR(15),QTS(15,1),QTR(15,2,722),ARMS(15),ARTR(15)
      DIMENSION FINT(722),RR(20),J1(20),J2(20),TP(20),TS(20)
      DIMENSION DELT(20)
C*************************************************************************
C  Computer programme for this subroutine is given in Appendix-A1(d)
C*************************************************************************
```

APPENDIX-B

Appendix-B1- INPUT DATA FILE FOR TIME AREA BASED MODEL

a) Input file TAC3.DAT

1.771E+5 10. .02 300. 11 .01 36. 10. .6 2 1.000
0.0 7.9E+3 1.41E+4 1.41E+4 2.52E+4 1.9E+4 3.33E+4 1.68E+4
2.19E+4 1.54E+4 9.4E+3

b) Input file MSH.DAT

8 8 1991
1.5 4.
11*.0648 10*.176 10*.413 10*.290 10*.176 10*.1477 10*.127 10*.107
10*.102 10*.097 10*.093 10*.090 10*.087 10*.083 10*.081 10*.078
10*.076 10*.074 10*.072 10*.07 10*.069 10*.067 10*.066 10*.065
0. 10*36. 10*60. 10*33. 10*15. 10*10.5 10*9. 10*7.5 10*6. 10*3.
60.

0. 10*72. 10*48. 10*18. 10*12. 10*9. 10*9. 10*6. 10*6. 10*0.
72.

Appendix-B2-INPUT DATA FILE FOR VARIABLE SOURCE AREA MODEL
(Subjective method of optimization)

a) Input file DM3.DAT

1.771E+5 1500. 290. 60. 3
0.01 4. 3.0E-3 667.
700. 200. 100. 280. 300. 1.5E+7 11.6 .003 .20 .24 .40 .60 .40

b) Input file MSH.DAT

Given in Appendix-B1

Appendix-B3-Input file for Variable source area model (Objective method of optimization)

a) Input file DM4.DAT

```
2.72E+6 2500. 290. 60. 0.005 6. 3.E-3 2
900. 200. 100. 300. 300. 1.50E+7 11.6 .003 .2 .24 .4 .6 .4
0 12 12 12 0 20 .001 .001
.32 .3 .64 .44 .33 .8 .15 .001 .1 .002 .5 .4
.001 .001 .001 .001 .001 .001 .001 .0001 .001 .0001 .001 .001
.00001
```

b) Input file MSH.DAT

Given in Appendix-B1

Appendix-B4-INPUT DATA FILE FOR DISTRIBUTED PHYSIOGRAPHIC MODEL

a) Input file SD3.DAT

```
1.771E+5 60. .50 6 6 0.50 74. 10. 40. 10. .6 4 1.4
0. 3.92E+3 2.35E+4 7.84E+3 1.724E+4 5.09E+4
0. 128. 320. 72. 84. 316.
0. .547 .375 .833 .476 .316
0. 1.3 1.47 1. 1.37 1.53
6*1.4
6*0.6
6*70.0
6*0.7
6*0.66
0. 3.29E+3 2.051E+4 1.99E+4 3.0E+4 0.0
0. 132. 184. 456. 496. 0.0
0. .606 .272 .482 .464 0.0
0. 1.25 1.57 1.38 1.39 0.0
6*1.4
6*0.80
6*90.0
6*0.66
6*0.6
6*.0055

1.771E+5 60. .50 6 6 0.50 74. 10. 34. 10. .6 4 0.8
0. 3.92E+3 5.03E+4 1.704E+4 2.33E+4 7.84E+3
0. 128. 284. 84. 280. 72.
0. .547 .316 .476 .375 .633
```

```
0. .733 .903 .773 .842 .695
6*1.4
6*0.6
6*70.0
6*0.7
6*0.6
0. 4.15E+3 2.134E+4 2.151E+4 2.769E+4 0.0
0. 132. 184. 456. 496. 0.0
0. .606 .272 .482 .464 0.0
0. .705 .959 .769 .780 0.0
6*1.4
6*0.8
6*90.0
6*0.66
6*0.5
6*.0055
```

b) Input file MSH.DAT

Given in Appendix-B1

Appendix-B5-OUTPUT FILE FOR STORM DATED 8-8-1991 USING DISTRIBUTED PHYSIOGRAPHIC MODEL

```
************************* INPUT DATA *************************

    CATCHMENT AREA= 177100.00      TIME STEP=   60.00
    BETA= .50      NO. OF TRIBUT.=   6      NO. OF M.S. SUB.=   6
    THETA=   .50      SORPT.=   74.00      PHI=   10.00
    FO=  40.000      FC=  10.000      PK= .6000
    INFK= 4      FACT=1.4000

  .00000   3920.00000 23500.00000  7840.00000 17240.00000 50900.00000
  .00000    128.00000   320.00000    72.00000    84.00000   316.00000
  .00000       .54700      .37500      .83300      .47600      .31600
  .00000      1.30000     1.47000     1.00000     1.37000     1.53000
 1.40000      1.40000     1.40000     1.40000     1.40000     1.40000
  .60000       .60000      .60000      .60000      .60000       .6000
70.00000     70.00000    70.00000    70.00000    70.00000     70.0000
  .70000       .70000      .70000      .70000      .70000       .7000
  .66000       .66000      .66000      .66000      .66000       .6600
  .00000   3290.00000 20510.00000 19900.00000 30000.00000       .0000
  .00000    132.00000   184.00000   456.00000   496.00000       .0000
  .00000       .60600      .27200      .48200      .46400       .0000
  .00000      1.25000     1.57000     1.38000     1.39000       .0000
 1.40000      1.40000     1.40000     1.40000     1.40000      1.4000
  .80000       .80000      .80000      .80000      .80000       .8000
90.00000     90.00000    90.00000    90.00000    90.00000     90.0000
  .66000       .66000      .66000      .66000      .66000       .6600
  .60000       .60000      .60000      .60000      .60000       .6000
  .00550       .00550      .00550      .00550      .00550       .0055

  SIMULATION FOR    8    8  1991
  NO. OF TIME STEPS=  241      NO. OF RAIN EVENTS=   91
  1        .0000000          11          36.0000000          21
          60.0000000          31          33.0000000          41
          15.0000000          51          10.5000000          61
           9.0000000          71           7.5000000          81
           6.0000000          91           3.0000000
    AV. RAIN RATE = 20.00      MAX. INTENSITY=  60.00
  GAMM(I)       BDMS(I)      ALPM(I)      GAMT(I)      BDTR(I)      ALPT(I)
   7.142857E-001          30.6250000  8.087433E-001  7.142857E-001
          24.9242400  8.018438E-001
   7.142857E-001          73.4375000  8.476999E-001  7.142857E-001
         111.4674000  9.070562E-001
   7.142857E-001         108.8889000  8.393902E-001  7.142857E-001
          43.6403500  8.107868E-001
   7.142857E-001         205.2381000  8.186640E-001  7.142857E-001
```

60.4838700 8.176550E-001
7.142857E-001 161.0759000 8.757569E-001 .0000000
.0000000 .0000000

BASE FLOW AT DIFFERENT PTS. INITIALLY

6	6.473365E-002	1.860499E-002	.0000000
5	4.612867E-002	1.178437E-002	5.482805E-003
4	2.886149E-002	6.502607E-003	3.636928E-003
3	1.872195E-002	1.233814E-002	3.748411E-003
2	2.635402E-003	2.034121E-003	6.012810E-004

SURFACE & SUBSUR. CONTRIBUTIONS
TRIBUTARIES CONTRIBUTIONS
MAIN STREAM ROUTING
TOT ORDI.= 13.1203 FLOW VOL.= 787.2154
EXCESS RAIN= 4.445 ARATE= 20.0000

0	.00	.00	.0647	.0647
10	36.00	33.12	.0647	.0683
20	60.00	30.92	.1760	.2348
30	33.00	28.93	.4127	.4827
40	15.00	15.00	.2900	.2693
50	10.50	10.50	.1760	.1640
60	9.00	9.00	.1477	.1208
70	7.50	7.50	.1267	.1022
80	6.00	6.00	.1067	.0939
90	3.00	3.00	.1020	.0901
100	.00	.00	.0973	.0881
110	.00	.00	.0933	.0869
120	.00	.00	.0900	.0861
130	.00	.00	.0867	.0855
140	.00	.00	.0833	.0850
150	.00	.00	.0807	.0845
160	.00	.00	.0780	.0841
170	.00	.00	.0760	.0837
180	.00	.00	.0740	.0834
190	.00	.00	.0720	.0830
200	.00	.00	.0700	.0827
210	.00	.00	.0687	.0823
220	.00	.00	.0673	.0820
230	.00	.00	.0660	.0817
240	.00	.00	.0653	.0814

F= -.115514 FSQ= .012122 RSQ= .948019 EFF= .922191
TTRAIN= 30.00 TG = .4417 PMAX= 60.00 FO= 35.30
ABS DIFF.= .3745 SDO= .0806 SDS= .0905
CVO= .681861 CVS= .735993 SE= .018369
TORUNO= 9.4101 TCRUNO= 9.7248

Appendix-C1

RAINFALL, INFILTRATION, RUNOFF RATES (OBSERVED & SIMULATED) AND TIME FROM THE START OF STORM EVENTS RECORDED AT BHAINTAN WATERSHED

1) STORM EVENT DATED: 14-8-1979

TIME (MIN)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
(1)	(2)	(3)	(4)	(5)
0	.00	.00	.0310	.0310
10	.60	.60	.0317	.0315
20	2.10	2.10	.0320	.0316
30	11.40	11.40	.0323	.0318
40	11.40	11.40	.0327	.0321
50	1.50	1.50	.0330	.0323
60	.30	.30	.0360	.0326
70	3.80	3.80	.0415	.0328
80	6.90	6.90	.0470	.0332
90	12.90	12.90	.0525	.0337
100	10.40	10.40	.0580	.0344
110	1.50	1.50	.0635	.0352
120	2.10	2.10	.0690	.0362
130	27.30	27.30	.0713	.0373
140	46.50	45.02	.0740	.0397
150	43.20	43.20	.0767	.0431
160	54.30	42.76	.0793	.0709
170	48.60	41.78	.1117	.1840
180	24.00	24.00	.2327	.2714
190	8.10	8.10	.3977	.3636
200	.90	.90	.5283	.4503
210	.30	.30	.4700	.5028
220	.00	.00	.4127	.5104
230	.00	.00	.3527	.4846
240	.00	.00	.2927	.4432
250	.00	.00	.2807	.3990
260	.00	.00	.2687	.3584
270	.00	.00	.2597	.3236
280	.00	.00	.2507	.2948
290	.00	.00	.2417	.2713
300	.00	.00	.2327	.2524
310	.00	.00	.2240	.2370
320	.00	.00	.2133	.2246
330	.00	.00	.2080	.2144

340	.00	.00	.2000	.2061
350	.00	.00	.1930	.1993
360	.00	.00	.1860	.1936

2) STORM EVENT DATED: 2-9-1980

TIME (MIN)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.2533	.2533
10	1.80	1.80	.2567	.2577
20	.60	.60	.2633	.2590
30	.00	.00	.2673	.2587
40	.60	.60	.2747	.2568
50	1.20	1.20	.2820	.2541
60	.30	.30	.2927	.2511
70	.30	.30	.3227	.2480
80	9.60	9.60	.3527	.2452
90	30.00	30.00	.3827	.2436
100	40.80	40.80	.4127	.2451
110	46.80	46.80	.4633	.2512
120	39.00	39.00	.4773	.2628
130	43.80	43.80	.5413	.2806
140	41.40	41.40	.6220	.3056
150	38.40	38.40	.7067	.3381
160	56.40	48.21	.7947	.3986
170	56.40	45.74	.8853	.5611
180	30.00	30.00	.9853	.6957
190	30.00	30.00	1.0607	.8283
200	27.00	27.00	1.1367	.9532
210	33.00	33.00	1.2133	1.0529
220	60.00	35.44	1.3007	1.2738
230	6.00	6.00	1.3907	1.4141
240	6.00	6.00	1.4933	1.4992
250	6.00	6.00	1.4593	1.5506
260	4.80	4.80	1.4367	1.5625
270	6.00	6.00	1.4133	1.5357
280	13.20	13.20	1.3907	1.4857
290	6.00	6.00	1.3680	1.4300
300	.00	.00	1.3453	1.3783
310	.00	.00	1.3193	1.3347
320	.00	.00	1.2933	1.2995
330	.00	.00	1.2673	1.2712
340	.00	.00	1.2420	1.2482
350	.00	.00	1.2167	1.2289
360	.00	.00	1.1947	1.2121

3) STORM EVENT DATED: 13-7-1981

TIME (MIN)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0413	.0413
10	16.80	16.80	.0413	.0422
20	2.40	2.40	.0425	.0432
30	32.40	32.40	.0440	.0450
40	4.80	4.80	.0455	.0481
50	19.80	19.80	.0470	.0522
60	2.40	2.40	.0485	.0578
70	22.40	22.40	.0525	.0651
80	1.80	1.80	.0646	.0746
90	1.20	1.20	.0789	.0859
100	6.00	6.00	.0979	.0994
110	33.00	33.00	.1180	.1158
120	36.60	36.60	.1391	.1368
130	7.20	7.20	.1650	.1624
140	18.60	18.60	.1972	.1922
150	60.00	60.00	.2345	.2278
160	15.60	15.60	.2759	.2703
170	34.80	34.80	.3173	.3190
180	2.40	2.40	.3587	.3735
190	10.80	10.80	.3992	.4318
200	1.20	1.20	.4450	.4921
210	3.60	3.60	.4976	.5515
220	57.00	57.00	.5617	.6102
230	31.80	31.80	.6342	.6699
240	33.00	33.00	.7092	.7301
250	6.00	6.00	.7867	.7904
260	12.00	12.00	.8778	.8498
270	32.40	32.40	.9770	.9090
280	57.00	52.09	1.0841	.9732
290	27.00	27.00	1.1934	1.0395
300	32.40	32.40	1.3152	1.1080
310	39.00	39.00	1.4441	1.1799
320	9.00	9.00	1.5444	1.2542
330	3.60	3.60	1.6459	1.3271
340	63.00	32.87	1.7476	1.5093
350	27.00	27.00	1.8391	1.6060
360	60.00	28.54	1.9555	1.8051
370	54.00	26.77	2.0751	2.3490
380	18.00	18.00	2.2184	2.5429
390	15.00	15.00	2.3606	2.6284
400	42.00	22.30	2.5048	2.6913
410	51.00	21.13	2.6514	2.9990

420	21.00	19.97	2.8007	2.9751
430	18.00	18.00	2.8827	2.8815
440	1.80	1.80	2.9405	2.7675
450	4.20	4.20	3.0054	2.6390
460	3.60	3.60	3.0300	2.5132
470	1.80	1.80	3.0645	2.4076
480	42.00	15.42	3.0795	2.4435
490	.00	.00	3.1048	2.4175
500	.00	.00	3.0382	2.3866
510	.00	.00	2.9458	2.3591
520	.00	.00	2.8668	2.3291
530	.00	.00	2.7912	2.2962
540	.00	.00	2.7163	2.2642
550	.00	.00	2.0001	2.2363
560	.00	.00	2.4337	2.2135
570	.00	.00	2.3428	2.1953
580	.00	.00	2.2521	2.1806
590	.00	.00	2.1601	2.1681
600	.00	.00	2.0751	2.1571
610	.00	.00	1.9921	2.1469
620	.00	.00	1.9268	2.1374
630	.00	.00	1.8618	2.1281
640	.00	.00	1.7968	2.1191
650	.00	.00	1.7334	2.1103
660	.00	.00	1.6788	2.1015

4) STORM EVENT DATED: 29-7-1982

TIME (MIN)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0140	.0140
10	12.00	12.00	.0147	.0144
20	24.00	24.00	.0153	.0156
30	3.00	3.00	.0167	.0178
40	9.60	9.60	.0200	.0208
50	3.20	3.20	.0240	.0247
60	1.20	1.20	.0267	.0294
70	3.60	3.60	.0400	.0351
80	82.80	38.07	.1667	.1946
90	36.00	35.61	.2667	.3220
100	12.60	12.60	.3333	.4411
110	79.20	31.50	.8000	.8646
120	9.00	9.00	1.1867	1.1661
130	6.00	6.00	1.2893	1.3182
140	3.00	3.00	1.3200	1.3368

150	1.20	1.20	1.2967	1.2492
160	.00	.00	1.1558	1.1185
170	.00	.00	1.0155	.9927
180	.00	.00	.8752	.8904
190	.00	.00	.7353	.8130
200	.00	.00	.6550	.7562
210	.00	.00	.6467	.7147
220	.00	.00	.6333	.6841
230	.00	.00	.6267	.6611
240	.00	.00	.6200	.6434
250	.00	.00	.6167	.6294
260	.00	.00	.6117	.6180
270	.00	.00	.6067	.6084
280	.00	.00	.6017	.6001
290	.00	.00	.5967	.5927
300	.00	.00	.5920	.5860
310	.00	.00	.5897	.5799
320	.00	.00	.5873	.5741
330	.00	.00	.5873	.5687
340	.00	.00	.5873	.5635
350	.00	.00	.5873	.5584
360	.00	.00	.5873	.5536

5) STORM EVENT DATED: 20-8-1982

TIME (MIN)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.2480	.2480
10	1.50	1.50	.2507	.2522
20	16.80	16.80	.2533	.2537
30	39.30	39.30	.2567	.2547
40	39.00	39.00	.2600	.2558
50	30.00	30.00	.2627	.2582
60	20.40	20.40	.2660	.2622
70	6.30	6.30	.2700	.2674
80	3.00	3.00	.2747	.2734
90	.90	.90	.2793	.2798
100	1.80	1.80	.2840	.2863
110	19.80	19.80	.2880	.2930
120	36.30	36.30	.2927	.3007
130	30.00	30.00	.3047	.3100
140	18.00	18.00	.3287	.3207
150	54.00	47.18	.3587	.3498
160	53.40	44.78	.4367	.4518
170	6.90	6.90	.5967	.5184

180	3.00	3.00	.9067	.5768
190	6.00	6.00	1.0287	.6293
200	7.50	7.50	1.0100	.6682
210	16.50	16.50	.9913	.6890
220	24.00	24.00	.9727	.6926
230	42.50	31.66	.9547	.7328
240	38.90	30.27	.9367	.8972
250	9.90	9.90	.9220	.9889
260	6.00	6.00	.9067	1.0630
270	9.60	9.60	.8933	1.1130
280	.00	.00	.8800	1.1237
290	.00	.00	.8667	1.0945
300	.00	.00	.8533	1.0395
310	.00	.00	.8427	.9752
320	.00	.00	.8320	.9132
330	.00	.00	.8213	.8588
340	.00	.00	.8113	.8137
350	.00	.00	.8000	.7773
360	.00	.00	.7893	.7484

TIME : TIME (MINUTES) FROM START OF THE STORM,
RAIN : RAINFALL INTENSITY (MM/HR) DURING THE PERIOD,
INFILT : INFILTRATION RATE (MM/HR) DURING THE PERIOD,
QOBS : OBSERVED RUNOFF RATE (CUMEC) DURING THE PERIOD,
QSIM : SIMULATED RUNOFF RATE (CUMEC) DURING THE PERIOD.

Appendix-C2-

RAINFALL, INFILTRATION, RUNOFF RATES (OBSERVED & SIMULATED) AND TIME FROM THE START OF STORM EVENTS RECORDED AT JHANDOO-NALA WATERSHED

1) STORM EVENT DATED: 4-7-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
(1)	(2)	(3)	(4)	(5)
0	.00	.00	.0127	.0127
10	60.00	60.00	.0255	.0131
20	100.80	75.81	.0843	.0528
30	75.60	69.54	.1500	.1776
40	24.00	24.00	.1407	.1478
50	9.00	9.00	.0700	.1068
60	9.00	9.00	.0613	.0782
70	7.80	7.80	.0546	.0600
80	3.00	3.00	.0481	.0484
90	1.20	1.20	.0415	.0409
100	1.20	1.20	.0350	.0360
110	3.60	3.60	.0309	.0327
120	3.00	3.00	.0300	.0304
130	6.00	6.00	.0293	.0290
140	3.00	3.00	.0287	.0280
150	2.40	2.40	.0280	.0273
160	2.40	2.40	.0276	.0268
170	2.40	2.40	.0273	.0265
180	1.80	1.80	.0270	.0263
190	1.80	1.80	.0267	.0262
200	1.20	1.20	.0267	.0261
210	3.00	3.00	.0267	.0260
220	1.80	1.80	.0267	.0260
230	1.20	1.20	.0267	.0259
240	1.20	1.20	.0267	.0259
250	1.20	1.20	.0267	.0259
260	.60	.60	.0267	.0259
270	.00	.00	.0267	.0259

2) STORM EVENT DATED: 10-8-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0272	.0272
10	6.00	6.00	.0277	.0277
20	66.00	32.40	.1227	.1134
30	24.00	24.00	.1167	.1220
40	24.00	24.00	.1167	.1011
50	21.00	21.00	.0676	.0815
60	6.00	6.00	.0676	.0673
70	3.00	3.00	.0567	.0577
80	6.00	6.00	.0528	.0513
90	3.00	3.00	.0515	.0470
100	3.00	3.00	.0503	.0442
110	1.80	1.80	.0490	.0424
120	1.20	1.20	.0477	.0411
130	.00	.00	.0467	.0402
140	.00	.00	.0455	.0396
150	.00	.00	.0444	.0391
160	.00	.00	.0433	.0388
170	.00	.00	.0422	.0385
180	.00	.00	.0411	.0382

3) STORM EVENT DATED: 11-8-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0389	.0389
10	12.00	12.00	.0389	.0409
20	.60	.60	.0389	.0407
30	7.20	7.20	.0389	.0406
40	15.00	15.00	.0515	.0408
50	18.00	18.00	.0585	.0415
60	36.00	19.25	.0811	.0783
70	12.00	12.00	.1080	.0824
80	33.00	17.50	.1003	.1114
90	5.40	5.40	.0927	.1042
100	1.20	1.20	.0782	.0880
110	1.80	1.80	.0782	.0752
120	27.00	14.98	.0963	.0920
130	15.00	14.50	.1259	.1350
140	4.20	4.20	.1066	.1210

150	.60	.60	.0863	.0989
160	.00	.00	.0719	.0827
170	.00	.00	.0614	.0724
180	.00	.00	.0614	.0661
190	.00	.00	.0561	.0622
200	.00	.00	.0528	.0598
210	.00	.00	.0515	.0582
220	.00	.00	.0497	.0571
230	.00	.00	.0497	.0564
240	.00	.00	.0497	.0558

4) STORM EVENT DATED: 16-8-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0216	.0216
10	30.00	30.00	.0515	.0228
20	12.00	12.00	.0515	.0230
30	36.00	33.51	.0515	.0245
40	60.00	31.27	.1430	.1632
50	24.00	24.00	.1760	.1625
60	18.00	18.00	.0676	.1082
70	18.00	18.00	.0541	.0742
80	9.00	9.00	.0619	.0557
90	.00	.00	.0515	.0455
100	.00	.00	.0411	.0398
110	.00	.00	.0378	.0364
120	.00	.00	.0348	.0343
130	.00	.00	.0319	.0331
140	.00	.00	.0291	.0322
150	.00	.00	.0291	.0317
160	.00	.00	.0281	.0313
170	.00	.00	.0281	.0310
180	.00	.00	.0272	.0308

5) STORM EVENT DATED: 18-8-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0272	.0272
10	1.80	1.80	.0272	.0277
20	4.20	4.20	.0272	.0280
30	12.00	12.00	.0272	.0282
40	15.00	15.00	.0272	.0285
50	3.00	3.00	.0272	.0290
60	4.20	4.20	.0272	.0294
70	4.80	4.80	.0272	.0298
80	9.00	9.00	.0272	.0303
90	24.00	24.00	.0300	.0310
100	6.00	6.00	.0455	.0320
110	12.00	12.00	.0319	.0330
120	27.00	27.00	.0389	.0343
130	54.00	37.63	.0690	.0602
140	39.00	35.00	.1760	.1374
150	12.00	12.00	.1230	.1270
160	6.00	6.00	.1230	.1047
170	12.00	12.00	.0805	.0872
180	15.00	15.00	.0805	.0756
190	9.00	9.00	.0782	.0683
200	3.00	3.00	.0747	.0637
210	.00	.00	.0690	.0608
220	.00	.00	.0605	.0588
230	.00	.00	.0605	.0574
240	.00	.00	.0528	.0564
250	.00	.00	.0477	.0556
260	.00	.00	.0433	.0550
270	.00	.00	.0400	.0545
280	.00	.00	.0378	.0541
290	.00	.00	.0357	.0538
300	.00	.00	.0338	.0534

6) STORM EVENT DATED: 25-8-1990

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0094	.0094
10	3.00	3.00	.0094	.0096
20	1.80	1.80	.0094	.0097

30	7.20	7.20	.0094	.0096
40	15.00	15.00	.0094	.0095
50	24.00	24.00	.0094	.0094
60	39.00	39.00	.0094	.0090
70	72.00	39.93	.0760	.0773
80	24.00	24.00	.0827	.0864
90	3.00	3.00	.0688	.0693
100	1.80	1.80	.0547	.0522
110	1.20	1.20	.0373	.0392
120	.00	.00	.0300	.0301
130	.00	.00	.0240	.0238
140	.00	.00	.0167	.0194
150	.00	.00	.0147	.0162
160	.00	.00	.0120	.0140
170	.00	.00	.0094	.0123
180	.00	.00	.0094	.0111

7) STORM EVENT DATED: 5-7-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0011	.0011
10	45.00	45.00	.0013	.0012
20	21.00	21.00	.0013	.0013
30	2.40	2.40	.0013	.0015
40	.00	.00	.0013	.0016
50	.60	.60	.0020	.0017
60	4.20	4.20	.0020	.0019
70	7.80	7.80	.0020	.0020
80	7.80	7.80	.0020	.0021
90	8.40	8.40	.0020	.0023
100	7.80	7.80	.0027	.0024
110	6.00	6.00	.0027	.0026
120	9.00	9.00	.0027	.0027
130	.00	.00	.0027	.0029
140	.00	.00	.0027	.0031
150	.00	.00	.0033	.0032
160	.00	.00	.0033	.0033
170	.00	.00	.0033	.0034
180	.00	.00	.0033	.0034
190	.00	.00	.0033	.0035
200	9.00	9.00	.0033	.0035
210	54.00	54.00	.0033	.0037
220	69.00	54.21	.0192	.0292
230	54.00	50.00	.0907	.1032

240	3.00	3.00	.0747	.0815
250	3.00	3.00	.0503	.0569
260	.00	.00	.0367	.0405
270	.00	.00	.0272	.0301
280	.00	.00	.0192	.0235
290	.00	.00	.0127	.0192
300	.00	.00	.0127	.0163
310	.00	.00	.0127	.0143
320	.00	.00	.0127	.0130
330	.00	.00	.0075	.0120
340	.00	.00	.0075	.0114
350	.00	.00	.0075	.0109
360	.00	.00	.0075	.0105

8) STORM EVENT DATED: 7-8-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0127	.0127
10	7.80	7.80	.0127	.0130
20	.60	.60	.0127	.0132
30	.00	.00	.0127	.0134
40	.60	.60	.0127	.0134
50	1.80	1.80	.0127	.0134
60	1.20	1.20	.0127	.0135
70	3.00	3.00	.0127	.0135
80	.00	.00	.0127	.0136
90	27.00	27.00	.0166	.0139
100	102.00	68.53	.1067	.0959
110	69.00	62.96	.2933	.3176
120	63.00	57.92	.2733	.3563
130	45.00	45.00	.1853	.2281
140	30.00	30.00	.1267	.1509
150	1.20	1.20	.1067	.1107
160	.00	.00	.0907	.0887
170	.00	.00	.0840	.0761
180	.00	.00	.0800	.0685
190	.00	.00	.0773	.0638
200	.00	.00	.0753	.0607
210	.00	.00	.0733	.0587
220	.00	.00	.0720	.0572
230	.00	.00	.0707	.0561
240	.00	.00	.0693	.0552
250	.00	.00	.0680	.0545
260	.00	.00	.0667	.0540

270	.00	.00	.0653	.0535
280	.00	.00	.0647	.0530
290	.00	.00	.0647	.0526
300	.00	.00	.0647	.0523

9) STORM EVENT DATED: 8-8-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0647	.0647
10	72.00	37.42	.1760	.1561
20	48.00	34.81	.4127	.4485
30	18.00	18.00	.2900	.3181
40	12.00	12.00	.1760	.2079
50	9.00	9.00	.1477	.1486
60	9.00	9.00	.1267	.1171
70	6.00	6.00	.1067	.0999
80	6.00	6.00	.1020	.0902
90	.00	.00	.0973	.0846
100	.00	.00	.0933	.0812
110	.00	.00	.0900	.0791
120	.00	.00	.0867	.0777
130	.00	.00	.0833	.0767
140	.00	.00	.0807	.0760
150	.00	.00	.0780	.0755
160	.00	.00	.0760	.0751
170	.00	.00	.0740	.0748
180	.00	.00	.0720	.0745
190	.00	.00	.0700	.0742
200	.00	.00	.0687	.0740
210	.00	.00	.0673	.0738
220	.00	.00	.0660	.0736
230	.00	.00	.0653	.0734
240	.00	.00	.0647	.0732

10) STORM EVENT DATED: 9-8-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0647	.0647
10	1.20	1.20	.0647	.0659
20	22.20	22.20	.0647	.0668
30	63.00	37.54	.1243	.1286

40	45.00	34.92	.3777	.3101
50	12.00	12.00	.2510	.2563
60	21.00	21.00	.1682	.1930
70	24.00	24.00	.1383	.1530
80	4.80	4.80	.1250	.1297
90	10.20	10.20	.1187	.1161
100	1.80	1.80	.1133	.1082
110	1.20	1.20	.1087	.1033
120	.60	.60	.1041	.1001
130	.60	.60	.1005	.0980
140	.60	.60	.0987	.0964
150	1.20	1.20	.0939	.0953
160	.00	.00	.0912	.0943
170	.00	.00	.0875	.0936
180	.00	.00	.0857	.0928

11) STORM EVENT DATED: 15-8-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0067	.0067
10	3.00	3.00	.0073	.0069
20	3.00	3.00	.0073	.0070
30	.00	.00	.0073	.0071
40	3.00	3.00	.0073	.0071
50	6.00	6.00	.0073	.0072
60	.00	.00	.0073	.0073
70	.00	.00	.0073	.0074
80	.00	.00	.0073	.0075
90	12.00	12.00	.0077	.0076
100	30.00	30.00	.0086	.0080
110	60.00	60.00	.0096	.0091
120	78.00	64.52	.0329	.0232
130	72.00	59.33	.1407	.0992
140	72.00	54.63	.1784	.2635
150	42.00	42.00	.2480	.2204
160	18.00	18.00	.1660	.1608
170	21.00	21.00	.1333	.1213
180	13.20	13.20	.1067	.0977
190	18.00	18.00	.0907	.0839
200	4.80	4.80	.0853	.0760
210	7.80	7.80	.0827	.0713
220	1.80	1.80	.0807	.0685
230	.60	.60	.0800	.0666
240	.00	.00	.0800	.0653

12) STORM EVENT DATED: 16-8-1991

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0647	.0647
10	3.60	3.60	.0647	.0660
20	78.00	53.43	.0647	.1125
30	60.00	49.30	.2600	.2563
40	60.00	45.56	.3313	.3994
50	42.00	42.00	.3123	.3195
60	54.00	38.82	.2900	.2706
70	31.80	31.80	.2700	.2215
80	42.00	33.36	.2510	.1967
90	24.00	24.00	.2330	.1725
100	21.00	21.00	.2150	.1547
110	18.00	18.00	.1976	.1433
120	15.00	15.00	.1793	.1363
130	12.00	12.00	.1604	.1323
140	7.20	7.20	.1526	.1301
150	7.20	7.20	.1430	.1289
160	7.20	7.20	.1383	.1283
170	4.20	4.20	.1337	.1280
180	3.60	3.60	.1247	.1278
190	2.40	2.40	.1207	.1276
200	1.20	1.20	.1207	.1274
210	1.20	1.20	.1207	.1270
220	1.20	1.20	.1207	.1266
230	.60	.60	.1207	.1262
240	.60	.60	.1207	.1257
250	.00	.00	.1207	.1251
260	.00	.00	.1207	.1245
270	.00	.00	.1207	.1239
280	.00	.00	.1207	.1233
290	.00	.00	.1207	.1226
300	.00	.00	.1207	.1220

13) STORM EVENT DATED: 22-7-1992

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0477	.0477
10	1.80	1.80	.0477	.0485
20	4.20	4.20	.0477	.0480

30	.00	.00	.0477	.0467
40	.00	.00	.0477	.0435
50	.00	.00	.0477	.0388
60	12.00	12.00	.0477	.0361
70	42.00	42.00	.0477	.0342
80	60.00	40.19	.0633	.0714
90	60.00	37.32	.2800	.2989
100	39.00	34.72	.4567	.4773
110	33.00	32.14	.2800	.2911
120	18.00	18.00	.1656	.1736
130	10.20	10.20	.1233	.1132
140	4.80	4.80	.0827	.0809
150	9.00	9.00	.0629	.0627
160	33.00	23.30	.0544	.0680
170	1.80	1.80	.0500	.0620
180	.60	.60	.0469	.0541
190	.00	.00	.0453	.0477
200	.00	.00	.0440	.0430
210	.00	.00	.0427	.0397
220	.00	.00	.0400	.0374
230	.00	.00	.0387	.0359
240	.00	.00	.0373	.0348
250	.00	.00	.0360	.0341
260	.00	.00	.0347	.0335
270	.00	.00	.0333	.0331
280	.00	.00	.0320	.0328
290	.00	.00	.0310	.0326
300	.00	.00	.0301	.0324
310	.00	.00	.0291	.0323
320	.00	.00	.0281	.0322
330	.00	.00	.0272	.0321
340	.00	.00	.0272	.0320
350	.00	.00	.0272	.0319
360	.00	.00	.0272	.0319

14) STORM EVENT DATED: 28-7-1992

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0192	.0192
10	4.20	4.20	.0192	.0196
20	1.20	1.20	.0192	.0198
30	1.20	1.20	.0192	.0199
40	35.40	35.40	.0208	.0202
50	78.00	78.00	.0291	.0214

60	180.00	125.27	.1952	.1782
70	60.00	60.00	.1808	.2021
80	30.00	30.00	.1430	.1643
90	4.80	4.80	.1290	.1294
100	.00	.00	.1051	.1049
110	.00	.00	.0955	.0887
120	.00	.00	.0875	.0781
130	.00	.00	.0811	.0712
140	.00	.00	.0747	.0665
150	.00	.00	.0718	.0633
160	.00	.00	.0690	.0611
170	.00	.00	.0661	.0596
180	.00	.00	.0633	.0584
190	.00	.00	.0605	.0575
200	.00	.00	.0554	.0568
210	.00	.00	.0477	.0563
220	.00	.00	.0444	.0558
230	.00	.00	.0444	.0554
240	.00	.00	.0444	.0550

15) STORM EVENT DATED: 4-8-1992

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0367	.0367
10	54.00	27.17	.0843	.0866
20	27.00	25.38	.1656	.0935
30	1.80	1.80	.1067	.0829
40	2.40	2.40	.0690	.0716
50	1.80	1.80	.0661	.0628
60	.00	.00	.0633	.0566
70	.60	.60	.0619	.0523
80	.60	.60	.0605	.0494
90	28.20	17.56	.0661	.0648
100	.60	.60	.0647	.0661
110	.60	.60	.0633	.0621
120	.60	.60	.0619	.0576
130	.00	.00	.0579	.0539
140	.00	.00	.0541	.0511
150	.00	.00	.0503	.0491
160	.00	.00	.0477	.0477
170	.00	.00	.0455	.0466
180	.00	.00	.0411	.0459
190	.00	.00	.0367	.0454
200	.00	.00	.0367	.0449

210	.00	.00	.0367	.0446

16) storm event dated: 7-7-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0005	.0005
10	3.60	3.60	.0005	.0005
20	2.40	2.40	.0005	.0005
30	2.40	2.40	.0005	.0005
40	.00	.00	.0005	.0005
50	.00	.00	.0005	.0005
60	6.60	6.60	.0005	.0005
70	1.80	1.80	.0005	.0005
80	.00	.00	.0005	.0005
90	.00	.00	.0005	.0005
100	1.20	1.20	.0005	.0005
110	1.80	1.80	.0005	.0005
120	7.20	7.20	.0005	.0005
130	9.00	9.00	.0005	.0005
140	33.00	33.00	.0005	.0005
150	31.20	31.20	.0006	.0005
160	10.80	10.80	.0010	.0005
170	60.00	60.00	.0010	.0005
180	36.00	36.00	.0011	.0005
190	82.20	66.38	.0067	.0118
200	16.20	16.20	.0256	.0151
210	.60	.60	.0163	.0141
220	1.80	1.80	.0096	.0119
230	.00	.00	.0048	.0096
240	1.20	1.20	.0048	.0077
250	.00	.00	.0041	.0062
260	.00	.00	.0037	.0050
270	.00	.00	.0024	.0041
280	.00	.00	.0013	.0034
290	.00	.00	.0010	.0028
300	.00	.00	.0008	.0024
310	.00	.00	.0007	.0021
320	.00	.00	.0007	.0018
330	.00	.00	.0007	.0016

17) STORM EVENT DATED: 15-7-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0029	.0029
10	8.40	8.40	.0029	.0030
20	15.00	15.00	.0029	.0030
30	51.00	51.00	.0029	.0031
40	36.00	36.00	.0029	.0031
50	18.00	18.00	.0029	.0032
60	33.00	33.00	.0029	.0033
70	9.00	9.00	.0034	.0034
80	.60	.60	.0056	.0035
90	.60	.60	.0048	.0035
100	1.80	1.80	.0056	.0036
110	10.20	10.20	.0052	.0036
120	9.00	9.00	.0052	.0037
130	58.80	48.11	.0127	.0129
140	9.60	9.60	.0179	.0147
150	3.60	3.60	.0140	.0138
160	1.80	1.80	.0120	.0122
170	3.00	3.00	.0092	.0105
180	.00	.00	.0092	.0092
190	.00	.00	.0080	.0081
200	.00	.00	.0080	.0072
210	.00	.00	.0064	.0065
220	.00	.00	.0064	.0060
230	.00	.00	.0056	.0057
240	.00	.00	.0056	.0054

18) STORM EVENT DATED: 17-7-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0037	.0037
10	42.00	42.00	.0052	.0038
20	46.80	46.80	.0056	.0043
30	22.20	22.20	.0056	.0049
40	24.00	24.00	.0052	.0057
50	75.00	55.93	.0192	.0336
60	60.00	51.56	.1500	.1561
70	26.40	26.40	.1656	.1284
80	2.40	2.40	.0718	.0879

90	4.20	4.20	.0579	.0614
100	3.00	3.00	.0528	.0455
110	1.80	1.80	.0357	.0359
120	2.40	2.40	.0272	.0299
130	1.20	1.20	.0240	.0261
140	.60	.60	.0224	.0237
150	.00	.00	.0216	.0220
160	.00	.00	.0208	.0209
170	.00	.00	.0200	.0201
180	.00	.00	.0192	.0196
190	.00	.00	.0192	.0192
200	.00	.00	.0192	.0188
210	.00	.00	.0192	.0186

19) STORM EVENT DATED: 22-7-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0348	.0348
10	3.00	3.00	.0367	.0355
20	1.80	1.80	.0367	.0357
30	3.00	3.00	.0367	.0356
40	3.60	3.60	.0367	.0354
50	11.40	11.40	.0367	.0353
60	7.20	7.20	.0367	.0353
70	6.60	6.60	.0357	.0354
80	11.40	11.40	.0411	.0355
90	7.80	7.80	.0422	.0357
100	15.00	15.00	.0433	.0359
110	6.00	6.00	.0411	.0361
120	9.00	9.00	.0422	.0364
130	12.00	12.00	.0433	.0366
140	16.20	16.20	.0503	.0369
150	19.80	19.80	.0515	.0373
160	9.60	9.60	.0503	.0377
170	7.20	7.20	.0490	.0380
180	13.20	13.20	.0503	.0384
190	13.80	13.80	.0528	.0387
200	34.20	34.20	.0633	.0392
210	57.00	33.52	.1003	.0959
220	10.20	10.20	.1035	.1004
230	3.00	3.00	.0907	.0852
240	1.80	1.80	.0795	.0712
250	3.60	3.60	.0718	.0613
260	3.60	3.60	.0528	.0547

270	1.80	1.80	.0515	.0505
280	1.80	1.80	.0503	.0478
290	1.80	1.80	.0477	.0460
300	1.20	1.20	.0477	.0449

20) STORM EVENT DATED: 2-8-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0075	.0075
10	3.00	3.00	.0075	.0077
20	33.00	33.00	.0075	.0078
30	72.00	72.00	.0107	.0079
40	90.00	66.64	.0224	.0441
50	30.00	30.00	.0528	.0517
60	18.00	18.00	.0389	.0441
70	3.60	3.60	.0310	.0353
80	4.20	4.20	.0264	.0281
90	8.40	8.40	.0224	.0229
100	10.80	10.80	.0166	.0192
110	6.00	6.00	.0146	.0166
120	3.00	3.00	.0140	.0147
130	3.00	3.00	.0133	.0134
140	3.00	3.00	.0127	.0125
150	2.40	2.40	.0127	.0118
160	3.60	3.60	.0120	.0113
170	3.00	3.00	.0113	.0109
180	3.00	3.00	.0107	.0106

21) STORM EVENT DATED: 23-8-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0477	.0477
10	16.80	16.80	.0477	.0487
20	13.20	13.20	.0527	.0491
30	42.00	42.00	.0554	.0489
40	48.00	40.62	.0592	.0539
50	42.00	37.39	.0748	.0755
60	39.00	35.00	.0907	.1040
70	8.40	8.40	.0747	.0951
80	21.60	21.60	.0718	.0829
90	7.20	7.20	.0567	.0730

100	22.80	22.80	.0779	.0659
110	33.00	28.46	.0779	.0656
120	72.00	27.68	.3181	.2612
130	9.00	9.00	.2900	.2561
140	4.80	4.80	.2300	.1921
150	9.00	9.00	.1433	.1427
160	12.00	12.00	.1227	.1105
170	.60	.60	.0875	.0902
180	.00	.00	.0843	.0773
190	.00	.00	.0690	.0689
200	.00	.00	.0592	.0634
210	.00	.00	.0554	.0597
220	.00	.00	.0554	.0572
230	.00	.00	.0541	.0555
240	.00	.00	.0541	.0543

22) STORM EVENT DATED: 24-8-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0527	.0527
10	5.40	5.40	.0527	.0537
20	22.20	22.20	.0527	.0542
30	27.00	27.00	.0554	.0542
40	24.00	24.00	.0554	.0542
50	75.00	46.18	.1107	.1199
60	69.00	42.74	.4760	.4199
70	18.00	18.00	.3313	.3417
80	34.20	34.20	.2480	.2350
90	4.80	4.80	.1807	.1668
100	1.80	1.80	.1430	.1260
110	.60	.60	.1207	.1015
120	.00	.00	.1051	.0863
130	.00	.00	.1003	.0767
140	12.60	12.60	.0952	.0705
150	13.80	13.80	.0923	.0662
160	.00	.00	.0908	.0630
170	.00	.00	.0845	.0606
180	.00	.00	.0817	.0588
190	.00	.00	.0808	.0576
200	.00	.00	.0763	.0567
210	.00	.00	.0747	.0561
220	.00	.00	.0718	.0557
230	.00	.00	.0690	.0553
240	.00	.00	.0633	.0551

250	.00	.00	.0633	.0549
260	.00	.00	.0633	.0547
270	.00	.00	.0605	.0546
280	.00	.00	.0579	.0545
290	.00	.00	.0567	.0544
300	.00	.00	.0554	.0543

23) STORM EVENT DATED: 25-8-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0477	.0477
10	1.20	1.20	.0477	.0486
20	2.70	2.70	.0477	.0486
30	10.50	10.50	.0477	.0481
40	36.00	36.00	.0477	.0475
50	57.00	57.00	.0477	.0472
60	60.00	60.00	.0477	.0472
70	85.50	85.50	.0477	.0476
80	76.50	76.50	.0477	.0483
90	57.00	57.00	.0477	.0493
100	63.00	63.00	.0477	.0503
110	37.50	37.50	.0477	.0513
120	84.00	77.40	.0477	.0543
130	103.50	70.99	.1500	.1508
140	60.00	60.00	.1500	.1593
150	72.00	59.44	.1808	.1560
160	66.60	54.73	.2120	.2063
170	35.40	35.40	.1693	.1785
180	13.50	13.50	.1320	.1453
190	3.30	3.30	.1035	.1199
200	1.80	1.80	.0936	.1021
210	5.40	5.40	.0824	.0901
220	6.30	6.30	.0808	.0819
230	3.30	3.30	.0744	.0763
240	1.80	1.80	.0728	.0725
250	.00	.00	.0712	.0699
260	.00	.00	.0651	.0680
270	.00	.00	.0690	.0667
280	.00	.00	.0633	.0657
290	.00	.00	.0605	.0650
300	.00	.00	.0567	.0645

24) STORM EVENT DATED: 29-8-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.1383	.1383
10	.60	.60	.1383	.1404
20	7.80	7.80	.1383	.1403
30	6.60	6.60	.1383	.1397
40	75.00	45.12	.3400	.2553
50	75.00	41.78	.7878	.7596
60	41.40	38.47	.4803	.5227
70	24.60	24.60	.3667	.3420
80	3.60	3.60	.2510	.2592
90	.60	.60	.2330	.2204
100	.00	.00	.2030	.2009
110	.00	.00	.1976	.1904
120	.00	.00	.1952	.1842
130	.00	.00	.1904	.1801
140	.00	.00	.1856	.1771
150	.00	.00	.1832	.1748
160	.00	.00	.1760	.1728
170	.00	.00	.1708	.1710
180	.00	.00	.1682	.1694
190	.00	.00	.1682	.1678
200	.00	.00	.1682	.1663
210	.00	.00	.1630	.1649
220	.00	.00	.1630	.1635
230	.00	.00	.1630	.1621
240	.00	.00	.1578	.1608
250	.00	.00	.1552	.1595
260	.00	.00	.1552	.1582
270	.00	.00	.1552	.1569

25) STORM EVENT DATED: 2-9-1993

TIME (MIN.)	RAIN (MM/HR)	INFILT (MM/HR)	QOBS (CUMEC)	QSIM (CUMEC)
0	.00	.00	.0127	.0127
10	1.80	1.80	.0127	.0133
20	.60	.60	.0127	.0135
30	1.20	1.20	.0127	.0135
40	1.20	1.20	.0127	.0134
50	1.80	1.80	.0127	.0134

60	7.20	7.20	.0127	.0134
70	9.00	9.00	.0127	.0135
80	3.00	3.00	.0127	.0137
90	4.20	4.20	.0127	.0140
100	1.20	1.20	.0127	.0143
110	6.00	6.00	.0127	.0146
120	30.00	20.79	.0127	.0198
130	45.00	19.77	.0127	.0692
140	15.00	15.00	.0843	.0827
150	42.00	17.92	.1333	.1161
160	24.00	17.16	.2680	.1819
170	24.00	16.48	.2480	.2380
180	33.00	15.87	.2480	.3147
190	16.20	15.31	.3667	.3714
200	9.00	9.00	.3313	.3342
210	21.00	14.30	.2210	.2809
220	7.80	7.80	.2060	.2266
230	11.40	11.40	.2000	.1830
240	7.80	7.80	.1952	.1505
250	4.20	4.20	.2050	.1267
260	3.00	3.00	.1928	.1093
270	1.80	1.80	.1904	.0964
280	.00	.00	.1880	.0867
290	.00	.00	.1856	.0793
300	.00	.00	.1495	.0736
310	.00	.00	.1293	.0692
320	.00	.00	.1113	.0657
330	.00	.00	.0906	.0630

Appendix-C3- Rainfall Depth, Excess Rainfall (with ϕ-index and Variable Rainfall Infiltration Approach), Total Runoff and Runoff Percent of Jhandoo-Nala and Bhaintan Watersheds.

Sl.No.	Storm date/ Watershed	Total Rainfall (mm)	Total Excess Rainfall (mm)		Runoff (mm)	Total Runoff (%)
			ϕ-index	VIRM		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
[A]	JHANDOO-NALA WATERSHED					
1	4.7.1990	54.7	2.140	2.149	4.00	7.31
2	10.8.1990	27.5	1.172	1.175	3.34	12.15
3	18.8.1990	45.5	1.942	1.950	5.38	11.82
4	25.8.1990	32.0	1.142	1.150	1.72	5.38
5	5.7.1991	52.0	0.895	0.901	1.68	3.23
6	7.8.1991	58.7	4.044	4.050	7.96	13.56
7	8.8.1991	30.0	4.100	4.100	9.39	31.30
8	9.8.1991	34.9	3.139	3.142	7.92	22.69
9	15.8.1991	77.7	2.434	2.442	6.35	8.17
10	16.8.1991	78.7	6.492	6.500	12.13	15.41
11	22.7.1992	54.9	4.836	4.842	9.37	17.07
12	28.7.1992	65.8	3.519	3.524	6.24	9.48
13	15.7.1993	44.9	0.308	0.310	0.61	1.36
14	17.7.1993	52.0	1.804	1.812	2.72	5.23
15	22.7.1993	49.6	0.983	0.992	5.38	10.85
16	2.8.1993	50.0	0.558	0.566	1.16	2.32
17	23.8.1993	66.9	3.767	3.775	8.01	11.97
18	24.8.1993	51.4	4.882	4.892	9.87	19.20
19	25.8.1993	157.3	2.780	2.791	7.96	5.06
20	29.8.1993	39.2	6.522	6.525	20.14	51.38
[B]	BHAINTAN WATERSHED					
21	14.8.1979	53.0	0.586	0.581	1.41	2.66
22	2.9.1980	105.9	3.347	3.288	9.00	8.50
23	13.7.1981	186.5	6.113	6.010	15.91	8.53
24	5.8.1982	61.7	0.653	0.658	4.88	7.91
25	20.8.1982	90.2	1.013	1.046	5.37	5.95

Appendix-C4- Information Regarding Rain Storms Registered at Jhandoo-Nala Watershed.

Sl. No.	Date	Total Storm Depth (mm)	Storm Duration (hrs)	Runoff (mm)	Runoff Rainfall Factor (%)	Average Rainfall intensity (mm/hr)	Peak Flow rate (lps)	API (mm)	Base Flow (%)
1	4.7.90	54.7	4.5	4.000	7.31	12.16	150.0	164	12.67
2	10.8.90	27.5	2.0	3.342	12.15	13.75	122.7	247	27.20
3	11.8.90	31.5	2.5	5.710	18.10	12.60	126.0	260	38.90
4	16.8.90	34.5	1.5	3.376	9.79	23.0	176.1	385	21.60
5	18.8.90	45.5	3.5	5.233	11.50	13.00	176.1	375	27.20
6	25.8.90	32.0	2.0	1.817	5.68	16.0	82.7	201	9.40
7	5.7.91	52.0	4.5	1.370	2.63	11.56	90.67	55	1.1
8	7.8.91	58.7	2.5	7.961	13.56	23.48	293.4	172	12.7
9	8.8.91	30.0	1.5	9.393	31.31	20.0	412.9	249	64.7
10	9.8.91	34.9	2.5	7.922	22.70	13.96	377.7	381	64.7
11	15.8.91	77.7	4.0	6.058	7.80	19.43	248.0	181	6.7
12	16.8.91	78.7	3.0	12.127	15.41	26.23	331.5	308	64.7
13	22.7.92	54.9	3.0	8.787	16.00	18.30	456.9	245	47.7
14	28.7.92	65.8	1.5	6.238	9.48	43.87	195.2	297	19.2
15	4.8.92	19.7	2.0	5.322	27.02	9.85	165.7	478	36.7
16	15.7.93	44.9	3.0	0.592	1.32	14.97	17.87	198	2.9
17	17.7.93	52.0	2.5	2.814	5.41	20.80	165.7	212	3.7
18	22.7.93	49.6	5.0	5.375	10.84	9.92	103.35	287	34.8
19	2.8.93	50.0	3.0	1.161	2.32	16.67	52.8	215	7.5
20	23.8.93	66.9	3.0	8.008	11.97	22.30	318.2	149	47.7
21	24.8.93	51.4	2.5	9.871	19.20	20.56	476.2	268	52.7
22	25.8.93	157.3	4.0	7.96	5.06	39.36	212.00	416	47.7
23	29.8.93	39.2	1.5	15.137	38.61	26.13	545.2	375	138.5
24	2.9.93	55.4	4.5	14.801	26.72	12.31	366.9	470	12.67
25	8.9.93	26.8	1.0	4.204	15.69	26.80	297.0	391	49.0
26	9.9.93	50.8	3.0	6.474	12.74	16.93	227.1	365	36.7

Appendix-C5- Information Regarding Rain Storms Registered at Bhaintan Watershed.

Sl. No.	Date	Storm Duration (hrs)	Total Rainfall depth (mm)	Total Storm Runoff (mm)	Runoff Rainfall factor (%)	Average Rainfall intensity during Storm (mm/hr)	Peak Flow Rate (lps)	Base Flow
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	14.8.79	4.5	53.1	1.37	2.58	11.80	528.5	31.0
2	2.9.90	5.0	105.9	9.61	9.07	21.18	1494.10	253.5
3	13.7.81	8.0	182.7	15.85	8.68	22.84	3106.0	41.3
4	29.7.82	2.5	47.7	4.73	9.92	19.08	1320.7	14.0
5	20.8.82	4.5	90.2	5.37	5.95	20.04	1029.0	248.1

APPENDIX-D

Appendix-D1-Amount of Rainfall, Total Runoff, Surface Runoff, Sub-surface Runoff for Various Rainfall Events at the Two Watersheds.

Event date	Rain depth (mm)	Total runoff mm (%)	Surface runoff mm (%)	Sub-surface mm (%)
Bhaintan watershed :				
14.8.1979 to 16.8.1979	238.4	67.7 (28.4)	13.34 (1.4)	64.37 (27.0)
21.7.1980	74.0	35.08 (47.4)	3.50 (4.73)	31.58 (42.67)
Sahastradhara watershed:				
4.7.1990 6.7.1990	54.7	23.2 (43.0)	1.17 (2.14)	22.35 (40.86)
7.7.1990 to 9.7.1990	85.5	33.00 (38.6)	5.70 (6.67)	27.30 (31.93)
18.7.1990 to 19.7.1990	38.5	25.86 (67.17)	3.36 (8.73)	22.50 (58.44)
20.7.1990 to 22.7.1990	46.0	30.30 (65.87)	3.22 (7.00)	27.08 (58.87)

Appendix-D2- Rainfall Depth, Duration of Rainfall and Duration of Runoff in Small Mountainous Watersheds Under Study.

Event dates	Rainfall depth (mm)	Rainfall duration (hr)	Runoff duration (hr)
Bhaintan watershed			
14.8.1979 to 16.8.1979	238.4	14.0	60.5
20.7.1980 to 22.7.1980	183.6	12.0	40.5
Sahastradhara watershed			
4.7.1990 to 6.7.1990	54.7	4.5	28.0
7.7.1990 to 9.7.1990	85.5	8.0	32.0
18.7.1990 to 19.7.1990	38.5	2.67	22.0
20.7.1990 to 22.7.1990	46.0	0.83	41.5

Appendix-D3- Percentage of Land in the Bhaintan Watershed Under Different Slope Groups.

Slope %	Slope group	% of total area
15-25	Moderately steep to steep	3
26-33	Steep	5
34-50	Very steep	20
51-100	Very very steep	56
>100	Extremely steep	16

Appendix-D4- Morphometric Characteristics of Bhaintan Watershed

Sl. No.	Description	Value
1.	Average aspect	NE
2.	Average slope	71.6 Percent
3.	Bifurcation ratio	4.86 , 7
4.	Drainage density	5.2 km/km^2
5.	Form factor	0.39
6.	Compactness coefficient	1.28
7.	Circulatory ratio	0.60
8.	Elongation ratio	0.70
9.	Ruggedness number	7.1
10.	Length of overland flow	0.1 km
11.	Drainage pattern	dendritic
12.	Shape of the watershed	elongated

Appendix-D5- Average Annual Rainfall, Annual Runoff and Runoff Per cent at Bhaintan Watershed (16 Years).

Water year	Average annual rainfall (mm)	Annual Runoff (mm)	Runoff (%)
June1975-May76	1959.8	823.1	42.0
June1976-May77	1532.8	337.2	22.0
June1977-May78	1837.2	N.A.	N.A.
June1978-May79	2273.3	886.6	39.0
June1979-May80	1653.0	248.0	15.0
June1980-May81	1651.2	495.4	30.0
June1981-May82	2711.0	N.A.	N.A.
June1982-May83	1705.0	145.0	8.5
June1983-May84	1395.0	48.0	3.4
June1984-May85	1970.0	256.0	13.0
June1985-May86	2568.0	388.4	15.1
June1986-May87	2254.0	320.0	14.2
June1987-May88	1325.0	7.7	0.6
June1988-May89	1730.0	211	12.2
June1989-May90	2090.8	318	15.2
June1990-May91	1871.0	287	15.3

Average annual rainfall of the watershed is 1908 mm

Appendix-D6- Average Annual Rainfall, Number of Rainy Days and Maximum Rainfall Intensities Recorded for Different Durations at Bhaintan Watershed.

Water year	Average annual rainfall (mm)	No. of rainy days	Maximum rainfali intensities recorded (mm/hr) 5 min	10 min	15 min	30 min	60 min
June1975-May1976	1959.8	107	108	90	80	64	39
June1976-May1977	1532.8	97	108	90	81	64	60
June1977-May1978	1837.2	115	192	138	110	110	74
June1978-May1979	2273.3	120	132	105	92	76	60
June1979 May1980	1653	77	100	84	72	55	45
June1980 May1981	1651.2	129	192	144	128	110	100
June1981 Dec.1981	1405.3	76	124	92	82	51	43

Appendix-D7- Average Daily Relative Humidity (Percentage) for Different Months in Bhaintan Watershed.

Name of month	Water years 1976-77	1977-78	1978-79	1979-80	1980-81	1981-82
June	N.A.	75.8	63.8	60.0	69.3	59.3
July	88.7	91.4	71.8	82.0	84.5	79.5
August	88.7	89.6	79.7	85.0	80.4	81.6
Sept.	83.7	85.3	76.5	71.0	71.6	61.3
Oct.	78.5	71.4	70.1	57.0	61.8	52.4
Nov.	65.0	76.5	65.3	50.0	55.5	74.3
Dec.	60.7	77.4	59.3	58.0	57.3	61.6
Jan.	63.3	48.0	63.0	61.4	65.1	N.A.
Feb.	52.8	69.8	62.0	54.9	49.6	N.A.
March	42.7	78.6	53.0	54.4	49.6	N.A.
April	64.5	61.1	50.0	40.2	47.2	N.A.
May	66.2	53.8	42.0	37.3	43.5	N.A.

N.A. = Not available

Appendix-D8- Average Maximum and Minimum Daily Temperatures for Different Months in Bhaintan Watershed.

Name of month	Average maximum temperature (^oC)	Average minimum temperature (^oC)
January	19.0	6.0
February	20.0	12.5
March	22.5	16.5
April	32.0	20.0
May	34.0	25.0
June	31.0	24.0
July	28.0	22.5
August	27.0	22.0
September	29.0	23.0
October	25.0	21.0
November	22.0	18.0
December	19.0	15.0

Appendix-D9- Average Daily Evaporation (mm) for Different Months in Bhaintan Watershed.

Name of month	1976-77	1977-78	1978-79	1979-80	1980-81	1981-82
June	6.9	6.7	6.3	8.0	4.7	9.1
July	3.6	3.1	3.8	3.9	2.6	2.9
August	2.8	3.3	2.3	2.4	3.0	3.6
September	3.7	2.9	2.9	4.2	3.4	4.0
October	3.7	3.2	3.2	4.1	3.6	4.0
November	2.9	2.6	2.4	3.3	2.9	2.7
December	2.3	2.3	1.8	2.0	2.0	2.2
January	1.7	2.1	1.7	2.0	1.7	NA
February	3.6	2.5	2.9	3.0	2.7	NA
March	6.8	3.3	3.8	4.5	3.8	NA
April	6.4	6.2	7.4	8.7	6.5	NA
May	6.8	8.4	8.2	9.9	8.9	NA

NA = Not availabe.

Appendix-D10- Percntage of Total Area, Bulk Density, Water Holding Capacity and Available Water Holding Capacity of Soils Under Different Soil Series in Bhaintan Watershed.

Soil series	Area under the soil series (ha)	Total % of area	Bulk density (g/cc)	Water holding capacity (%)	Available water holding capacity (%)
Malas	54.4	20	1.07	54.4	15.2
Pata	87.04	32	1.07	57.0	14.2
Katkore	81.6	30	1.11	47.4	12.4
Bhaintàn	13.60	5	1.05	57.4	18.9
		Miscellaneous land types			
Rocks	32.64	12	-	-	-
Rock cut and land slide debris	2.72	1.0	-	-	-
Total	272.0	100.0			

Appendix-D11- Present Land Use of Bhaintan Watershed Upto Ghursera (as per Survey Conducted by Bhardwaj et al., 1974).

Description of land use	Symbol	Area (ha)	Percentage of total area (%)
Wasteland unfit for agriculture	W_2	131.5	48.4
Cropped area-			
cropping at intervals	Co	5.0	1.8
Single cropped area	C_2	50.5	18.6
Double cropped area	C_3	5.0	1.8
Forest Area-			
No cauopy (forest)	Fo	28.3	10.4
Thin forest	F_1	12.8	4.7
Moderate deuse forest	F_2	38.5	14.1
Orchard	O	0.4	0.2
Total		272.0	100.0

Appendix-D12-Physico-Chemical Characteristics of Sahastradhara Mine-spoil/Debris and its Comparision with Normal Soils of Dhoolket, Dehradun.

Characteristic and unit	Geojute project area*	Normal soils ** Dhoolkot,Dehradun
Textural class	sl (Sandy loam)	sicl
Sand(%)	66.6	40.0
Silt (%)	19.5	38.0
Clay (%)	13.9	23.0
pH	8.1	5.8-6.5
Organic Carbon (%)	0.25	0.65
Calcium Carbonate (%)	68.1	NA
Total Nitrogen (%)	0.016	0.08
Available P_2O_5(Kg/ha)	3.78	28.0
Available K_2O (kg/ha)	44.1	225.50

*(Dhruva Narayana et al, 1987) **(Singh et al, 1976)

NA- Not Available

Appendix-D13- Monthly, Annual and Average Rainfall (mm) Jhandoo-Nala Watershed.

Water year	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
1984-85	606.0	1019.0	609.0	434.0	0.0	0.0	0.0	142.0	8.0	14.0	24.6	56.5	2913.1
1985-86	148.3	1139.5	1275.3	435.7	163.5	0.0	65.0	13.0	86.7	27.5	25.9	102.9	3483.3
1986-87	250.0	1048.6	1059.3	243.1	126.7	7.6	37.8	87.8	62.0	22.5	10.5	102.5	3058.4
1987-88	29.0	487.0	614.0	235.6	36.9	0.0	12.2	4.3	36.8	23.3	42.8	10.7	1533.3
1988-89	406.6	678.5	725.6	258.1	0.0	0.0	57.0	64.5	34.8	32.0	4.5	12.5	2274.1
1989-90	164.1	676.0	561.6	346.0	25.6	34.5	67.0	0.0	128.8	109.5	41.5	140.6	2295.2
1990-91	337.6	963.2	779.1	357.7	56.3	6.1	99.0	12.7	40.7	64.7	41.4	27.0	2785.5
1991-92	255.7	318.5	844.5	447.4	0.0	9.5	0.0	92.8	40.0	16.3	0.0	55.5	2080.2
1992-93	135.3	810.8	1455.2	288.1	0.0	0.5	0.0	60.2	53.5	134.7	78.5	70.8	3087.6
1993-94	166.8	760.8	1037.1	597.4	0.0	2.5	0.0	61.0	64.3	0.0	40.5	0.0	2730.4

Average railfall 2624mm

(10 years average)

Appendix-D14- Average Annual Rainfall, Monsoon Rainfall, Number of Rainydays and Maximum Rainfall Intensities Recorded for Different Durations at Jhandoo-Nala Watershed.

Water year	Monsoon Rainfall (mm)	Average Annual Rainfall	No. of Rainy Days	Maximum Rainfall Intensites (mm/hr)						
				5 min	10min	15min	20min	30min	60min	120min
June 1984-May 1985	2668.0	2913.0	76	180	120	96	90	80	72	40
June 1985-May 1986	2998.0	3483.3	83	240	180	142	120	110	8 2	60
June 1986-May 1987	2601.0	3058.4	73	240	180	150	132	120	110	80
June 1987-May 1988	1366.3	1533.3	53	141	126	112	101	98	69	51

Appendix-D15- Monthly Average Rainfall, Rainy Days, Evaporation, Temperature and Sunshine Hours at Rajpur near Sahastradhara (Dehradun District).

Month	rainfall (mm)	rainy days	daily velocity (km/hr)	daily evap. (mm.)	temp. (max.)	(°C) (min.)	daily sunshine (hrs/day)
January	69.3	4	1.5	1.6	20.2	3.6	7.7
February	6.8	6	1.9	2.9	23.6	5.7	7.9
March	43.2	5	2.2	4.3	28.4	9.0	8.7
April	24.4	3	3.0	7.0	34.4	13.6	9.1
May	39.4	4	3.4	9.1	36.2	16.6	10.2
June	246.1	9	2.8	7.0	37.2	22.1	8.0
July	968.0	22	1.6	3.7	32.2	23.6	3.4
August	1058.90	24	1.2	3.2	30.5	23.1	5.4
September	392.40	12	1.3	3.6	31.1	20.9	7.5
October	43.90	3	1.1	2.9	29.6	12.9	9.5
November	9.10	2	1.1	2.1	25.1	6.5	8.6
December	25.7	3	1.2	1.5	22.2	3.6	7.7
Total	2968.0	97					

Appendix D-16(a)-

The main vegetation found in the forest area of Bhaintan watershed are listed below. The local names are given within the brackets.

a) Trees :

Quercus incana (Banjh), Grewia optiva (Bhimal), Terminalia tomentosa (Asain), Adina cordifolia (Haldu), Pyrus pashia (Mole), Cedrella toona (Toon), Anogeissus latifolia (Dhaura), Ougeinia dalbergioids (Sandhan), Boehameria regulosa (Gainthee), Acacia catechu (Khair), Bombax ceiba (Semal), Bauhinia retusa (Gond), Ficus roxburghii (Timla), Cassia fistula (Amaltas), Erythrina suberosa (Madara), Myrica nagi (Kaphal), Butea frondosa (Dhak), Rhododendron arboreum (Buras), Sterculia pallens (Khardala), Oougeinia ogeinesis (Sandhan) etc.

b) Shrubs:

Mimosa himalayana (Kingrai), Vitex negundo (Samalu), Hamiltonia suaveolens (Padora), Carissa opaca (Karonda), Berberis asiatica (Kingor) Murraya koenigii (Gandhela), Calotropis procera (Aak), Adhatoda vasica (Bansa), Cocculus laurifolius (Tilfara), Lantana camara, Woodfordia floribunda (Dhaula) Agave americana (Rambans), Zizyphus sp. (Ber), Rhus cotinus (Tungla), Artemisia nilagarica (Kunja), Euphorbia royleana (Thore) etc.

c) Grasses:

Chrysopogon fulvus, Dichanthium anulatum, Eulaliopsis binata, Cynodon dactylon, Erogrostis curvula, Apluda mutica, Desmodium sp., Heteropogon contertus, Lepida-gathis sp., Themeda anathera, Arundinella nepalensis etc.

APPENDIX-D16(b)-

Under forest vegetation there are two types of vegetation, namely natural and artificial or with human efforts (Planted and sown). The details of vegetation found in Jhandoo-Nala watershed is given below.

I) **Natural Vegetation**

Natural vegetation in the watershed comprises of tree species, shrubs and grasses, which are given below (Local names of the species are given within the brackets) :

Tree Species :

Cedrella toona (Toon), Acacia catechu (Khair), Bauhinia retusa (Gond), Bauhinia variagata (Kachnar), Erythrina Suberosa (Madara), Bombax ceiba (Semal), Sapium insigne (Chirni), Lannea grandis (Jhingan), Terminalia bellerica (Bahera), Butea frondosa (Dhak), Ficus roxburghii (Timla), Adina cardifolia (Haldu), Emblica Officinalis (Amla), Celtis caucasica (Kharik), Albizzia lebbek (Siris), Salix tetrasperma (Semla), Grewia Optiva (Bhimal), Mallotus philippinensis (Raini) etc.

Shrubs : Following shrub species are found in Jhandoo-nala watershed :

Vitex negundo (Samalu), Lantana camara, Murraya koenigii (Gandhela), Eupatorium glandulosum, Adhatoda vasica (Bansa), Berberis asiatica (Kingor), Rhus parviflora Euphorbia royleana etc.

Grasses : Following grass species are found in Jhandoo-Nala watershed :

Chrysopogon fulvus, Apluda mutica, Saccharum sp., Cynodon dactylon, Erogrostis sp., Heteropogon sp., Desmodium sp. etc.

ii) Artificial Vegetation :

Vegetation established through human efforts eg. by sowing and planting of different species : species of tree, shrubs and grasses are given below which have been planted are sown inn the watershed.

Tree Species :

Dalbergia sissoo (Shisham), Albizzia lebbek (Siris), Cedrella toona (Toon), Sapium insigne (Chirni), Lannea grandis (Jhingan), Bombax ceiba (Semal), Bauhinia variagata (Kachnar), Eucalyptus hybrid, Acacia catechu (Khair), Mangifera indica (Mango), Psidium guava (Guava), Emblica Officinalis (Amla), Erythrina suberosa (Madara), Salix tetrasperma (Semla). Leucaena leucocephala (subabul) etc.

Shrub species :

Arundo donax (Narkul), Vitex negundo (Samalu), Ipomoea carnea (Besharm).

Grass species :

Chrysopogon fulvus, Saccharum spontaneum (Kans) Hybrid napier (Hathi ghas), Eulaliopsis binata (Bhabhar), Kudzu etc.

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