SCS-CN BASED LONG TERM HYDROLOGIC SIMULATION

A THESIS

Submitted in partial fulfilment of the
requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY
in
HYDROLOGY

by

DILIP G. DURBUDE

DEPARTMENT OF HYDROLOGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)
SEPTEMBER, 2010

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **SCS-CN BASED LONG TERM HYDROLOGIC SIMULATION** in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the **Department of Hydrology of the Indian Institute of Technology Roorkee, Roorkee** is an authentic record of my own work carried out during the period from August 2007 to September 2010 under the supervision of Dr. M. K. Jain, Assistant Professor, Department of Hydrology and Dr. S. K. Mishra, Associate Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee.

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

(DILIP G. DURBUDE)

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

(S.K. MISHRA)
Supervisor

(M.K. JAIN)
Supervisor

Date: September 23rd, 2010

The Ph.D. viva-voce Examination of **Mr. Dilip G. Durbude**, Research Scholar, has been held on________________

Signature of Supervisors

Signature of External Examiner

ABSTRACT

The hydrologic cycle is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and hydrosphere. Continuous accounting of this movement of water involves consideration of precipitation, surface loss, infiltration, and surface transport processes as a part of surface flow process and evapotranspiration, soil moisture redistribution, and ground water transport as a part of sub-surface flow. The Soil Conservation Service Curve Number (SCS-CN) method which is based on proportionality and water balance hypotheses has been widely used in the past to model the surface flow component via direct surface runoff of hydrologic cycle. Though the SCS-CN method was initially developed for computation of surface runoff from isolated storm events, it has been successfully employed in several long term hydrologic simulation (LTHS) models by accounting for the soil moisture status at previous time steps. Of late, Michel et al. (2005) critically reviewed the soil moisture accounting (SMA) procedure lying behind the original SCS-CN method and proposed a procedure more consistent from SMA view point. They pointed out several structural inconsistencies in the existing SCS-CN methodology, and in treatment of the antecedent soil moisture condition (AMC). A rigorous scrutiny of the procedure proposed by Michel et al. reveals a need for refinement particularly in defining the initial moisture level (V_0) and the proposed SMA procedure. Hence, in this study, this SMA procedure is modified in different ways by re-casting and re-conceptualization; by incorporating variation of daily CN based on antecedent moisture amount (AM) and moisture availability prior to rainfall to avoid unrealistic sudden jump in computation of V_0 and further quantum jump in computation of direct runoff to make the SMA procedure amenable to continuous hydrologic simulation.

In the existing SMA based long-term simulation models, the SMA concept based on SCS-CN method is used for computation of surface flow only and the potential of its extension to sub-surface flow computation has yet to be explored. There are numerous models, and programmes existing in literature for modeling sub-surface flow. For examples, Water and Agrochemicals in the Soil, Crop and Vadose Environment (WAVE) (Vanclooster

et al., 1996), Soil Water Assessment Programme (SWAP) (Van Dam et al., 1997), DRAINMOD (Skaggs, 1980), Yuan et al. (2001) model, Base flow separation techniques and programmes, etc. Among these, Yuan et al. (2001) model uses the SCS-CN method to model sub-surface flow by modifying it through analogy for estimation of sub-surface drainage flow from rainfall. Their conceptual frame-work is further modified in this study to simulate the sub-surface flow components. In addition, the stores which are common component of rainfall-runoff model are used to route surface and sub-surface flow (for example, Putty and Prasad's (2000) two-stores SAHYADRI model, Mishra and Singh (2004a) versatile two-stores model, and Geetha et al. (2007) LCRR three-stores model, etc.). The single linear reservoir (SLR) is used to route surface flow and the exponential store as described by Putty and Prasad for sub-surface flow.

In the present study, the above three concepts of Michel et al., Yuan et al., and Putty and Prasad are amalgamated, and four new/modified LTHS models proposed to carry out the long term hydrologic simulation. The first model (Model-I) is designated as LTHS MICHEL I and it uses the expressions proposed by Michel et al. (2005) for soil moisture store level prior to rainfall occurrence (V_0) for various antecedent moisture conditions (AMCs), via AMC I, II, and III based on the antecedent rainfall to compute direct runoff (RO) and sub-surface flow computation based on the conceptual behavior of soil moisture store (SMS) and ground water store (GWS) as given by Putty and Prasad (2000). The second model (Model-II), designated as LTHS MICHEL II, is formulated based on AM due to 5 days antecedent rainfall (prior to the storm) to avoid sudden jump in CN and further quantum jump in V_0 and, in turn, the modification in the computation of RO. In the previous two LTHS models, V_0 plays a vital role in the improvement of SMA procedure via improvement in surface flow components. Despite this improvement, these models, however, do not contain any expression for V_0. Therefore, in the third model (Model-III), designated as LTHS ASMA I, where ASMA stands for Advance Soil Moisture Accounting, an expression for V_0 is proposed based on the value of pre-antecedent moisture level before the onset of rainfall (V_{00}). This forms the advanced soil moisture accounting (ASMA) procedure. In both, LTHS MICHEL II and LTHS ASMA I models, the sub-surface flow components are modeled similar to LTHS MICHEL I model. The fourth model (Model-IV), designated as LTHS ASMA II, is similar to Model-III (LTHS ASMA I) for surface runoff computation but differs in computation of sub-surface drainage

flow. In this model, apart from use of ASMA procedure, an expression for sub-surface drainage flow is developed by modifying the concept of Yuan et al.

In all these models, the total stream flow from watershed is quantified by incorporating sub-modules for surface and sub-surface flow components such as surface runoff, evapotranspiration, sub-surface drainage, lateral flow, percolation, base flow, and deep percolation. These models were tested for their performance using daily hydro-meteorological annual and seasonal (monsoon season from June to November) data series of 17 watersheds of various sizes/shapes and physical characteristics, and located in various agro-climatic zones of India. The available data was split into two groups, one for calibration and the other for validation using non-linear Marquardt (1963) algorithm by minimizing the sum of squares of the errors between observed and model computed runoff. The performance of these models was evaluated using different statistical criteria such as Nash-Sutcliffe efficiency (NSE), standard error (SE), and relative error (RE). For performance evaluation, the study watersheds were grouped into three categories depending on the runoff coefficient (C) (Gan et al., 1997, Geetha et al., 2008)) as dry ($C \leq 0.36$), average ($0.36 < C < 0.65$), and wet ($C \geq 0.65$). It is found that all the proposed models perform very good on the data of wet watersheds, good to satisfactory on normally dry watersheds, and poorly in most dry watersheds and are capable of capturing the variability of curve numbers representing hydrological characteristics of the complex watersheds. Among the proposed models, the LTHS ASMA II model produces better results than others, followed by LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models. The existing lumped continuous SCS-CN based long term simulation models such as Michel et al. (2005) and Geetha et al. (2008) models were also tested on annual data series of study watersheds. When compared, the best performing model LTHS ASMA II also worked better than the existing models.

The performance of the proposed LTHS models is also analyzed on the basis of subjective assessment through visual comparison between the observed and simulated runoff. The results were plotted for calibration and validation for all the models for all study watersheds, showing a close match between simulated and observed stream flows for most of the watersheds except for some deviation in simulating peak flows. Since the models also help understand and identify various processes/components involved in runoff generating mechanism, these components are quantified to compare their significance in various high/low runoff potential watersheds. For example, the base flow is more significant in high runoff producing coastal watersheds than low runoff producing watersheds in the study, while the evapotranspiration shows reverse trends. All other components except deep percolation show linearly increasing trends with runoff coefficient and are more significant/dominant in high runoff producing watersheds. Deep percolation is dormant in high runoff producing watersheds.

The sensitivity analysis of the above better performing 15- parameter LTHS ASMA II model indicates that the coefficient (γ), related with pre-antecedent soil moisture store level (V_{00}), most sensitive parameter among all other parameters, while the curve numbers at the starting day of simulation for surface flow (CN_0) and sub-surface drainage flow (CNd_0) are also highly sensitive, in addition to the parameters related with soil characteristics, wilting point (θ_w) and field capacity (ψ_f). An effort was also made to minimize the number of parameters by fixing the insensitive or less sensitive parameters based on statistical analysis and this, in turn, resulted in formulation of a nine-parameter simplified LTHS ASMA SIMP model. The LTHS ASMA SIMP model performed as well as did ASMA LTHS II model, but with little reduction in model efficiency. For pragmatic application, model parameters are also related with measurable physical characteristics of the watersheds using step-wise backward elimination procedure via p-value of F-statistic of multiple regression analysis. In most cases, the parameters exhibited a good relationship.

Keywords: Antecedent moisture condition, curve number, initial soil moisture level, long term hydrologic simulation models, SCS-CN, soil moisture accounting procedure, stream flow, watershed.

ACKNOWLEDGEMENTS

First and foremost I want to thanks and express my deep sense of gratitude and indebtness to my supervisor, **Dr. M. K. Jain,** Assistant Professor, Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee for his keen interest, persistent guidance, and continuous encouragement throughout this research work. His extraordinary efforts, ideas, contribution of time, continuous support and constructive criticism made my Ph.D. experience productive, stimulant and completing this work in an enjoyable manner.

With respect and gratitude I express my sincere thanks to my supervisor **Dr. S. K. Mishra,** Associate Professor, Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee for his invaluable guidance, meticulous observations, personal interest, and co-operation at every stage of investigation. His wide knowledge and logical way of thinking contribute a lot in the present research work.

I am highly grateful to the members of research committee, Prof. D. K. Srivastava and Prof. Ranvir Singh, Dept. of Hydrology and Prof. C. S. P. Ojha, Civil Engineering Dept., Indian Institute of Technology Roorkee, Roorkee for their suggestions and support.

I express my sincere thanks to Prof. Himanshu Joshi, Head, Dept. of Hydrology, and Prof. N. K. Goyal, Dean of Student Welfare, Indian Institute of Technology Roorkee, Roorkee for providing me the necessary administrative supports during this research work.

I am extremely grateful to Sri R. D. Singh, Director, National Institute of Hydrology, Roorkee for his inspiring supports and encouragement. Thanks are also due to him for providing all the necessary official support and facilities.

I also express my cordial thanks to Dr. V. K. Choubey, Head, Environmental Hydrology Division, National Institute of Hydrology, Roorkee for being very supportive and considerate making it possible for me to concentrate on my research work.

I thankfully acknowledge the help by the fellow researchers Mr. Sunil Maske, Mr. Deepak Zhazaria, Mr. Mohanti, Mr. Rao, Mr. Vinit Jain, Mr. Sohan Singh, Mr. Anil Kar, Mr. Ravindra Kale, Mr. Vaibhav Gosai, and my respected colleagues, Mr. Omkar Singh, Dr. M. K. Sharma, Mr. Suhas Khobragade and all others from National Institute of Hydrology, Rookee for their direct and indirect help at various stages of this research work. I also thankfully acknowledge the help by the colleagues from Regional Centre, National Institute of Hydrology, Belgaum (Karnataka), India.

It gives me immense pleasure to express my special thanks to my wife **Pravada**, whose technical and moral support, continuous loving care, and wholehearted co-operation helped me a lot to complete this research work efficiently, and therefore I dedicate this research work to her. I especially thankful to my daughter **Gargi** and my son **Ayush** for bearing with me for the inconvenience caused, while I was busy working on this thesis. I also thankful to all my relatives and friends who helped me during the course of this research work.

I bow my head with great reverence to my parents Sri Govindrao Durbude and Smt. Sita Durbude and grandmother-in-law Smt. Nira Thakare, father-in-law Sri Subhashrao Bharatkar and mother-in-law Dr. Jyoti Bharatkar for their good wishes, invocation and enthusiasm throughout this research work.

I further bow my head in great faith and reverence before the great **ALMIGHTY SADGURU SRI SAI BABA**, whom I have worshipped.

Roorkee

Date 23rd Sept., 2010

(D. G. DURBUDE)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF NOTATIONS

ABBREVIATIONS

Agril.	Agricultural
AMA	Antecedent moisture amount
AMC	Antecedent moisture condition
Ame.	American
amsl	Above mean sea level
Appl.	Applied
ASAE	American Society of Agricultural Engineer
ASCE	American Society of Civil Engineer
ASMA	Advance soil moisture accounting
Assoc.	Association
Ave.	Average
Bull.	Bulletin
Cm	Centimeter
Co.	Company
Conf.	Conference
Cons.	Conservation
Cu. m.	Cubic metre
Cumec	Cubic metre per second
CWC	Central Water Commission
DEM	Digital elevation model
Deptt.	Department
Div.	Division
Drain.	Drainage
E	East
Ed	Edition
Engg.	Engineering

Envir.	Environment
Eq.	Equation
Eqs.	Equations
ET	Evapotranspiration
Fig.	Figure
Figs.	Figures
Geol.	Geological
Geophys.	Geophysics
GIS	Geographical Information System
GWS	Ground water store
ha	Hectare
Hydrau.	Hydraulic
Hydro.	Hydrology
Hydrol.	Hydrologic
Hydrolog.	Hydrological
Inc.	Incorporation
Inst.	Institute
Int.	International
Irrig.	Irrigation
ISAE	Indian Society of Agricultural Engineers
J.	Journal
Km	Kilometre
LCRR	Lumped conceptual rainfall-runoff
Ltd.	Limited
LTHS	Long term hydrologic simulation
m	Metre
Math.	Mathematical
Mgt.	Management
mm	Millimetre
N	North
N. A.	Not available
No.	Number

NSE	Nash-Sutcliffe efficiency
Oper.	Operational
Photogramm.	Photogrammetric
Plan.	Planning
pp.	page number
Proc.	Proceeding
Process.	Processes
Publi.	Publication
RE	Relative error
Ref.	Reference
Rem.	Remote
Res.	Research
Resour.	Resource
RMSE	Root mean square error
RS	Relative sensitivity
Scienc.	Science
SCS	Soil Conservation Service
SCS-CN	Soil Conservation Service-Curve Number
SE	Standard error
Semi.	Seminar
Sens.	Sensing
SMA	Soil Moisture Accounting
SMS	Soil Moisture Store
Soc.	Society
SOI	Survey of India
Sq. km.	Square kilometer
Sys.	System
Trans.	Transaction
Un.	Union
Univ.	University
USDA	United States Department of Agriculture

W	West
WRDO	Water Resources Development Organization

SYMBOLS

A	Total watershed area
A_c	Area of circle with same perimeter as basin
AM(t)	Antecedent moisture amount at any time ‘t’
BF(t)	Base flow at any time ‘t’
C	Constant of channel maintenance
CN(t)	Curve number at any time ‘t’
CNd(t)	Curve number for sub-surface (drainage) flow at time ‘t’.
d	Diameter of circle with same area as basin
DPR(t)	Deep percolation at any time ‘t’
DR(t)	Subsoil drainage at any time ‘t’
DSP(t)	Deep seepage at any time ‘t’
E_g	Exponent of ground water zone
E_s	Exponent of unsaturated moisture zone
ET(t)	Evapotranspiration at any time ‘t’
F	Cumulative infiltration or infiltration depth
F_d	Actual retention after flow begin
I_a	Initial abstraction
I_d	Initial abstraction for subsurface flow at time‘t’
K	Storage coefficient
Lb	Total stream length
Lm	Hydraulic longest of watershed
P	Perimeter of watershed
p	Probability level
P(t)	Total precipitation at any time ‘t’
P_1	Coefficient of transpiration from soil zone
P_2	Subsoil drainage coefficient

P_3	Unsaturated soil zone runoff coefficient
P_4	Ground water zone runoff coefficient
$P_5(t)$	5-day antecedent rainfall at time 't'
$P_e(t)$	Effective rainfall at any time 't'
PR(t)	Percolation at any time 't'
Q	Surface runoff
Q_d	Drainage flow depth
R	Multiple correlation coefficient
r^2	Coefficient of determination
R^2	Multiple squared R
Rb	Bifurcation ratio
R_C	Circularity ratio
Re	Elongation ratio
RO(t)	Direct runoff) at any time 't'
S(t)	Soil moisture retention at any time 't'
S_a	Intrinsic parameter of SMA procedure proposed by Michel et al. (2005)
Sd(t)	Potential maximum retention in saturated zone at time 't'
SM(t)	Modified soil moisture retention at any time 't'
SRO(t)	Accumulated surface runoff at outlet at time 't' along a storm
SRO(t)	Surface runoff at any time 't', if t>5-days
THR(t)	Lateral flow at any time 't'
TR(t)	Transpiration at any time 't'
TRO(t)	Total stream flow at any time 't' in SCS-CN-based LTHS model
V(t)	Soil moisture store level at time 't'
$V_0(t)$	Initial soil moisture level at any time 't'
$V_{00}(t)$	Pre-antecedent moisture level before the onset of rainfall at time't'
α	Coefficient of S_a, parameter of SMA procedure
α'	Exponent of initial abstraction (I_a)
β	Coefficient of initial soil moisture store level (V_0)
γ	Coefficient of pre-antecedent soil moisture store level (V_{00})
δ	Coefficient of antecedent moisture

$\theta(t)$	Soil moisture content at time 't'
θ_f	Field capacity of the soil in unsaturated zone
θ_w	Wilting point of the soil
λ	Coefficient of initial abstraction (I_a)
λ_d	Coefficient of initial abstraction in saturated zone (I_d)
$\psi(t)$	Ground water at time 't'
ψ_0	Initial ground water content
ψ_f	Field capacity of the soil in the ground water zone

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Stream flow records are major hydrologic data, which provide general regional information and can be used for planning, design, operation and management of water resources projects. Inadequate stream flow records always impair the precision of design in water resources projects. The available hydrologic records may lack a critical sequence of years of low or high runoff, and the most severe drought or flood in a short record which may not be representative of the statistical population. Design for water resources projects that are based on a sequence of flows, which are not representative of the true potential of a given drainage basin can only result in inefficiencies. The project will be over designed if the water supply is less than the short term records shows or it may be under designed if the water supply is greater than the short term record shows. Consequently, some of the potential benefits from the project may not be realized. Thus, the planning and management of water and other natural resources from a watershed require knowledge of availability of water at short and long term bases. Such an analysis of water availability requires continuous long term hydro-meteorological data such as rainfall and stream flow at different locations of the watershed.

In India and many other countries, the observation network for rainfall measurement and availability of rainfall data for longer time periods at different locations is better than that of stream flow data. Also, the stream flow records are generally not available at desired locations and contain data missing due to variety of reasons. As a result, many hydrological models have been developed in the past (Singh, 1989; Singh and Woolhiser, 2002; Singh et al., 2006) ranging from simple conceptual models to complex physically based models for transformation of rainfall into stream flow, largely due to easy availability of rainfall data for longer time periods at different locations. The process of transformation of rainfall into runoff is highly complex, dynamic, non-linear, and exhibits temporal and spatial variability. It is further affected by many and often inter-related physical factors and interactions occurring at the soil–vegetation–atmosphere interface.

Soil moisture is one of the key hydrological variable, which largely influences the partition of rain between runoff and infiltration, and thus, controls the flow at the outlet of a catchment (David et al., 2003). It is the natural state variable of the land surface. The soil moisture content of the watershed at a particular point in time is influenced by antecedent moisture, water holding capacity of soil, land slope and cropping pattern. Its temporal variability generally decreases with increasing soil depth (Georgakakos and Baumer, 1996) and it is often assessed through long term simulation studies mainly using water balance approach (Mishra and Singh, 2003a). The spatial and temporal variability of soil moisture over the catchment area of watershed affects not only surface and sub-surface runoff; it also modulates evaporation and transpiration processes. Hence, a better representation and proper accounting of soil moisture over the catchment should be considered to increase the predictive abilities of the hydrologic models. The main focus of the present study is to develop appropriate soil moisture accounting (SMA) procedure for use in SCS-CN concept based continuous models for long term hydrologic simulation of daily stream flow.

1.2 SIGNIFICANCE OF HYDROLOGIC MODELING

Modeling is now a common tool in many fields of scientific endeavor. Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. Hydrologic modeling basically provides a prognosis of the future performance of catchment behavior and helps in understanding complex and dynamic interaction of different processes operating on a watershed. They are useful in quantifying the water availability in spatial and temporal domain. Hydrologic models are fundamental to water resources assessment, development and management and can be employed to understand dynamic interactions between climate and land surface processes. Water resources development and watershed management require an understanding of hydrological variations owing to changes in watershed characteristics over long-term period (Bhaduri et al., 2000). Therefore, simulation of stream flow on a daily basis using a long-term hydrologic model that is simple to operate with readily available data is needed (Choi et al., 2002). Continuous models, also called long term hydrologic models or continuous stream flow models typically are focused on estimating water yield from a watershed.

In attempting creation of an efficient hydrologic model or to improve existing ones, there arise two challenges (i) in deciding the model structure and (ii) incorporating an adequate level of process representation for the proposed model structure. Model structure ensembles of mathematical functions and devices must be chosen to reflect the hydrological behavior at the catchment scale. The model should contain sufficient number of parameters to achieve optimal performance. Structure and complexity are linked with each other and therefore must be considered together while the model is being developed. Generally, more mathematical functions involve more parameters in the model. Hydrological models differ in terms of process representation, spatial discretization adopted, and time base of the model depending on the modeling objectives and the degree of realism sought in the model (Anderson and Burt, 1985). Owing to intricate spatial and temporal variability, natural processes are too complex to model by physical means, leading to simplifications to reduce the degree of complexity. It has led to the development and use of conceptual, lumped models (Ibbit, 1972; Donnelly-Makowecki and Moore, 1999) requiring minimal amount of data related with physical characteristics of the watersheds. Additionally, these models are simple and easy to understand and apply (Basha, 2000). Excellent reviews of various mathematical models of watershed hydrology is available in Singh (1989, 1995), Singh and Frevert, 2002, Singh and Woolhiser (2002), Singh et al. (2006), Limbrunner et al. (2006), http://www.usbr.gov/pmts/rivers/html/index.html, etc.

1.3 MOTIVATION FOR THE STUDY

Long term hydrologic simulation plays a vital role in development and management of water resources of a catchment. It is required for analyses of water yield and its availability to augment hydrologic data, water resources assessment for planning and management of watershed etc. Among many theories and approaches existing in literature, the infiltration-excess overland flow theory is incorporated in one of the well-known rainfall-runoff model known as Soil Conservation Service Curve Number (SCS-CN) model (Mishra and Singh, 2003a; Kumar and Jain, 2004; Geetha et al., 2008). The SCS-CN model has been used extensively in the past for estimating the direct runoff. This was primarily developed to compute surface runoff from isolated storm events. In spite of some limitations as stated by Ponce and Hawkins (1996), this method has been successfully employed in several long term hydrologic simulation models by accounting soil moisture status at previous time steps. A great deal of published material on SCS-CN method along with application is available in hydrologic literature (Williams and LaSeur, 1976; Hawkin, 1978; Smith and Williams, 1980; Arnold et al., 1990; Pandit and Gopalakrishnan, 1996; Mishra et al., 1998; Mishra and Singh, 2004a; Michel et al., 2005; Geetha et al., 2008; Durbude et al., 2010).

Recently, Michel et al. (2005) critically reviewed the soil moisture accounting (SMA) procedure lying behind the original SCS-CN method and proposed a modified procedure more consistent from the SMA viewpoint. They pointed out several structural inconsistencies in the existing SCS-CN methodology and in treatment of the antecedent soil moisture condition. However, the simplified version of the Michel et al. model also needs refinement particularly in defining the initial moisture level (V_0) and the proposed SMA procedure. The simplified Michel et al. (2005) model, an improved version of the SCS-CN methodology, also allows the unrealistic sudden jump in V_0 and, in turn, a quantum jump in the computation of surface runoff. In the generalized form of the Michel et al. model, V_0 at the beginning of rainfall event is optimized whereas it depends on the antecedent moisture conditions (AMCs) in simplified form as pointed out by Sahu et al. (2007). This results in unrealistic sudden jump in V_0. An expression for computation of V_0 and intrinsic parameter (S_a) of SMA procedure proposed by Michel et al., (2005) does not appear to have been suggested in literature.

In addition, in the existing SMA based long term simulation model, the SMA concept lying behind SCS-CN method is used for computation of surface flow only and the potential of its extension to base flow computation viz., sub-surface drainage flow (Yuan et al., 2001) has yet to be explored. The SCS-CN concept, which is basically used for estimating direct surface runoff, has been used by Yuan et al. (2001) for estimation of sub-surface drainage flow from rainfall. The generalized SCS-CN method as given by Mockus (1964) can be expressed as: When accumulated natural runoff is plotted versus accumulated natural rainfall, runoff starts after some rainfall has accumulated and the line of relation curve becomes asymptotic to a line of 45^0 slope. This analogy with the original SCS-CN method can be used to estimate the sub-surface drainage flow.

Thus, there is a need to recast the SMA procedure proposed by Michel et al. (2005) by incorporating variation of daily CN with respect to the variability of antecedent rainfall and moisture availability prior to the rainfall. In the SMA procedure proposed by Michel et al., V_0 plays a vital role in the computation of surface runoff. Hence, there is a scope to develop an expression for V_0 to preclude the sudden jump in V_0 and computed RO, and thus, to make the SMA procedure amenable to continuous hydrologic simulation of daily stream flow. In addition, there is also a scope to develop further the conceptual frame-work proposed by Yuan et al. (2001) to simulate the sub-surface flow components based on the SCS-CN concept.

Thus, the motivation of the present study is to develop a continuous long term hydrologic simulation (LTHS) model to establish a relationship between rainfall and runoff, for better describing the most important hydrological phenomenon of the hydrological cycle. It leads to understanding and identification of the stream flow generation processes based on the re-conceptualization of SMA procedure proposed by Michel et al (2005). The study also considers development of a sub-surface drainage flow model based on SCS-CN concept.

1.4 OBJECTIVES OF THE STUDY

On the basis of gaps identified from the cited literature and further scope for development and improvement in the existing SCS-CN based long term hydrologic simulation models, the present study envisages development of continuous long term hydrologic simulation (LTHS) models based on the SCS-CN concept, incorporating an appropriate conceptual soil moisture accounting (SMA) procedure and variation of daily CN-based on antecedent moisture amount (AMA), for long term hydrologic simulation of daily stream flow with minimum input data. The specific objectives of the present study are as follows:

1. To investigate the available long term simulation models employing the SMA concept.

2. To propose continuous hydrologic simulation models based on SCS-CN concept and an advanced SMA procedure to simulate stream flow.
3. To explore the possibility of representing sub-surface flow in the proposed model using a concept similar to SCS-CN model.
4. To test the performance of the developed models using a large set of data derived from watersheds located in different agro-climatic zones of India and compares the available and proposed models for their performance.
5. To perform the sensitivity analysis of parameters of the selected model for their relative significance and correlate model parameters with the physical characteristics of the selected watersheds.
6. To propose simplified version(s) of the selected models for field application.

1.5 ORGANIZATION OF THESIS

This thesis contains eight chapters as below.

Chapter 1 introduces the importance of the subject of study, particularly the significance of hydrological modeling. The scope and motivation to carry out the proposed research work have been emphasized, and objectives are set.

Chapter 2 presents the literature survey relevant to the object of this thesis including the review of the existing general hydrological simulation models, SCS-CN-based long term simulation models and their limitations. Theories and hypotheses of conceptualization and modeling of various components of the hydrological cycle are highlighted.

Chapter 3 describes the proposed four different long term hydrologic simulation models based on modified SMA procedure of the SCS-CN concept to simulate the daily stream flow and its components involved in stream flow generation using rainfall as input data. It explains the model formulation based on physical concepts and its calibration by optimization.

Chapter 4 briefly describes the study watersheds belonging to various agro-climatic zones of India selected for the present study and the length of data availability for model calibration and validation.

Chapter 5 tests the proposed long term hydrologic simulation models based on modified SMA procedure of the SCS-CN concept using the data of study watersheds. Models are applied to study watersheds using two different data sets: annual data and seasonal data (monsoon period). The results of this application are presented in this chapter. The inter-comparison among proposed models is also highlighted. Apart from this, the comparative performance of existing SCS-CN-based long term simulation models, when applied to the study watersheds, and the best performing model among the proposed LTHS models is also presented.

Chapter 6 discusses the various concepts of sensitivity analysis and its application for model simplification. The sensitivity analysis of the best performing model is carried out to identify the sensitivity of model parameters in influencing the simulated stream flow. The relative sensitivity plots of simulated stream flow with respect to model parameters are presented. Based on the sensitivity analysis, the values of less sensitive or not sensitive model parameters are statistically fixed to further simplify the model. The simplified model is further tested to the study watersheds, and the results presented.

Chapter 7 correlates model parameters with the physical characteristics of watershed. Various geomorphological and physiographical aspects of watershed and their influence on runoff generation are discussed, and the results presented.

Chapter 8 summarizes and concludes the research work. It also discusses the research contribution as well as the suggestions for future work.

CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

This chapter presents a critical review of the literature on theories and hypotheses describing the mechanisms of stream flow generation processes and hydrological modeling within the scope of the objectives of the present study. The inventory of various theories of conceptualizing the stream flow generation and several processes and mechanisms are discussed. These processes include interception, evaporation, transpiration, overland flow, and stream flow. Subsequently, a brief overview of a few well known and some storage concept-based conceptual models is presented and discussed. A comprehensive review is available elsewhere (Singh, 1989, 1995; Singh and Frevert, 2002a, b; Singh and Woolhiser, 2002; Mishra and Singh, 2004a; Mishra et al., 2004a; Singh et al., 2006; etc.).

2.2 STREAM FLOW GENERATION PROCESS

The broad relationship between precipitation and stream flow is obvious and has been evident since the work of Mariotte in the Seine basin during the seventeenth century. On a seasonal basis, stream flow tends to reach its maximum during the wet season and declines slowly during the drier part of the year, while in the short term it usually peaks sharply during a storm and declines relatively slowly after the end of rainfall. In other words, quite clearly, stream flow results from precipitation and some water arrives in the channel quickly while some arrives much more slowly and continues to arrive even during prolonged dry periods (Ward, 1967). For many years most explanations and analyses of runoff behavior have been made in terms of the infiltration theory of runoff developed by Horton, termed as Horton's infiltration model or more popularly known as infiltration-excess overland flow theory. Later the theory of saturation-excess overland flow was also postulated (Hewlett, 1961; Hewlett and

Hibbert, 1967; Dunne and Black, 1970 (a, b); Dunne, 1978; Walter et al., 2000; Garen and Moore, 2005; etc.). The infiltration and saturation-excess generating mechanisms are not mutually exclusive on a watershed, nor even mutually exclusive at a point on a watershed. The rainfall rate may exceed the infiltration capacity for some storms, and for others the rain may come slowly until the surface soil layer is saturated. Each mechanism has a different response to precipitation in terms of volume of runoff produced, the peak discharge rate, and the timing of contributions to stream flow in the channel. The relative importance of each process is affected by climate, geology, topography, soil characteristics, vegetation and land use. The dominant process may vary between large and small storms.

2.3 HYDROLOGICAL SIMULATION MODELS

Hydrologic simulation models use mathematical equations to calculate quantities like runoff volume or peak flow. These models can be classified as either theoretical or empirical models. A theoretical model includes a set of general laws or theoretical principles. If all the governing physical laws were well known and could be described by equations of mathematical physics, the model would be physically based. However, all existing theoretical models simplify the physical system and often include obviously empirical components. For exampe, the conservation of momentum equation used to describe surface flow includes an empirical hydraulic resistance term and the Darcy equation used in sub-surface problems is an empirical equation. Therefore, they are considered as conceptual models.

As stated earlier, the main focus of present study is to develop relationship between rainfall and stream flow conceptually. Generally the term 'conceptual' is used to describe those models relaying on a simple arrangement of a relatively small number of interlinked conceptual element, each representing a segment of the land phase of the hydrological cycle. The conceptual model approach to rainfall-runoff modeling lies in intermediate position, between physically based models and black box models. The conceptual models can be grouped into lumped and distributed models. The difference between lumped and distributed systems routing is that in a lumped system model, the flow is calculated as a function of time only at a particular location. In a distributed system routing, the flow is calculated as a function of space and time throughout the system. Lumped models are based on a spatially "lumped" form of the continuity equation, often called water balance and a flux relation expressing storage as a function of inflow and outflow (Singh, 1988). Since coupling of these two equations leads to a first order ordinary differential equation, only an initial condition is needed to solve this equation. This equation does not explicitly involve any spatial variability and expresses the flow routing variable as a function of time only. Distributed models are based on the St. Venant equations or simplifications thereof (Singh, 1996; ASCE, 1996). The hydraulic equations are applied to each reach of a watershed, and the system of equations corresponding to all the reaches are solved simultaneously. When the full St. Venant equations are applied, the computational demands may be formidable and the solution may be inefficient and may incur a large accumulated error. This may explain the reason for the increasing popularity of simplified hydraulic models. Lumped models are faster than distributed ones because they do not require a large amount of data and calibration of parameters is easy. On the other hand, distributed models describe in detail all processes influencing the hydrologic response, but it is difficult to find data to calibrate and validate the model. Thus, the lumped models are quite simple and fast to use and hence these are commonly used in runoff estimation.

The most commonly used element in a conceptual model is the storage component (Jain, 1993). Each storage usually has one input and one or more output and is used to represent basin storage such as surface detention, soil moisture etc. Linear reservoirs and channels are usually used for routing purposes. The first step in application of the conceptual model to a basin is model calibration aimed at to determine the model parameters such that an acceptable match is obtained between the observed behavior of the variable of the interest and the computed behavior. Basically, two approaches are followed for the calibration: manual fitting of parameters using trial and error and automatic fitting using an optimization algorithm (Jain, 1993). To model the hydrologic system completely, some simplifications have to be made for physical processes governing water movement and the way they interact. The catchment system, its input and responses can be represented mathematically using only the dimensions of depth and time. The most common simplification made in the catchment modeling is lumping or spatial averaging. In such a system no account is taken of variations within the catchment precipitation, vegetation, soils, geology or topography (Blackie and Eeles, 1985). The entire physical process in the hydrologic cycle is mathematically formulated in conceptual models. Some of the popular lumped conceptual models are briefly reviewed and presented in the following sections.

2.3.1 Stanford Watershed Model

The Stanford watershed model (SWM) is a history of the confluence of professional needs, newly emerging computing technology, and the curiosity of Ray Linsley and Norman Crawford (Crawford and Burges, 2004). Crawford and Linsley (1966) developed the Stanford Watershed Model, which is a pioneering effort to make watershed modeling practical for general use (James, 1972). The Stanford watershed model (Version II) published as Crawford's Ph. D. thesis in July 1962 attracted some, but not great attention. The basic Stanford Watershed Model (version II) was revised in 1966. In keeping with the invention process, Versions III and V were not published. While Stanford IV report (Crawford and Linsley, 1966) was published. In Stanford Watershed Model IV, more attention was given to making model indices non-dimensional, to make model parameters as independent as possible, and to reduce the number of parameters obtained by calibration. It is the most widely accepted model for simulations of the land phase of the hydrologic cycle (Singh, 1989). This model represented each process by an equation or series of equations containing parameters which vary from watershed to watershed and for which specific values are read in the input data. This model explains the Horton's law considering both spatial and temporal variability (Franchini and Michele, 1991) and calculates the total runoff available for transfer as the sum of four components: (1) direct runoff, (2) surface runoff, (3) sub-surface runoff, and (4) base flow. This lumped parameter model containing 34 parameters requires hourly or daily precipitation, daily temperature radiation, wind, monthly or daily evaporation and calculates the hourly or daily stream flow at the watershed outlet. Out of 34 parameters, 4 parameters pertain to infiltration, soil moisture zones and interflow. The remaining parameters are evaluated from the map, surveys, or hydrometorological records. If snowmelt is not of concern, the model parameters reduce to 25. This model attempts to grasp different interactions of various phases of rainfall-runoff transformation within the soil but is not advantageous for computation purpose; it result in a useless increase in number of parameters and consequent increase in difficulty in the calibration procedure (Franchini and Michele, 1991). Continuous development of this model has resulted in its many modified version like

Tank model (Sugawara, 1961; Sugawara, et al., 1984), Hydrologic Simulation Program (Johanson et al., 1980) etc.

2.3.2 Kentucky Watershed Model

According to Liou (1970), the Kentucky watershed model is a modified version of the Stanford watershed Model (SWM). The Kentucky FORTRAN Version of model is self-calibration watershed model as described by James (1970, 1972) and Ross (1970). This is 22 parameters model. The six parameters out of the total 22 parameters were estimated from measurable watershed characteristics. The remaining parameters were estimated using 'OPSET' a computer program for getting the optimized values. Putty and Prasad (1994) also developed a similar model for Sahyadri ranges of Western Ghats of India.

2.3.3 The Institute of Hydrology Model

The Institute of Hydrology Model, essentially a research tool, has several different forms and can be applied over hourly or daily time period. The work described by Nash and Sutcliffe (1970) and Mandeville et al. (1970) is the origin of the development of this Model. This model was subsequently modified in 1972, 1974, 1978, and 1979 for specific applications (Blackie and Eeles, 1985). A recent version of this Institute of Hydrology lumped model is designed to produce hourly estimates of stream flow using hourly catchment rainfall and hourly potential evaporation derived from meteorological data using Penman expression. It consists of four stores for surface water, and one store for ground water. In this form the model has 15 parameters and the values of these have to be determined either from field knowledge or by optimization. The total runoff is assumed to be partitioned into 2 parts: (i) surface runoff and (ii) ground water runoff.

2.3.4 Boughton Model

The simple conceptual daily Boughtan rainfall-runoff model (Boughton, 1966) was developed primarily for estimating water yield in ungauged catchments. This is a catchment water balance model (AWBM) to relate runoff to rainfall with daily or hourly data, and calculate losses from rainfall for flood hydrograph modeling. This was originally developed in Australia for assessing water yield from catchment in dry region. This model operates on daily basis and suitable for a large number of watersheds from which daily rainfall data and evaporation records are available (Singh, 1989). Functions are incorporated to calculate the daily amounts of evapotranspiration from the upper and lower soil stores, the daily infiltration from the drainage store to the lower soil store and the amount of runoff.

2.3.5 MODHYDROLOG Model

MODHYDROLOG model (Chiew and McMahon, 1991) is a complex conceptual daily rainfall-runoff model and a modified version of the HYDROLOG model (Porter and McMohan, 1976) with improved representation of ground water processes. This model attempts to include as many component parts as necessary to simulate the hydrological processes and which can be described adequately in simple mathematical terms of physical significance. This model has 19-parameters. In this model, the runoff components reaching the channel store are taken as surface runoff, interflow, and base flow. The total flow is routed to the catchment outlet using a non-linear routing technique. The complex conceptual MODHYDROLOG model is operated on daily time step using daily rainfall and potential evapotranspiration data as input and simulates for daily, monthly and annual flows (Chiew et al., 1993; Chiew and McMohan, 1994). This model was applied to 28 catchments in Australia with different climatic and physical characteristics and shows satisfactory result of runoff but has some difficulty of long periods of zero flows followed by peak flows (Chiew and McMohan, 1994).

2.3.6 HRUT Model

A model based on the concept that a watershed conceptually consists of seven regulating reservoirs and describes hourly dynamics of water and heat transfer in a forested catchment was developed by the laboratory of Hydrology and River Hydraulics at University of Tokushima is termed as HRUT model (Yao et al., 1996). The upper four layers of regulating reservoirs are considered to be significant both for heat and water transfer, while remaining three layers of regulating reservoirs are effective only for the water cycle. This model was tested in an experimental site of the laboratory of Hydrology and River Hydraulics at University of Tokushima. The input data, viz., air temperature, relative humidity, net radiation, wind speed, rainfall, and soil water were used in this model. This conceptual model involved 37 parameters in which, 22 model parameters are determined from direct investigation and the remaining 15 parameters are determined by simplex optimization technique. This model is assumed to have four runoff components, viz., surface flow, rapid topsoil through flow, delayed root-soil through flow, and base flow.

In the recent advancement, the development of model parameterization methodologies using geographic information systems (GIS) is becoming increasingly important in hydrologic modeling applications, especially given the continued trend of comprehensive and readily available geospatial data bases. Some of the conceptual models described below derive the model parameters for a complex soil moisture accounting using the available GIS database and that the use of seasonal or multi-parameter sets improves model performance.

2.3.7 HMS - SMA Algorithm

The 12-parameter soil moisture accounting (SMA) algorithm recently added to the Hydrologic Modeling System (HMS) program by the Hydrologic Engineering Center (HEC) (Bennett, 1998; HEC, 2000; Anderson et al., 2002). The U.S. Army Corps of Engineers, Nashville District considers HMS as a tool for continuous hydrologic simulation in the Cumberland River basin (Fleming and Neary, 2004). The study demonstrates that parameters for a complex soil moisture accounting model can be derived from GIS database.

2.3.8 LBR Model

Similar to HEC-SMA algorithm, Large Basin Runoff (LBR) model also uses the GIS database. The spatially lumped LBR model has been developed (Croley and He, 2006) by National Oceanic and Atmospheric Administrations' Great Lakes Environmental Research Laboratory, as a serial and a parallel cascade of linear reservoirs, representing moisture storage, upper soil surface, upper soil zone, lower soil zone, and ground water zone within a watershed. This modified LBR model has tested on Kalamazoo River watershed in Michigan and Maumee River watershed in Ohio. The result of this study shows that the addition of sub-surface intraflows in the model improved the watershed representations.

2.3.9 WATFLOOD Model

WATFLOOD model, which is a distributed hydrologic model to forecast flood flows for watershed uses a GIS database. It is a hybrid simulation model (Bingeman et al., 2006) of the watershed hydrologic budget, uses a mixture of physically based and conceptual equations to represent the hydrological processes. The study has conducted explicit validations of several internal state variables like soil moisture, evaporation, ground water flow in addition to stream flow calibration and validation. This study showed the model to behave realistically.

Apart from these model, there are several other models existing in hydrologic literature, as for example, Long Term Hydrologic Impact Assessment (LTHIA) model (Harbor, 1994); Soil and Water Assessment Tools (SWAT) model (Spruill et. al., 2000) and AVSWAT (Arc View SWAT) (Pandey et al., 2006); A Cell based Long Term Hydrological (CELTHYM) model (Choi et al., 2002); A GIS based distributed rainfall-runoff model (Jain et al., 2004, Park et al., 2004, Gosain and Rao, 2004); Semi-distributed conceptual rainfall–runoff (Crook and Naden, 2007, Gupta et al., 2008) model, etc. These employ GIS database for estimating the major physical characteristics of watershed that significantly influence the runoff characteristics of watershed, such as watershed geographical area, length, slope, shape, land use, and soil characteristics of watershed.

In the present study, Geological Information System (GIS) namely, Integrated Land and Water Information System (ILWIS) of ITC, Netherland (ITC, 1997) is used for the delineation of watershed and computation of measurable physical characteristics of watershed such as size (geographical area, perimeter, length parallel to principle drain, hydrologic length), shape (watershed shape factors includes form factor, circulatory ratio, and elongation ratio), topography (total relief), and surface culture (vegetation) etc.

2.4 HYDROLOGICAL SIMULATION MODELS BASED ON SCS-CN CONCEPT

The SCS-CN model of the United States Department of Agriculture Soil Conservation Service (USDA SCS) has been widely used in the past to determine the direct surface runoff. It was primarily developed to compute surface runoff from isolated storm events and estimation of design hydrographs for small agricultural watersheds (SCS, 1956, 1964, 1971, 1985, 1993, 2004). In last three decades, this model has received significant attention in the hydrologic literature and several issues concerning with the capabilities, advantages, limitations, applications and modifications have already been published in the literature by numerous researchers ((Ponce and Hawkins, 1996; Mishra and Singh, 2003a; Mishra et al., 2006; Michel et al., 2005; Jain et al., 2006 a, b, c; Sahu et al., 2007, Kannan et al., 2008; Kim and Lee, 2008; Geetha et al., 2008; Durbude et al., 2010; etc.). Hjelmfelt (1991), Hawkins (1993), Bonta (1997), and Bhunya et al. (2003) suggested the computational procedures to determine the curve numbers for a watershed using field data. Neitsch et al. (2002) formulated an empirical relation to account for the effect of watershed slope on CN. Hjelmfelt (1991), Svoboda (1991), and Mishra and Singh (1999a, b; 2002a; 2003a, b) suggested the analytical treatments of the SCS-CN methodology. Jain et al. (2006a) incorporated the storm duration and a nonlinear relation for initial abstraction (I_a), to enhance the SCS-CN based Mishra and Singh (2003a) model. The research works of Simanton et al. (1973), McCuen (1982, 2002), Hjelmfelt (1980, 1982, 1991), Hawkins (1993), Steenhuis et al. (1995), Ponce and Hawkins (1996), Bonta (1997), Mishra and Singh (1999 a, b; 2002 a, b; 2003 a, b; 2004 a, b), Mishra et al. (2003 a, b; 2006), Michel et al. (2005), Jain et al. (2006 a, b, c), Sahu et al. (2007), Geetha et al. (2007, 2008), etc., are worth citing among many others.

There exist numerous hydrologic simulation models of varying complexity in the literature that simulate stream flow. In many of these models, Soil Conservation Service Curve Number (SCS-CN) model has been used for surface runoff computations, for example, CREAMS (Knisel, 1980); EPIC (USDA, 1990); HELP (Schroeder et al., 1994); LTHIA (Harbor, 1994); PRZM (Carsel et al., 1997); SWIM (Krysanova et al., 2000); CELTHYM (Choi et al., 2002); SWAT (Arnold et al., 1993; Arnold and Fohrer, 2005); etc. Since the original SCS-CN method is an infiltration loss model that does not account for evaporation and evapotranspiration, its use was shown to be restricted to modelling storm losses and associated surface runoff (Boughton, 1968). However, the method has been used successfully in several long term hydrologic simulation models by accounting soil moisture status at previous time steps, viz., Williams and LaSeur, 1976; Hawkin, 1978; Smith and Williams, 1980; Arnold et al., 1990; Pandit and Gopalakrishnan, 1996; Mishra et al., 1998; Mishra and Singh, 2004 a; Michel et al., 2005; Geetha et al., 2007, 2008; etc.

2.5 ORIGINAL SCS-CN METHOD

In 1954, the USDA SCS proposed a method (SCS-CN method) to determine outflow hydrographs for use in small structural design and appraisal of land use changes. This method is based on a non-linear rainfall-runoff relation that uses a land condition factor to calculate depth of rainfall-excess, and uses a triangular unit hydrograph to route rainfall excess to produce an outflow hydrograph. This method has been described in the SCS National Engineering Handbook, Section 4: Hydrology (NEH-4). It is a well established method in hydrological engineering and environmental impact analysis. Its popularity is rooted in its convenience, simplicity, authoritative origin, and responsiveness to four major catchment properties; soil type, land use/land treatment, surface condition, and antecedent moisture condition. These are the major factors affecting the infiltration characteristics of soil. Hydrologically, soil categorized into four groups on the basis of intake of water, on bare soil, when thoroughly wetted (Singh, 1992). The types of land covers such as bare soil, vegetation impervious surface, etc., establish runoff production potential.

A common assumption in hydrologic modeling is that rainfall available (P) for runoff is separated into three parts: i) Direct surface runoff, ii) initial abstraction, and iii) infiltration loss (McCuen, 1989). Therefore in the development of the SCS-CN-based rainfall-runoff model, the total rainfall is considered to be separated into three components: (i) Direct (surface) runoff (Q), (ii) initial abstraction (I_a), and (iii) actual retention (F). The SCS-CN method is based on the water balance equation and two hypotheses (Mishra and Singh, 2003a). It is also based on the concept that the runoff begins only after the initial abstraction (I_a) is satisfied. This initial abstraction consists of interception, surface storage, and infiltration (Singh, 1992).

The water balance equation and the two proportional equality hypotheses can be written as follows (SCS, 1956):

$$P = I_a + F + Q \tag{2.1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2.2}$$

$$I_a = \lambda S \tag{2.3}$$

where P=total precipitation, I_a=initial abstraction, F=cumulative infiltration, Q=direct runoff; S=potential maximum retention or infiltration, and λ=initial abstraction coefficient varies from 0 to ∞ and is assumed 0.2 for average conditions (Mishra and Singh, 1999 a).

Combination of Eqs. (2.1) and (2.2) lead to the popular form of the SCS-CN method as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}, \qquad \text{if } P > I_a \tag{2.4}$$

Eq. (2.4) is valid only if $P > I_a$; Q = 0 otherwise. The initial abstraction (I_a) accounts for the short-term losses, such as interception, surface storage, and infiltration. Parameter λ is frequently viewed as a regional parameter dependent on geologic and climatic factors. The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications (SCS, 1972, 1985).

$$I_a = 0.2\ S \tag{2.5}$$

Physically, this means that for a given storm, 20% of the potential maximum retention is the initial abstraction before runoff begins. Substituting Eq. (2.5) into Eq. (2.4) gives the following relationship.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2.6}$$

Eq. (2.6) contains only one unknown parameters S, which depends on characteristics of the soil-vegetation-land use (SVL) complex and antecedent moisture conditions in a watershed. Of late, $\lambda = 0.05$ has also been advocated for field use (Hawkins et al., 2001), which can, however, vary from 0 to ∞ (Mishra and Singh, 1999a, 2003a).

2.5.1 Curve Number

The existing SCS-CN method as shown in Eq. (2.6) is a single parameter model for computing direct surface runoff from daily storm rainfall. To determine the unknown parameter S, in the above Eq. (2.6), a dimensionless number named as 'curve number (CN)' was introduced (SCS, 1956). Here, the linear index of watershed storage, S, is transformed to the index 'CN' which represents the hydrologic soil group and land use and treatment class, ground surface condition, and antecedent moisture. It is a relative measure of retention of water by a given soil-vegetation-land use (SVL) complex. This curve number method is a widely used technique for estimating storm runoff from the rainfall depth that was pioneered and developed by USDA SCS in 1954 and published in section 4, National Engineering Handbook in 1956. Subsequent revisions followed in 1964, 1965, 1971, 1972, 1985, 1993, 2004 (Mishra and Singh, 2003a; Ponce and Hawkins, 1996). As a need to relate S that can vary in the range $(0, \infty)$ to a number varying in a limited range of (0, 100), the following relationship is established:

$$S = \frac{1000}{CN} - 10 \tag{2.7}$$

where S is in inches and CN is non-dimensional. In SI units

$$S = \frac{25400}{CN} - 254 \tag{2.8}$$

where S is in mm and CN is non-dimensional. Here curve number CN varies in the range $0 \leq CN \leq 100$ (Hjelmfelt, 1980; McCuen, 1982, 1989; Boszany, 1989; Mishra and Singh, 2003a).

The combination of major watershed characteristics which is referred as soil vegetation-land use (SVL) complex, as stated above, primarily affects the infiltration potential of a watershed. The SCS-CN parameter S or CN also depends on the SVL combinations, on which the parameter S or CN depends, and these are broadly classified into urban, agricultural, woods and forests. The curve number CN values for different land use and treatment, hydrologic conditions for each soil group are suggested by SCS (1971).

2.5.2 Antecedent Moisture Condition

Antecedent moisture condition (AMC) refers to the wetness of the soil surface or the water content present in the soil prior to the occurrence of rainstorm, or alternatively the degree of saturation before the start of rainfall. If the soil is fully saturated, the whole amount of rainfall will directly convert to runoff without infiltration losses and if the soil is fully dry, it is possible that the whole rainfall amount is absorbed by the soil, leading to no surface runoff. Thus, the runoff estimates are based on soil type, land use practices within a basin and influence of the AMC for a specific storm (Silveria et al., 2000). The AMC value is intended to reflect the effect of infiltration on the volume and rate of runoff according to infiltration curve (Singh, 1992). SCS developed three antecedent moisture conditions and labeled them as I, II, and III. These conditions correspond to the soil conditions given in Table 2.1.

Table 2.1 Antecedent Moisture Conditions (McCuen, 1982; Singh, 1992)

AMC	Soil Condition
I	Dry soil, but not to the wilting point; satisfactory cultivation has taken place
II	Average condition
III	Heavy rainfall, or light rainfall and low temperatures have occurred within last 5-days; saturated soil

Hjelmfelt et al. (1982) statistically related AMC I (dry), AMC II (normal), and AMC III (wet) levels, respectively, to 90, 50, and 10% cumulative probability of the exceedance of runoff depth for a given rainfall. It is noted that high antecedent moisture or rainfall amount infers high CN and, therefore, high runoff potential, and vice versa. There are three concepts generally used in hydrologic literature to identify the antecedent moisture conditions (AMCs) of the soil. These are the antecedent precipitation index (API), antecedent base flow index (ABFI), and the soil-moisture-index (SMI) (Ponce and Hawkins, 1996). The API approach is simple, easy to grasp and apply in field. On the other hand, ABFI relies on the amount of antecedent base flow and seldom used in practice. The concept of SMI is generally used in long-term hydrologic simulation for water balance (Williams and Laseur, 1976; Hawkins, 1978; Soni and Mishra, 1985; Mishra et al., 1998; Mishra and Singh, 2004a). The API is based on the amount of antecedent rainfall. In literature the term antecedent varies from 5 to 30 days. However, there is no guideline available to vary the soil moisture with the antecedent rainfall of certain duration (SCS, 1971; Mishra and Singh, 2003a). The National Engineering Handbook (NEH)-4 (SCS, 1971) uses the antecedent 5-day rainfall as API for AMC. Table 2.2 provides seasonal limits of antecedent rainfall for the three antecedent soil moisture conditions.

Table 2.2 Seasonal Rainfall for Various AMCs (Mishra and Singh, 2003a)

Antecedent Moisture Condition (AMC)	**Total 5-days Antecedent Rainfall (cm)**	
	Dormant Season	Growing Season
I	Less than 1.3	Less than 3.6
II	1.3 – 2.8	3.6 – 5.3
III	More than 2.8	More than 5.3

From the tables, it is observed that the curve number CN corresponding to AMC I refers to the dry CN or the lowest runoff potential; CN corresponding to AMC II stands for the average CN or the average runoff potential; and the CN corresponding to AMC III refers to the wet CN or the highest runoff potential. In other words, higher the antecedent moisture or rainfall amount, higher the CN and higher the runoff potential and vice versa. The average condition was taken to mean average response, which was later extended to imply average soil moisture condition (Miller and Croshney, 1989). Depending on the 5-day antecedent rainfall, CNII is convertible to CNI and CNIII by referring the table given in NEH-4 (SCS, 1972; McCuen, 1982, 1989; Ponce, 1989) or by using the relationship given by Sobhani (1975), Hawkins et al. (1985), Chow et al. (1988), Neitsch et al. (2002), and Mishra et al., (2008) as given below in Table 2.3.

Table 2.3 AMC Dependent CN Conversion Formulae

Conversion Method	**AMC I**	**AMC III**
Sobhani (1975)	$CN_I = \frac{CN_{II}}{2.334 - 0.01334 CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.4036 + 0.005964 CN_{II}}$
Hawkins et al. (1985)	$CN_I = \frac{CN_{II}}{2.281 - 0.01281 CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.427 - 0.00573 CN_{II}}$
Chow et al. (1988)	$CN_I = \frac{CN_{II}}{10 - 0.058 CN_{II}}$	$CN_{III} = \frac{23 CN_{II}}{10 + 0.13 CN_{II}}$
Neitsch et al. (2002)	$CN_I = CN_{II} - \frac{20(100 - CN_{II})}{\left\{100 - CN_{II} + \exp\left[2.533 - 0.0636\left(100 - CN_{II}\right)\right]\right\}}$	$CN_I = CN_{II} \exp\left\{0.00673(100 - CN_{II})\right\}$
Mishra et al. (2008)	$CN_I = \frac{CN_{II}}{2.2754 - 0.012754 CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.430 + 0.0057 CN_{II}}$

Apart from this, Hawkins (1993) suggested the mathematical expression to compute average CN value (or S value) using the rainfall (P)-runoff (Q) data of gauged watershed as;

$$S = 5\left[P + 2Q - \sqrt{Q(4Q + 5P)}\right] \tag{2.9}$$

Hawkins (1993) identified watershed behavior as 'standard', 'violent', and 'complacent' and Hjelmfelt (1980) suggested another approach to estimate CN from rainfall-runoff data by rank-order method, where the P-Q data are sorted and rearranged on rank-order basis to have equal return period. However, the individual runoff values are not necessarily associated with the causative rainfall values (Hawkins, 1993). Bonta (1997) evaluated the potential of derived distributions to determine curve numbers from measured P-Q data treating them as separate distributions. Similar to Hawkins (1993), this method also identifies the different behaviour of watershed. This method has potential to estimate CN with limited data availability. Schneider and McCuen (2005) developed a method based on lognormal frequency distribution of observed P-Q data, which is found to be more accurate than Hawkins (1993) and the rank-order method. Mishra and Singh (2006) investigated the variation of CN with AMC and developed a power relationship between S (or CN) and the 5 days antecedent rainfall.

The original SCS-CN model is a conceptual model of hydrologic abstraction from rainfall, and is supported by empirical data based on two parameters i.e., Curve number and initial abstraction. But initial abstraction being dependent on curve number makes the method to practically a single parameter model. Thus, it is a simple, conceptual model, capable of computing surface runoff excluding base flow. Even though this method has several advantages over other methods, it has several drawbacks too (Smith, 1997; Yu 1998). Ponce and Hawkins (1996) cautioned against the use of the method to watersheds larger than 250 sq. km. To overcome some of the above drawbacks, the distributed watershed modeling was introduced based on the SCS-CN concept, like Moglen's approach, modified Moglen method (Mishra and Singh, 2003a), Hawkins method (Hawkins, 1978), CELTHAM model (Choi et al., 2002), etc.

2.5.3 Advantages

Ponce and Hawkins (1996) critically reviewed SCS-CN method to examine its conceptual and empirical bases. They further enumerated some of the important advantages of this method as follows:

i. It is a simple, predictable, and stable conceptual method for predicting direct runoff from storm rainfall amount.
ii. It relies on only one parameter, the runoff curve number, which varies as a function of four major runoff producing watershed properties; hydrologic soil group, land use and treatment class, hydrologic surface condition, and antecedent moisture condition.
iii. It is the only methodology whose features are readily grasped with reasonably well documented inputs.
iv. It is a well established method, having been widely accepted for use in various countries.
v. It is a widely employed method in majority of the computer-based hydrologic simulation models used currently (Singh, 1995).

2.5.4 Limitations

The major limitations of this method are summarized as below;

i. The method was originally developed using regional data, mostly from the Midwestern USA and therefore some caution is necessary when it is applied to other geographic or climatic regions.
ii. Lack of clear guideline on how to vary antecedent moisture conditions, especially for lower curve numbers and rainfall amount. For lower curve numbers and/or rainfall depths, the method is very sensitive to curve number and antecedent moisture condition.
iii. This method considers only rainfall available on current day without taking into account of the moisture available prior to the storm.
iv. The method is best suited for agricultural sites, for which it was originally intended, and has since been extended to urban sites.
v. The method rates fairly in applications to range sites, and generally does poorly in application to forest sites. The implication here is that the method is best suited for storm rainfall-runoff estimates in streams with negligible base flow, i.e. those for which the ratio of direct runoff to total runoff is close to one.

vi. The method has no explicit provision for spatial scale effects. Without catchment subdivision and associated channel routing, its application to large catchments (greater than 250 sq. km.) should be viewed with caution.

vii. The method fixes the initial abstraction ratio at 0.2. In general, however, this ratio could be interpreted as a regional parameter based on geological and climatic settings. Hence the method does not properly predict initial abstraction for shorter, more intense storm.

2.6 SCS-CN BASED LONG TERM HYDROLOGIC SIMULATION MODELS

As stated earlier, despite the limitations of the SCS-CN method, it has widely been employed in numerous rainfall-runoff models to compute direct runoff. The extensive amount of work has been carried so far to refine further the SCS-CN concept (e.g. McCuen, 1982; Hjelmfelt, 1991; Hawkins, 1993; Steenhuis et al., 1995; Ponce and Hawkins, 1996; Bonta, 1997; Mishra and Singh, 1999a, 1999b, 2002a, b, 2003a, b, 2004a, b; Mishra et al., 2004a, b; Neitsch et al., 2002; Jain et al., 2006 a, b, c; etc.). But, comparatively less effort has been made toward the use of this method for long term hydrologic simulation. Williams and LaSeur (1976) were the first to incorporate soil moisture accounting procedure in SCS-CN methodology for continuous hydrological simulation. Many others worked on the SMA concept and refined it further. The works of Hawkins (1978), Smith and Williams (1980), Arnold et al. (1990), Mishra et al. (1998), Mishra and Singh (2004), Michel et al. (2005), and Geetha et al. (2008), etc., are worth citing. Details of some of the important models and their limitations are highlighted below.

2.6.1 Williams and Laseur Model

Williams and LaSeur (1976) computed daily direct runoff volume using the antecedent 5-days rainfall dependent CN values and linked potential maximum retention (S) with the soil moisture (M) as given below to develop a Water Yield Model (WYM) based on the existing SCS-CN methodology.

$$M = S_{abs} - S \tag{2.10}$$

where S_{abs} is the absolute potential maximum retention equal to 20 inches and M is varied with the lake evaporation as;

$$M(t) = \frac{M}{1.0 + b_c M \sum_{t=1}^{T} E(t)} \tag{2.11}$$

where t is time, b_c is the depletion coefficient, M is the soil moisture index at the the beginning of the first storm, M(t) is the soil moisture index at any time t, E(t) is the average monthly lake evaporation (a climatic index) for day t and T is the number of days between rainstorms. The value of M is varied with the amount of water infiltrated during a rainstorm (P- Q) and with modification for the first storm, S is computed from Eq. (2.7) for $S_{abs} = 20$ inches to determine the runoff for the second storm. For each rainstorm in the series, this procedure is repeated. The model is calibrated by adjusting depletion coefficient (b_c) until the computed average annual runoff closely matches with the observed average annual runoff. The initial estimate of b_c is derived from the average annual rainfall and runoff values based on certain assumptions. The simulation begins 1 year before the actual calibration period because of a priori determination of the initial soil moisture index. Thus, the value of CN varied continuously with M.

In nutshell, the Williams–LaSeur model has following characteristics;

i. It is single parameter model with daily or pre-determined time step
ii. It requires simple inputs to produce single output as runoff volume
iii. It avoids, to some extent, sudden jumps in the CN values when changing from one AMC to the other.
iv. Its operation requires (a) an estimate of the curve number (CN) for average AMC, (b) observed monthly runoff, (c) daily rainfall and (iv) average monthly lake evaporation.
v. The model computed b_c value imposes an agreement between the observed and the computed average annual runoff.

vi. Its application to nearby ungauged watershed requires the proper adjustment of the curve number in proportion to the ratio of the AMC II curve number to the average computed curve number for the calibrated watershed.

However, this model has some limitations such as:

i. It utilizes an arbitrarily assigned value of 20 inches for S_{abs} and it simulates runoff on monthly and annual bases even though runoff is computed daily, treating rainfall in any day as a storm.

ii. Despite, the continuous SMA procedure adopted in the formulation of this model, the model still relies on the existing SCS-CN method for runoff computation, which itself lacks in the proportionality concept.

iii. Apart from the undesirable loss of 1 year rainfall–runoff information, this method loses the physical soundness due to iterative procedure required for the adjustments of soil moisture index (b_c) (Singh et al., 2001).

iv. The physically unrealizable decay of soil moisture with lake evaporation, this model yield the variation of Q with P, which is analogous to F in existing SCS-CN method, and thus, contradicts the SCS-CN approach (Mishra and Singh, 2004a).

2.6.2 Hawkins Model

Hawkins (1978) related evapotranspiration (ET) and CN to formulate a continuous soil moisture accounting procedure for use in continuous hydrologic simulation model. This model accounts for site moisture on a continuous basis using the volumetric concept, which overcomes the limitations Williams and LaSeur (1976) model. Hawkins (1978) developed a daily simulation model by the following expression:

$$Q = P - S(1.2 - \frac{S}{P + 0.8S}), \text{ for } P \geq 0.2S \tag{2.12}$$

For P→∞, the maximum possible water loss is equal to S_t, which equals 1.2S. Taking into account the evapotranspiration (ET), the maximum water loss at a higher time level

$(t+\Delta t)$ for the storm duration of Δt, can be derived from the moisture balance as given by Mishra and Singh (2004a) as:

$$S(t+\Delta t) = S(t) + [ET-(P-Q)](t, t+\Delta t) \tag{2.13}$$

where $(t, t+\Delta t)$ denotes the Δt duration between time t and $(t+\Delta t)$ and ET intuitively accounts for the interim drainage, if any. It follows that $S(t+\Delta t)=1.2S(t+\Delta t)$. Combining these water loss relationships and substitution of Eq. (2.6) into the resulting expression gives (Mishra and Singh, 2004a):

$$CN(t+\Delta t) = \frac{1200}{1200/CN(t) + [ET-(P-Q)](t, t+\Delta t)} \tag{2.14}$$

Thus, direct surface runoff can be computed from Eq. (2.4) with known ET, P and Q at different time levels.

The site moisture is accounted on a continuous basis using the volumetric concept which is analogous to a bottomless reservoir in Hawkins (1978) model, which implies that the reservoir never depletes fully or the reservoir is of infinite storage capacity. Thus, S_t (=1.2S) will also vary from 0 to ∞ similar to S. In this view, S_{abs}=20 inches in the Williams-LaSeur model appears to be a forced assumption. Although, Soni and Mishra (1985) also used a similar assumption by fixing the depth of the soil profile to the root zone depth of 1.2m for computing S while applying the Hawkins model in their study.

The advantage of Williams–LaSeur model is similar to the Hawkins model, which eliminates sudden quantum jumps in the CN values when shifting from one AMC level to the other due to consideration of average AMC for computation of CN value. However, the model also has some limitations, that it does not distinguish the dynamic infiltration from the static one. The water drained down to meet the water table may not be available for evapotranspiration. ET intuitively accounts for the interim drainage. According to the model formulation (Eq. 2.13), the term (I_a+S) takes part in the dynamic infiltration process, rather than the S alone. Due to a very high capillary suction, the initial abstraction (I_a) is not available for transpiration, and hence, does not play a part in the dynamic infiltration process. Thus, the follow up in this method leads to the assumption of the SCS-CN method to be based on the (I_a+S) scheme, whereas I_a is separate from S. It is observed that the Hawkins model considers the maximum F amount equal to (I_a+S).

Also, for no rainfall condition, substitution of P=0 in Eq. (2.12) yields Q=0.05S, which is impossible. Although Eq. (2.4) is mentioned to be valid for $P \geq 0.2S$, it carries its impact by allowing an additional storage space of 20% of S available for water retention at every time level that leads to unrealistic negative infiltration at $P \rightarrow 0$. Thus, S at time t (=S (t)) corresponds to CN at time t (=CN (t)), Eq. (2.14), therefore, needs modification by substitution of 1000 for 1200 (Mishra and Singh, 2004a).

2.6.3 Smith and Williams Model

Smith and Williams (1980) further modified the SCS curve number method by defining the retention parameter (S) and introduced the weighing factor to account for the soil moisture in the soil profile. The following expression was given by Smith and Williams (1980) to determine retention parameter S (mm).

$$S = S_{mx}\left[1.0 - \sum_{i=1}^{N} W_i \frac{M_i}{SAT_i}\right] \tag{2.15}$$

where

$$S_{mx} = \frac{25400}{CN_I} - 254 \tag{2.16}$$

The CN_I is defined as a function of CN_{II} (CN for AMC II) by a third degree polynomial as:

$$CN_I = -16.91 + 1.348\,(CN_{II}) - 0.01379\,(CN_{II})^2 + 0.0001177\,(CN_{II})^3 \tag{2.17}$$

where W_i is the weighing factor, M_i is the initial soil moisture content in layer i, and SAT_i is the upper limit of water storage in layer i. Smith and Williams (1980) reduce the CN_{II} (CN for

AMC II) to CN_I (CN for AMC I) and then adjust it to the moisture distribution in the soil profile using the weighing technique. The weighing factor decreases with depth and is defined as:

$$W_i = e^{-4.16\left(\frac{D_{(i-1)}}{RD}\right)} - e^{-4.16\left(\frac{D_i}{RD}\right)} \tag{2.18}$$

where D_i is the depth to the bottom of layers i, and RD is the root zone depth. The representative continuous models based on the Smith and Williams (1980) method is CREAMS (Knisel, 1980) model.

To improve the runoff computation capability of Smith and Williams (1980) model, further modifications were made by Shirmohammadi (1997) who indicated that the Smith and Williams (1980) method tends to underestimate runoff. The expression for maximum retention parameter (S_{mx}) was modified to replace the curve number for average AMC (CN_{II}) with CN_I. Hence, Eq. (2.15) may be rewritten as:

$$S_{mx} = \frac{25400}{CN_{II}} - 254 \tag{2.19}$$

However, the intrinsic meaning of the S_{mx} disappeared because it becomes the average retention parameter. This may avoid the sudden quantum jumps in the CN values when shifting from one AMC level to the other, similar to the Williams–LaSeur (1976) model and the Hawkins (1978) model.

2.6.4 Arnold et al. Model

Arnold et al. (1990) hypothesized that the CN could be varied non-linearly based on soil `moisture condition and soil characteristics such as field capacity, wilting point, and saturated moisture content. Specifically, the retention parameter (S) is allowed to vary with soil moisture content (M). The representative continuous models based on the Arnold et al. (1990) method are SWRRB (Simulator for Water Resources in Rural Basins), SWAT (Soil and Water Assessment Tool), SWIM (Soil and Water Integrated Model) etc. In these models, S is changing dynamically due to variations in the soil moisture content according to the following equation:

$$S = S_{mx}\left[1.0 - \frac{M}{(M + \exp(w1 - w2M))}\right] \tag{2.20}$$

where S_{mx} is the maximum value of the retention parameter on any given day, which is associated with CN_I, M is the soil moisture content of the entire profile excluding the amount of water at wilting point, and w1 and w2 are the first and second shape coefficients, respectively. The following assumptions are made for determining the shape coefficients of w1 and w2:

$$S = S_{mx} \qquad \text{for } M = WP \tag{2.21}$$

$$S = S_{III} \qquad \text{for } M = FC \tag{2.22}$$

$$S = 2.54 \qquad \text{for } M = SAT \tag{2.23}$$

where S_{III} is the retention parameter corresponding to CN_{III}, 2.54 is the retention parameter value for a curve number of 99, WP is the wilting point moisture content, FC is the field capacity moisture content, and SAT is the fully saturated moisture content. Under the assumptions of Eqs. (2.20-2.23), the shape coefficients are calculated from the simultaneous solution of the following equations:

$$w_1 = \ln\left[\frac{FC}{1 - S_{III}S_{III}^{-1}} - FC\right] + w_2 FC \tag{2.24}$$

$$w_2 = \frac{\left(\ln\left[\frac{FC}{1 - S_{III}S_{mx}^{-1}} - FC\right] - \ln\left[\frac{SAT}{1 - 2.54S_{mx}^{-1}} - SAT\right]\right)}{(SAT - FC)} \tag{2.25}$$

Further improvement has been made by Krysanova et al. (2000) who developed the Soil and Water Integrated Model (SWIM), which is derived from the SWAT model, by modification of the nutrient, crop, and routing modules. SWIM uses the Arnold et al. (1990) method with some modification to compute surface runoff by incorporating the depth-weighted soil moisture content as follows:

$$M' = \frac{\sum_{i=1}^{N} M_i \frac{Z_i - Z_{i-1}}{Z_i}}{\sum_{i=1}^{N} \frac{Z_i - Z_{i-1}}{Z_i}} \tag{2.26}$$

where M' is the depth-weighted soil moisture content, Z_i is the depth to the bottom of soil layers i, and N is the number of soil layers.

From the above Eq. (2.26), it is observed that the depth-weight is proportional to the thickness of each layer and is inversely proportional to the depth to each bottom layer. This modification is able to reflect more realistic situation where the upper layers have more influence on runoff estimates than do the lower layers. Eckhardt et al. (2002) further modified SWAT model for its application to the hilly regions of German that have thin soil layers. This modification generated the development of the SWAT-G model. This model does not use the entire soil moisture content for estimating daily CN values. But, it uses only the soil moisture content in upper first and second layers. Therefore, the entire soil moisture content, M in Eq. (2.20) is replaced with the sum of soil moisture content in the first layer (M1) and second layer (M2) altogether.

2.6.5 Mishra et al. Model

Mishra et al. (1998) used the linear regression approach analogous to the unit hydrograph scheme to transform rainfall excess into direct runoff, which enables the application of this method to even large basin. This model assumes CN variation with time t dependent on AMC (Ponce and Hawkins, 1996) only. The computed rainfall-excess Q (Eq. 2.4) is transformed to direct runoff amount (RO) using a linear regression approach. Taking base flow (O_b) as a fraction of F along with the time lag, the total daily flow Q(t), is computed as the sum of RO(t) and O_b. The model parameters were optimised by minimising the sum of squares of errors between the computed and observed runoff. The advantage of the Mishra et al. (1998) model is that it allows the transformation of rainfall excess to direct runoff and takes into account the base flow, enabling its application to even large basins.

This approach also leads to certain limitations such as the model does not distinguish between dynamic and static infiltration. It allows sudden jumps in CN values when changing from one AMC level to the other and problem of mass balance. The base flow is taken as a fraction of F, which is not rational. The water retained in the soil pores may not be available for base flow, rather the water that percolates down to the water table may appear at the outlet as base flow.

Thus, there exists a need for an improved model that eliminates for the most part these limitations, leading to the formulation of a model based on the modified SCS-CN method (Mishra and Singh, 2002a). The variability due to antecedent moisture is widely recognized in terms of AMCs and employs the concepts of antecedent precipitation index (API); antecedent base flow index (ABSF); and soil-moisture index (SMI) to identify the antecedent moisture condition. Thus, the antecedent moisture is the leading factor for the CN variability and has led to statistical (Hjemfelt, 1980; Hawkins, 1993, 1996; Bonta, 1997; McCuen, 2002) and stochastic (Hjelmfelt, 1982; Bhunya et al., 2003) consideration of curve number.

2.6.6 Mishra and Singh Model

In order to incorporate the antecedent moisture instead of AMCs to preclude the sudden jumps in the CN-variation, Mishra and Singh (2002a) modified the first hypothesis by including antecedent moisture (M) or initial soil moisture (V_0) in Eq. (2.2) as:

$$\frac{Q}{P-I_a}=\frac{F+V_0}{S+V_0} \tag{2.27}$$

Here, V_0 represents the amount of moisture content in the soil profile before the start of a rainstorm. The combination of Eqs. (2.1) and (2.27) leads to the following modified form of the SCS-CN model:

$$Q = \frac{(P - I_a)(P - I_a + V_0)}{P - I_a + V_0 + S} \tag{2.28}$$

For practical application, V_0 can be computed as:

$$V_0 = \frac{(P_5 - I_a)S_I}{P_5 - I_a + S_I} \tag{2.29}$$

where P_5 is the 5 days antecedent precipitation amount and S_I is the potential maximum retention corresponding to AMC I. Eq. (2.29) assume the watershed to be dry 5 days before the onset of the rain storm. Replacing S_I with $S+V_0$ in Eq. (2.29) and solving for V_0 gives the following expression for V_0.

$$V_0 = 0.5\left[-1.2S + \sqrt{0.64S^2 + 4P_5S}\right] \tag{2.30}$$

Here, + sign before the square root indicaties V_0 to be a positive value. A generalized form of Eq. 2.30 can be written as;

$$V_0 = 0.5\left[-1.2\lambda S + \sqrt{(1-\lambda)^2 S^2 + 4P_5S}\right] \tag{2.31}$$

where λ is equal to 0.2. Eqs. (2.28), (2.30) and (2.31) form the modified Mishra-Singh model. This model has only one-parameter similar to existing SCS-CN method and obviates the sudden jump in CN corresponding to changes in the antecedent moisture condition. The performance of this model is better than the existing SCS-CN method when tested with field data. Since, I_a relies on interception, surface storage, and infiltration (Ponce and Hawkins, 1996), which are highly dependent on initial soil moisture, there should be some explicit relationship between I_a and V_0. But, this model does not have any explicit relationship between I_a and V_o. The relationship S_I=$S+V_0$ is valid only for $I_a = 0$(Chen, 1982). Apart from this, there is no continuous formulation to use it for long term hydrologic simulation. term hydrologic simulation.

Mishra et al. (2002a) extended their approach as described above in Eqs. (2.27-2.29) by dividing the total infiltration (F) into the dynamic portion of infiltration (F_d) and the static portion of infiltration (F_c). Excluding the static infiltration F_c similar to I_a, in Eq. (2.27), this can be written as:

$$\frac{Q}{P-I_a-F_c}=\frac{F_d+V_0}{S+V_0} \tag{2.32}$$

Furthermore, the water balance equation can be expressed as:

$$P = I_a + F_c + F_d + Q \tag{2.33}$$

By combining Eq. (2.32) with Eq. (2.33), the modified form of the SCS-CN model with dynamic infiltration, static infiltration, and soil moisture can be obtained as:

$$Q=\frac{(P-I_a-F_c)(P-I_a-F_c+V_0)}{P-I_a-F_c+V_0+S} \tag{2.34}$$

If the condition of $P \geq I_a+F_c$ is satisfied, then direct runoff occurs.

Later, Mishra and Singh (2004a) presented a versatile long-term hydrological simulation model based on the modified SCS-CN method as expressed in Eq. (2.31). By discretizing the Eqs. (2.33 and 2.34) for time t, the water balance equation and the modified SCS-CN runoff of Mishra and Singh (2002b) can be described as:

$$P(t, t+\Delta t) = I_a(t) + F_c(t, t+\Delta t) + F_d(t, t+\Delta t) + Q(t, t+\Delta t) \tag{2.35}$$

$$Q(t, t+\Delta t) = \frac{\left[P(t, t+\Delta t) - I_a(t) - F_c(t,t+\Delta t)\right]\left[P(t,t+\Delta t) - I_a(t) - F_c(t,t+\Delta t) + V_0(t)\right]}{P(t,t+\Delta t) - I_a(t) - F_c(t,t+\Delta t) + V_0(t) + S(t)},$$

$$\text{for } P(t, t+\Delta t) \geq (I_a(t)+F_c(t.\ t+\Delta t)) \tag{2.36}$$

$$= 0 \qquad \text{otherwise}$$

where (t+Δt) is the time interval.

The dynamic infiltration, $F_d(t, t+\Delta t)$ means an increase in the amount of volumetric soil moisture during the time interval, so $F_d(t)$ is equal to $V_0(t)$. Therefore, $V_0(t)$ in Eq. (2.36) can be obtained from the $V_0(t, t+\Delta t)=F_d(t, t+\Delta t)$), and the dynamic infiltration $F_d(t, t+\Delta t)$ can be computed by using Eq. (2.35). The retention parameter S(t) in Eq. (2.36) is calculated by considering the evapotranspiration ET(t, t+Δt) and the soil moisture $V_0(t, t+\Delta t)$ as follows:

$$S(t+\Delta t) = S(t)-V_0(t, t+\Delta t)+ ET(t, t+\Delta t) \qquad (2.37)$$

The static infiltration $F_c(t, t+\Delta t)$ in Eq. (2.36) is regarded as gravitational infiltration, which is the product of final infiltration rate, f_c and the time interval (t+Δt). Details of the long term hydrological simulation model based on the above modified SCS-CN method are described in Mishra and Singh (2004a). Due to the inclusion of F_c and V_0, the Mishra and Singh model is the advanced approach for the improvement of runoff prediction performance. However, the number of calibration parameters is increased relative to the original curve number method, and the spatially averaged final infiltration rate, f_c, should be determined for direct runoff calculation. Apart from this, this model requires a priori knowledge of minimum infiltration rate.

2.6.7 Michel et al. Model

Recently, Michel et al. (2005) critically reviewed the soil moisture accounting procedure that lies behind the original SCS-CN method and pointed out severe structural inconsistencies in the treatment of antecedent condition. The original SCS method was time dependant, but it has long been applied to the cumulative rainfall at a number of points within the cumulative rainfall hyetograph in order to yield a rainfall-excess hydrograph (ASCE, 1996). One of the reasons for this is that the separation of events generally results from an arbitrary procedure, where some events can be cut into successive events depending on the chosen time threshold. However, if the SCS-CN formula is to be used within a continuous watershed model one cannot restrict the method to the total storm runoff depth. Therefore, Michel et al. (2005) hypothesize that the SCS-CN model is valid not only at the end of the storm but at any instant along a storm. Based on this hypothesis, they proposed a procedure more consistent from the SMA view point. Michel et al. considered an SMA store which would absorb that part of the rainfall that is not transformed into runoff by the SCS-CN equation (this amount is noted as (F+I_a) in the original SCS-CN method). Their SMA procedure is based on the notion that higher the moisture store level, higher the fraction of rainfall that is converted into runoff. If the moisture store level is full, all the rainfall will become runoff. The following SMA equation was given:

$$V = V_0 + P - Q \tag{2.38}$$

where V_0 is the soil moisture store level at the beginning of the rainfall event and V is the soil moisture store level at time when the accumulated rainfall is equal to P.

Based on the above hypothesis and Eq. (2.38), Michel et al. pointed out severe structural inconsistencies in the original SCS-CN method, arising partly from the confusion between intrinsic parameter and the initial condition, and partly from an incorrect use of the underlying SMA procedure. Then, with a change of parameter, by incorporating a new parameter 'S_a' and eliminating the initial abstraction term I_a and a sounder perception of the underlying SMA procedure, they proposed the generalized discrete and continuous forms and further simplified forms to compute the direct runoff. The generalized discrete Michel et al. (2005) sub-model for three different cases is given as follows:

If $V_0 \le S_a - P$, then $Q = 0$ (2.39)

If S_a-P< V_0 <S_a, then

$$Q = \frac{(P + V_0 - S_a)^2}{P + V_0 - S_a + S} \tag{2.40}$$

If $S_a \le V_0 \le S_a + S$, then

$$Q = P\left[1 - \frac{(S + S_a - V_0)^2}{S^2 + (S + S_a - V_0)P}\right] \tag{2.41}$$

As can be seen from the above model formulations, the third case ($S_a \le V_0$) corresponds to I_a<0, which is not found in the formulation of original SCS-CN method. Similarly, the generalized continuous Michel et al. sub-model based on their SMA procedure is given as follows:

$$q = P\left(\frac{V - S_a}{S}\right)\left(2 - \frac{V - S_a}{S}\right) \quad \text{for } V \ge S_a \qquad (2.42)$$

$$= 0 \quad \text{otherwise}$$

In application of both the models, V_0 is optimized. In the simplified form of Michel et al. sub-model, the parameter S_a is set as a fraction of S and V_0 is replaced by a fraction of S i.e. 0.33S, 0.61S, and 0.87S to accommodate the three AMCs via., AMC I, AMC II, and AMC III, respectively. On substituting the values of V_0 and S_a into Eq. (2.41), the corresponding expression for various AMCs are as follows:

for AMC I (V_0=0.33S) $$Q = p\frac{P}{P+S} \qquad (2.43)$$

for AMC II (V_0=0.61S) $$Q = p\frac{(0.48S + 0.72P)}{(S + 0.72)} \qquad (2.44)$$

for AMC I (V_0=0.87S) $$Q = p\frac{(0.79S + 0.46P)}{(S + 0.46P)} \qquad (2.45)$$

Thus, in the generalized form of Michel et al. model, V_0 is optimized, while it depends on the antecedent moisture condition in simplified form as also pointed out by Sahu et al. (2007). This simplification allows the unrealistic sudden jump in V_0 and further quantum jump in the computation of surface runoff. Sahu et al. suggested a need to develop a continuous equation to compute the antecedent or initial soil moisture and proposed an expression for V_0 using discrete data from 84 small watersheds from USA. Hence, there is a need to recast the SMA procedure proposed by Michel et al. by incorporating variation of daily CN with respect to the variability of antecedent rainfall and moisture availability prior to the rainfall. In the SMA procedure proposed by Michel et al., V_0 plays a vital role in the computation of surface runoff. Hence, there is a scope to develop an expression for V_0 to preclude the sudden jump in V_0 and computed surface runoff, and thus, to make the SMA procedure amenable to continuous hydrologic daily stream flow simulation.

2.6.8 Geetha et al. Model

Geetha et al. (2007) proposed an SCS-CN based lumped conceptual rainfall-runoff (LCRR) model to further modify soil retention parameter (S) and initial abstraction coefficient (I_a). Similar to Mishra-Singh model (2002a), this model also obviates the sudden jumps in CN values when changing from one AMC level to the other by incorporating the variation of daily CN with respect to the variability of antecedent rainfall and moisture availability prior to the storm. In this model, the curve number is attributed to antecedent moisture amount rather than the antecedent moisture conditions. The retention parameter is modified (SM(t)) as follows:

$$SM(t) = \frac{S(t)^2}{AM(t) + S(t)} \tag{2.46}$$

where AM(t) is antecedent moisture amount at time ‘t’ and can be computed by using the following expression:

$$AM(t) = \delta\sqrt{P_5(t)} \tag{2.47}$$

Here, δ is the coefficient of antecedent moisture and $P_5(t)$ is 5 days antecedent rainfall at time ‘t’. As can be seen from the original formulation of the SCS-CN method, in I_a-S relationship (Eq. 2.3), the value of λ is assumed as 0.2 for average conditions for practical applications. Many other studies carried out in the United States and other countries (SCS, 1972; Springer et al., 1980; Cazier and Hawkins, 1984; Ramasastri and Seth, 1985; Bosznay, 1989) report λ to vary in the range of 0 to 0.3. However, as the initial abstraction component accounts for the short-term losses such as interception, surface storage, and infiltration before runoff begins, the value of λ can take any value ranging from 0 to ∞ (Mishra and Singh, 1999a). Of late, Hawkins et al. (2001) reported that value of λ as 0.05 gives better fit to data and would be more appropriate for use in runoff calculations. By incorporating the storm duration and a non-linear relation for I_a, Jain et al. (2006b) suggested a more general I_a-S relation including P as:

$$I_a = \lambda S\left(\frac{P}{P+S}\right)^{\alpha'} \tag{2.48}$$

Here, α' is exponent of initial abstraction (I_a). Geetha et al. (2007) uses this expression for the formulation of long term hydrological simulation of stream flow using the single soil moisture store. The sub-surface flow component (i.e. base flow) is formulated based on the conceptual behaviour of soil moisture store (SMS) as given by Putty and Prasad (2000). Further, Geetha et al. (2008) proposed SCS-CN based continuous simulation model for hydrologic forecasting using surface store along with two sub-surface stores viz., soil moisture store (SMS) and ground water store (GWS) for sub-surface flow components (i.e. through and base flow).

Stores in the form of linear and non linear reservoirs are generally used in lumped rainfall-runoff models (Michel et al., 2003). Among these stores, the linear store is the simplest and most widely used as production or routing tool. The output of this store is proportional to the amount of stored water. There exist numerous rainfall-runoff models which use linear store (e.g. HBV model (Bergstorm and Forsman, 1973); IHACRES model (Jakeman et al., 1990); NAM model (Nielsen and Hansen, 1973); SMAR model (Kachroo, 1992); Sacramento model (Burnash and Ferral, 1982); Tank model (Sugawara, 1995a, b). Another efficient tool is the exponential store. It is generally considered to be a tool for recession and base flow simulation. Various mathematical laws are used to describe the outflow of such stores. An incorrect store formulation influences not only the exponential store parameters but also most of the other calibrated parameters (Michel et al., 2003). Therefore, the exponential store is more appropriate formulation of through flow and base flow components. Among the linear store, the Single Linear Reservoir (SLR) was commonly used to route the direct runoff in the existing SCS-CN based long term simulation model (e.g. Mishra and Singh (2004a) versatile two-stores model; Geetha et al. (2007) LCRR two-stores model; Geetha et al. (2008) LCRR three-stores model, etc.) due to its simplicity. Mishra and Singh (2004a) and Geetha et al. (2007) models are capable of simulating stream flow and its components such surface runoff and base flow, while model proposed by Geetha et al. (2008) can simulate the stream flow components such as through flow (lateral flow) and base flow.

2.7 SUB-SURFACE FLOW

Sub-surface flow, a hydrologic component of stream flow, is the flow of water beneath ground surface. It occurs when infiltrated rainfall meets an underground zone of low transmission, travels above the zone to the soil surface downhill and appears as a seep or spring. Generally, the stream flow analysis includes both surface and sub-surface flows. The analysis of surface flow is already discussed in the previous section. In comparison to the surface flow analysis, sub-surface flow analysis is more complex. It considers the movement of water throughout the entire hydrologic cycle. Its prediction is performed with models of varying complexity depending on the applications, requirements, and constraints. The model used may be discrete, which utilized relatively simple techniques for estimating sub-surface contribution to a flood hydrograph or continuous, which accounts for the movement of water throughout the entire hydrologic cycle. Continuous accounting of water movement involves the consideration of precipitation, snow melt, surface loss, infiltration, and surface transport processes as a part of surface flow process and evapotranspiration, soil moisture redistribution, and ground water transport as a part of sub-surface flow.

As such, the total stream flow consists of combination of surface flow and sub-surface flow viz., through flow and base flow. After satisfying the initial demand of soil moisture zone, the excess water drained out of it to contribute as a sub-surface flow. The sub-surface flow further percolates down into the groundwater zone. Generally, the sub-surface flow is modeled with more numbers of stores than surface flow. The surface flow is modeled with surface store, while sub-surface flow is modeled with soil moisture store (SMS) and ground water store (GWS) (e.g. CEQUEAU model (Girard et al., 1972); SAHYADRI model (Putty and Prasad, 2000); LCRR model (Geetha et al., 2008), etc. Examples exist in literature where rainfall-runoff model uses even more than two stores. BUCKET model (Thronthwaite and

Mather, 1957), ABCD model (Thomas, 1981), and IHACRES model (Jakeman et al., 1990) considered three store such as SMS, channel store 1, and channel store 2. GR5J (Ma et al., 1990) and ARNO model (Todini, 1996) considered SMS, GWS, and channel store. SACRAMENTO (Burnash et al., 1973) and CATPRO model (Rapper and Kuczera, 1991) considered interception store, SMS, GWS and channel store. TOPMODEL (Beven and Kirkby, 1979) considered interception store, SMS, and channel store and HBV model (Bergstrom, 1995) considered upper soil store, lower soil store and GWS, while TANK model (Sugawara, 1961, 1984, 1995a) consider one additional store, surface store, than HBV model. XINAJIANG (Zaho et al., 1980) considered upper soil store, lower soil store, channel store 1 and channel store 2.

In general, the hydrological models are developed and utilized either for generating stream flow or to determine how runoff is affected by factor such as afforestation, urbanization or rainfall augumentation. However, it is also possible to utilize the model as an investigation tool for learning catchment response and inferring about the runoff processes in the catchment. Beston (1964) studied the response of partial source area of runoff by developing the regression model. Freeze (1972) made deductions about soil parameters using a sub-surface flow model. Smith and Hebbert (1983) used an unsaturated vertical flow model to infer the influence of soil depth and anisotropy on source areas and runoff. Comparing stream flows predicted by catchment model with observed flows, Ward (1984) suggested physical processes to which the differences between predicted and observed flows are linked with the stream flow generation mechanism in the region. Putty and Prasad (2000) developed a three-component (two-store model) watershed model (SAHYADRI) to understand runoff processes in the Western Ghats, India. The results of SAHYADRI model, which is developed in accordance with the postulations of the theory of variable source areas forms a useful first step in understanding the response characteristics of the catchments in the Western Ghat regions of South India.

2.7.1 SAHYADRI (Putty and Prasad, 2000) Model

Putty and Prasad (2000) has developed a lumped parameter SAHYADRI model to simulate saturated source area runoff, lateral flow through pipes and the saturated zone groundwater flow. SAHYADRI model simulates daily runoff as a combination of three components, such as, the saturated source area runoff (also called quick flow), the soil zone lateral seepage or flow through pipes and macro pores (called lateral flow) and the saturated soil zone discharge (called groundwater flow). The source area is modelled as an exponential function of the storage in the soil zone (Θ) and in the groundwater zone (ψ). The evaporative demand on the storage in the soil zone is modeled as:

$$\text{EVPT} = \text{EVP-CEP} \tag{2.49}$$

where EVP is the potential rate of evapotranspiration, and CEP is the interception.

Transpiration (ET) from the soil zone is a function of EVPT and the storage available in the soil zone (Θ), which is supplied by infiltration (INFL= RAINET – SARO). ET is calculated as;

$$ET = EVP\left(\frac{\theta - \theta_w}{\theta - \theta_p}\right) \tag{2.50}$$

where Θ_w is the wilting point and Θ_p is a parameter of the soil zone representing its water holding capacity. The soil zone storage begins to get depleted due to drainage, when the storage exceeds the field capacity (θ_f). The rate of drainage (DR) is taken to be the outflow of a linear reservoir, given by

$$\text{DR} = P_2 (\Theta - \Theta_f) \tag{2.51}$$

where P_2 is the soil zone recession coefficient. A constant proportion (P_3, the pipe flow runoff coefficient) of the draining water is assumed to become pipe flow (THR). A non-linear model for drainage was found to offer no particular advantage (Putty and Prasad, 1994), and in the interests of keeping the number of model parameters low, the linear model was adopted. The remaining part (PR) percolates down into the groundwater zone. The groundwater flow (BF), which is assumed to form the delayed component of streamflow, is modelled as outflow from a non-linear store as:

$$BF = P_4(\psi)^{E_g} \tag{2.52}$$

where ψ is the water content in the ground water zone and the parameters P_4 and E_g are, respectively, termed as the coefficient and exponent of the zone. The daily water balance of each zone is maintained separately and the total runoff for any day is calculated by summing the three components.

El-Sadek et al. (2001) performed the comparative analysis of lateral field drainage sub-programme by using WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) (Vanclooster et al., 1996), SWAP (Soil Water Assessment Programme) (Van Dam et al., 1997) and DRAINMOD (Skaggs, 1980) to simulate lateral sub-surface drainage flow. It was observed that the WAVE model, in comparison to the SWAP and DRAINMOD model, provided as good a prediction of the lateral sub-surface drainage flow to drains. Similarly, Yuan et al. (2001) modified SCS-CN method to estimate sub-surface drainage flow from rainfall.

2.7.2 Yuan et al. Model

Based on the results obtained through the testing of SCS-CN concept in the modified form to five drainage monitoring stations in the Little Vermilion River (LVR) watershed in East-Central Illinois, Yuan et al. (2001) found that SCS-CN concept can be used to predict the sub-surface drainage flow. The concept behind the SCS-CN method was modified through theoretical analogy to estimate sub-surface drainage flow from rainfall. When accumulated sub-surface drainage flow is plotted versus accumulated infiltration, sub-surface drainage flow starts after some infiltration has accumulated and the relationship becomes asymptotic to a line of 45° slope, just as the generalized SCS rainfall-runoff relationship as shown in Fig. 2.1.

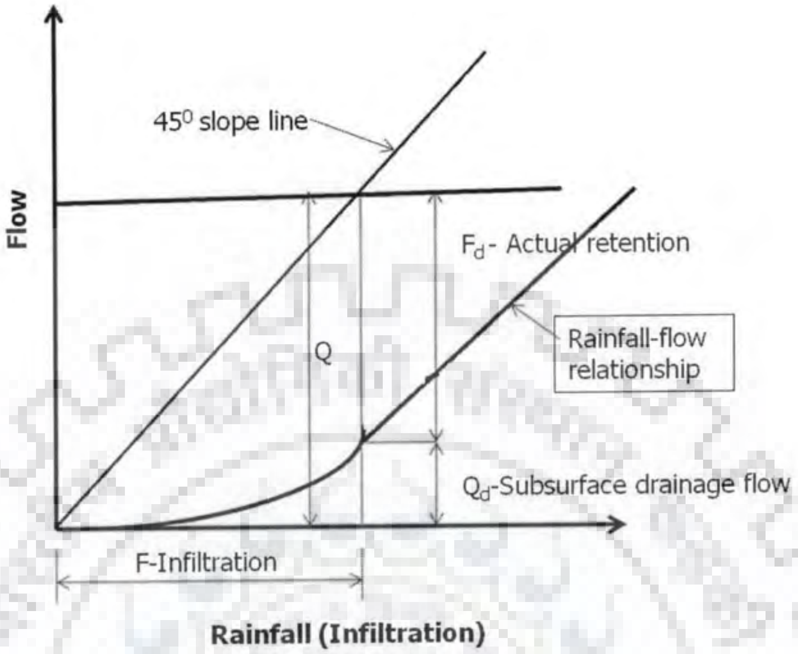


Fig. 2.1 Typical Rainfall and Flow Relationship (Source: Yuan et al., (2001))

Yuan et al. introduced the procedures for modification of the SCS-CN method and determination of curve numbers for sub-surface drainage flow. By analogy, for sub-surface drainage flow, the SCC-CN equation becomes as follows:

$$\frac{F_d}{S_d} = \frac{Q_d}{F} \tag{2.53}$$

where F_d = actual retention after flow begin, S_d = potential maximum retention, Q_d= drainage flow depth ($F>Q_d$), and F=infiltration depth.

If there is no initial abstraction or if one begins the water accounting after initial abstractions, then Eq. (2.53) can be rewritten as:

$$\frac{F-Q_d}{S_d} = \frac{Q_d}{F} \tag{2.54}$$

However, initial abstractions in the form of moisture store changes must be considered and the amount of infiltration available for drainage flow is (F-ΔS_m). By substituting (F- ΔS_m) in Eq. (2.54) gives the following equation:

$$\frac{F-\Delta S_m - Q_d}{S_d} = \frac{Q_d}{F-\Delta S_m} \tag{2.55}$$

If, for simplicity, it is assumed that no surface runoff occurs then Q=0 and after substituting this in Eq. (2.1), gives the following expression:

$$F = P - I_a \tag{2.56}$$

Then, substituting Eq. (2.56) into Eq. (2.55), gives the following equation:

$$\frac{P-I_a-\Delta S_m - Q_d}{S_d} = \frac{Q_d}{P-I_a-\Delta S_m} \tag{2.57}$$

Now, assuming $I_d = I_a + \Delta S_m$, gives

$$\frac{P-I_d-Q_d}{S_d} = \frac{Q_d}{P-I_d} \tag{2.58}$$

Solving for Q_d, it yields into the following expression to compute the sub-surface drainage flow.

$$Q_d = \frac{(P-I_d)^2}{P-I_d+S_d} \tag{2.59}$$

Eq. (2.59) is valid only if $P > I_d$; $Q_d = 0$, otherwise. If it is assumed that the surface runoff occurs, then Eq. (2.1) gives

$$F = P - I_a - Q \tag{2.60}$$

where P=rainfall depth (P>I_a), I_a = interception, and Q = surface runoff. After substituting Eq. (2.60) into Eq. (2.57) and assuming $I_d = I_a + \Delta S_m$, gives

$$\frac{P-I_d-Q-Q_d}{S_d}=\frac{Q_d}{P-I_d-Q} \tag{2.61}$$

Solving for Q_d, the following expression is yields for sub-surface drainage flow as:

$$Q_d=\frac{(P-I_d-Q)^2}{(P-I_d-Q+S_d)}, \qquad P>I_d \tag{2.62}$$

$$=0 \qquad \text{otherwise}$$

Eq. (2.62) can be used for computation of sub-surface drainage flow.

2.8 Concluding Remarks

From the cited literature, it is observed that most of the existing lumped conceptual hydrological models include the limited hydrological processes like surface runoff, base flow, infiltration, interception, and evapotranspiration (for example, the model like Boughton model, Kentucky watershed model, Institute of Hydrology model, etc.). There are a very few hydrologic simulation models existing in the hydrologic literature which account most of the hydrologic processes such as transpiration, drainage, percolation including deep percolation, through flow, and moisture in unsaturated and saturated soil zones (see e.g. Putty and Prasad (2000), Geetha et al. (2008), etc.).

Despite the limitation of the original SCS-CN method, this method has been successfully employed in several long-term simulation models by using appropriate SMA procedure to compute the surface runoff (e.g. Williams and LaSeur, 1976; Hawkins, 1978; Arnold et al., 1990; Mishra and Singh, 2004; Geetha et al., 2007; Geetha et al., 2008). Of late, Michel et al. (2005) reviewed the SMA procedure that lies behind the original SCS-CN method and pointed out several structural inconsistencies in the treatment of antecedent condition and, in turn, proposed a procedure that is more consistent from SMA view point. Michel et al. (2005) proposed generalized form for continuous as well as discrete computation of surface runoff and simplified form of model for discrete computation of surface runoff. However, the Michel et al. concept also needs refinement particularly in defining the initial moisture level and the proposed SMA procedure to incorporate it for the long term simulation. In the generalized form (continuous as well as discrete) of Michel et al. model, V_0 is optimized, whereas it depends on the different AMCs in simplified form. This allows an unrealistic sudden jump in the estimation of CN and V_0 and further quantum jump in the computation of surface runoff. In the SMA procedure proposed by Michel et al., V_0 plays a vital role in the computation of surface runoff. But, there is no expression for computation of V_0 and intrinsic parameter (S_a) suggested in literature.

A great deal of published material on SCS-CN method along with application is available in hydrologic literature. However, comparatively less effort has been put towards the use of SCS-CN method for long term hydrologic simulation. It is also observed from the cited literature that the SMA concept based on SCS-CN method is used for computation of surface flow only and the potential of its extension to base flow computation (Yuan et al., 2001) has yet to be explored. The concept behind the SCS-CN method can also be applied to compute the sub-surface flow components via sub-surface drainage flow computation from rainfall (Yuan et al., 2001). Hence, there is also a scope to develop further the conceptual frame work proposed by Yuan et al. (2001) to simulate the sub-surface flow components based on the modified SCS-CN concepts.

Thus, there exists a need for recasting the soil moisture accounting (SMA) procedure by incorporating the variation of daily CN with respect to the variability of antecedent rainfall and moisture availability prior to the rainfall and with possibility of representing the sub-surface flow components based on the modified SCS-CN concept by using linear and exponential stores to make it amenable to continuous long term simulation of daily stream flows.

CHAPTER 3

DEVELOPMENT OF SCS-CN BASED MODELS FOR LONG TERM HYDROLOGIC SIMULATION OF STREAM FLOW

3.1 GENERAL

The process of transformation of rainfall into runoff is highly complex, dynamic, non-linear, and exhibits temporal and spatial variability. It is further affected by many and often inter-related physical factors and interactions occurring at the soil–vegetation–atmosphere interface. It is impossible to have a complete representation of every process existing in the system. However, with present technological capabilities and availability of data, it is possible to identify and understand the response of major processes quite accurately, and this, in turn, allows simplification of the system (Geetha et al., 2008).

Hydrological models can be formulated by following four steps: conceptualization, formulation, calibration, and validation (McCuen, 2005). The conceptualization of the various processes concerned is the composite of all of the thought processes that take place in analyzing a new problem and inventing a solution. It is a non-definable mixture of art and science (James, 1970). In the formulation stage of model development, the concepts are converted to a form that can be computed in the form of equations or graphical relations. In brief, conceptualization involves deciding what effect the model will simulate or determining which specific hydrologic processes are important in solving the problem at hand, while the formulation is the phase where functional forms are selected to represent the concepts and hence provide a structural representation of the selected processes. The calibration stage of modeling to the relevant conditions is a necessary task and an important determinant of the accuracy of future predictions. It represents the extraction of knowledge from data. The last stage of modeling is the validation of model that enables testing of the calibrated model and also measures the accuracy of the model under a wide array of conditions, even conditions beyond the range of the data used in model calibration.

In this Chapter, the soil moisture accounting (SMA) procedure that lies behind the original Soil Conservation Service Curve Number (SCS-CN) method is modified in different ways to eliminate the limitations and demerits of this conventional technique for direct surface runoff computation. Also, the conceptual frame-work proposed by Yuan et al. (2001) for sub-surface drainage flow is re-formulated for the computation of sub-surface drainage flow in one of the proposed models. Employing these modified versions of SCS-CN concept, four different long-term hydrologic simulation models are proposed to simulate watershed response to input daily rainfall. The details about the model formulation and computational procedure for optimization of various parameters involved in proposed models in the present study are described in this Chapter.

3.2 DEVELOPMENT OF SCS-CN BASED SMA MODELS FOR LONG TERM HYDROLOGIC SIMULATION

As stated earlier (Chapter 2), Michel et al. (2005) proposed a new SMA procedure that lies behind the SCS-CN method for computation of direct runoff. However, the proposed SMA procedure also needs refinement particularly in defining the initial moisture level (V_0). The initial soil moisture store level (V_0) depends on the antecedent moisture conditions (AMCs), which allows the unrealistic sudden jump in V_0 and, in turn, a quantum jump in the computation of surface runoff. Hence, there is a need to recast the SMA procedure proposed by Michel et al. (2005) to make it amenable for long term simulation. Therefore, in the present study, the simplified model of Michel et al. (2005) is modified to make it continuous long term hydrologic simulation model.

Thus, the long term hydrologic simulation (LTHS) models are formulated in this study by modifying the SMA procedure that lies behind the existing SCS-CN concept in four different ways, and hence, four different lumped conceptual LTHS models are proposed to carry out long term simulation of daily stream flows. The first model (Model-I) is designated as LTHS MICHEL I in the present study and uses the expressions proposed by Michel et al. (2005) for soil moisture store level prior to rainfall occurrence (V_0) for various antecedent moisture conditions (AMCs), via AMC I, II and III (Hawkins, 1978; Hawkins et al., 1985) based on the antecedent rainfall (Table 2.1 and Table 2.2) to compute direct runoff (RO) and sub-surface flow computation based on the conceptual behavior of soil moisture store (SMS) and ground water store (GWS) as given by Putty and Prasad (2000). The second model (Model-II), designated as LTHS MICHEL II is formulated based on antecedent moisture amount (AM) due to 5 days antecedent rainfall prior to the storm to avoid the sudden jump in CN and further quantum jump in V_0 and, in turn, the modification in the computation of RO. In the previous two LTHS models, V_0 plays a vital role in the improvement of SMA procedure via improvement in surface flow components. Despite this improvement, these models, however, do not contain any expression for V_0. Therefore, in the third model (Model-III), designated as LTHS ASMA I, where ASMA stands for Advance Soil Moisture Accounting, an expression for V_0 is proposed based on value of pre-antecedent moisture level before the onset of rainfall (V_{00}). This forms the advanced soil moisture accounting (ASMA) procedure. In both, LTHS MICHEL II and LTHS ASMA I models, the sub-surface flow components are modeled similar to LTHS MICHEL I model. The fourth model (Model-IV), designated as LTHS ASMA II, is similar to Model-III (LTHS ASMA I) for surface runoff computation but differs in computation of sub-surface drainage flow. In this model, apart from use of ASMA procedure, an expression for sub-surface drainage flow is developed by modifying the concept of Yuan et al. (2001).

The formulations of all four LTHS models described below are primarily based on realistic concepts that describe water movement through a watershed. They incorporate the original SCS-CN concept and modified form of SMA procedure proposed by Michel et al. (2005). These models are conceptualized to have two different moisture stores via SMS and GWS and accounting of these stores are considered on daily basis. The total stream flow of watershed is quantified by incorporating sub-modules for surface runoff, lateral flow, and base flow. The initial soil moisture level is used to calculate the space available for water retention. The details about the proposed modified SCS-CN concept based SMA models for long term hydrologic simulation is described in the following sections of this Chapter.

3.3 MODEL-I: LTHS MICHEL I

As discussed earlier (Chapter 2), Michel et al. (2005) proposed a new SMA procedure for long term simulation of stream flow and it, in turn, led to two models for continuous and discrete computation of direct runoff. In the present study, the discrete formulation of the Michel et al. (2005) model was modified to convert it into continuous simulation model after modification and incorporation of expressions for V_0 to form a new LTHS model designated here as LTHS MICHEL I model. Thus, model I is a modified form of Michel et al. (2005) discrete model after recasting the SMA procedure in the SCS-CN concept to make it usable for long term hydrologic simulation. It consists of three major stream flow generation components; (i) direct surface runoff, (ii) lateral flow and (iii) base flow. The stream flow is quantified by incorporating sub-modules for each of these components. The surface runoff is computed based on modified SCS-CN concept for SMA procedure proposed by Michel et al. (2005), while the sub-surface flow components, viz., lateral flow and base flow are modeled as conceptual behavior of SMS and GWS as given by Putty and Prasad (2000). The model has been formulated by accounting the major hydrologic phenomena such as initial soil moisture level, surface runoff, evapotranspiration, sub-surface drainage, percolation, lateral flow, deep percolation, base flow, deep seepage, etc. which control the water movement in a watershed. Accounting for soil moisture and ground water store is considered on daily basis. The initial soil moisture level is used to calculate the space available for water retention. In this model, the daily maximum potential water retention S(t) is varied depending on various AMC levels for which, the expression for initial soil moisture (V_0) is formulated.

The daily computation of direct runoff in this model largely depends on AMCs due to which the daily curve number varies. The computed direct runoff is routed to the outlet of the catchment using a single linear reservoir. Since the SCS-CN method is an infiltration loss model, a portion of the infiltrated water is added into SMS and further in GWS. A portion of the SMS is taken as lateral flow, routed exponentially to the catchment outlet, while the portion of GWS is routed exponentially to the catchment outlet as base flow contribution in the total stream flow. The total stream flow is the sum of the routed surface runoff, lateral flow, and base flow and it is quantified by incorporating sub-modules for each these stream flow components. The mathematical formulations for of various components of stream flow generating process in this model is presented in Fig. 3.1 and further discussed in the following sections.

3.3.1 Surface Flow

The surface flow occurs only when the rainfall rate is greater than the infiltration rate. It is that part of rainfall which appears in the total stream flow after the initial demands of the interception, infiltration, and surface storage have been satisfied. In the LTHS MICHEL I model, the SMA procedure proposed by Michel et al. (2005) for simplified case is modified and used for direct runoff computation. As stated earlier, Michel et al. hypothesized that the SCS-CN model was valid not only at the end of the storm but also at any instant during a storm. They considered an SMA store which would absorb that part of the rainfall not transformed into runoff by the SCS-CN equation. This amount is noted as F + I_a in the original SCS-CN method. Their SMA procedure is based on the notion that higher the moisture store level, higher the fraction of rainfall that is converted into runoff. If the moisture store level is full, all the rainfall will become runoff.

The Michel et al. (2005) gives the SMA equation as mentioned in the previous chapter 2 (Eq. 2.38). This SMA equation (Eq. 2.38) at time‘t’ can be re-written as follows:

$$V(t) = V_0(t) + P(t) - RO(t) \tag{3.1}$$

where $V_0(t)$ = soil moisture store level prior to occurrence of rainfall (mm) at time ‘t’. V(t) = soil moisture store level at time ‘t’, i.e. when the accumulated rainfall is equal to P(t), (mm), and RO(t) = direct runoff at time ‘t’.

Based on the above hypothesis and Eq. (3.1), Michel et al. pointed out several structural inconsistencies in the original SCS-CN method, arising partly from the confusion between the intrinsic parameter and the initial condition, and partly from an incorrect use of the underlying SMA procedure. Then, by incorporating a new parameter ‘S_a’ and

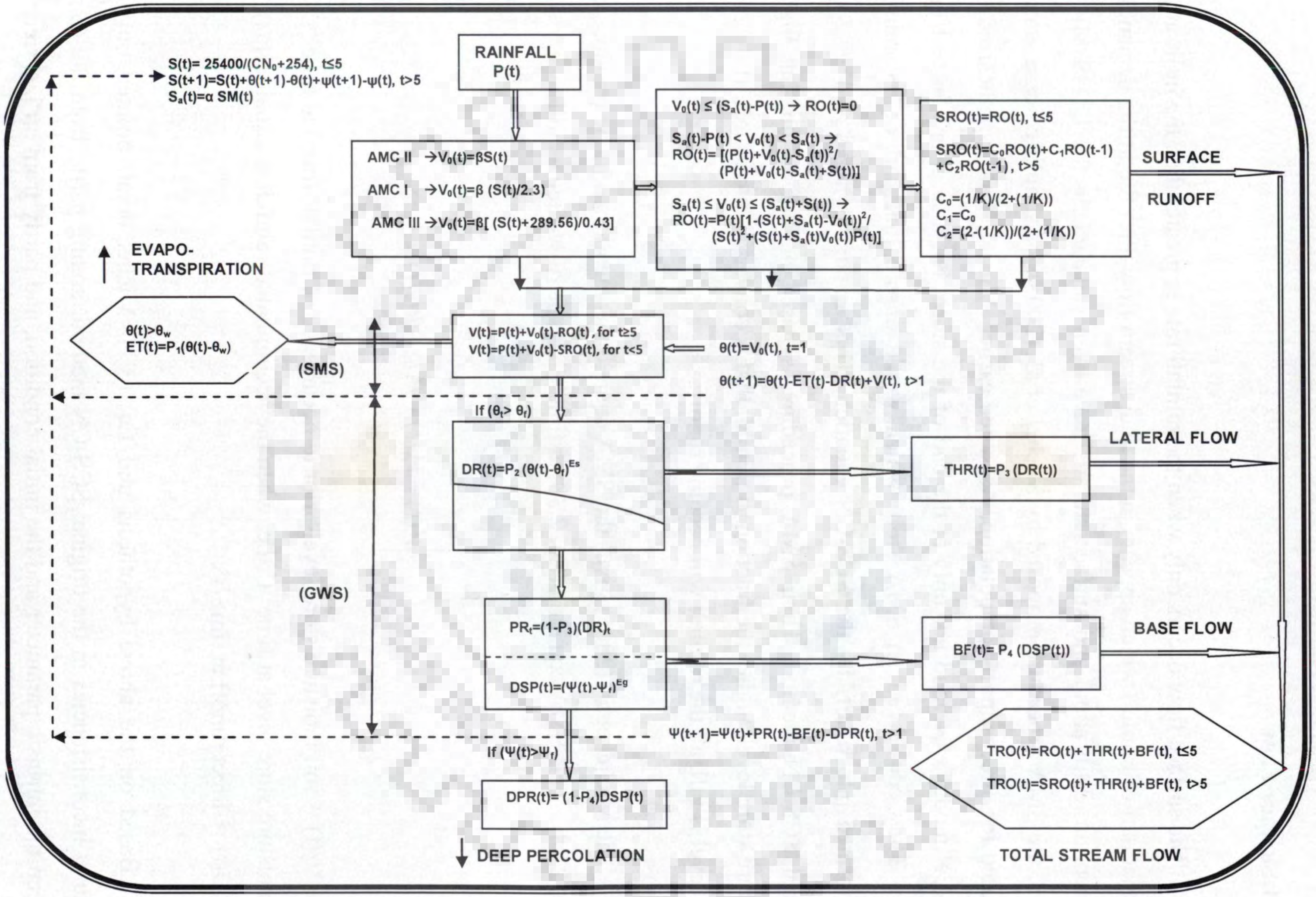


Fig. 3.1 Block Diagram Showing Mathematical Formulations of Various Components of Stream Flow for the Proposed LTHS MICHELI Model

eliminating the initial abstraction term I_a, they proposed a sounder SMA procedure. Based on this concept, a continuous long term hydrologic simulation model is formulated to compute the direct surface runoff by re-writing the Eqs. (2.39-2.41) described in Chapter 2, at time‘t’, as follows:

$$\text{If } V_0(t) \le S_a(t) - P(t), \text{ then RO(t)} = 0 \tag{3.2}$$

If $(S_a(t) - P(t) < V_0(t) < S_a(t))$, then

$$\text{RO(t)} = \frac{(P(t) + V_0(t) - S_a(t))^2}{(P(t) + V_0(t) - S_a(t) + S(t))} \tag{3.3}$$

If $S_a(t) \le V_0(t) \le (S_a(t) + S(t))$, then

$$\text{RO(t)} = P(t)\left[1 - \frac{(S(t) + S_a(t) - V_0(t))^2}{(S(t))^2 + (S(t) + S_a(t) - V_0(t))P(t)}\right] \tag{3.4}$$

The parameter S_a is set as a fraction of S as proposed by Michel et al. (2005);

$$S_a(t) = \alpha\, \text{S(t)} \tag{3.5}$$

where α = a parameter (fraction) determined by optimization. The parameter S(t) is potential maximum retention at time ‘t’. It can be obtained using the relationship given in the previous Chapter 2 (Eq. 2.8) at time‘t’, as follows:

$$S(t) = \frac{25400}{CN(t)} - 254 \tag{3.6}$$

Here, the value of S(0) (in mm) corresponds to CN_0 for first day of simulation, but it is further updated for next day by using the daily changes in SMS and GWS accounting, the losses through evapotranspiration and deep seepage and the daily input to the soil moisture store level, in order to get the possible space for water retention. In the simplified form of Michel et al. (2005) model, V_0 is replaced by a fraction of S and expression for this is described below.

As already stated in section 2.5.2 of Chapter 2, SCS defines the antecedent moisture condition as an index of watershed wetness and classifies it into three levels via AMC I, AMC II and AMC III. These conditions refer to wet, normal, and dry conditions, respectively. In the formulation of this model, AMC II (average or normal condition) is taken as the basis from which adjustments to daily curve numbers are made. AMC I and AMC III are the lower and upper bounds of curve number (Hjelmfelt, 1991). The term antecedent varies from previous 5 to 30 days in literature (SCS, 1992; Singh, 1992; Mishra and Singh, 2003 a). However, no explicit guideline is available to vary the soil moisture with the antecedent rainfall of certain duration. Since the NEH-4 (SCS, 1971) uses 5-day rainfall based on the exhaustive field investigations; this duration of 5 days is retained here also. In this model, the curve number CN is considered as initial curve number (CN_0) for the first day of the simulation (June 1). As the time advances, CN varies with respect to AMC level, based on the antecedent rainfall (P_5). The antecedent rainfall at time't' ($P_5(t)$) can be computed by using the following expression:

$$P_5(t) = P(t-1) + P(t-2) + P(t-3) + P(t-4) + P(t-5) \tag{3.7}$$

Here, 't' is the current day and P is the rainfall of the respective day. Different AMC class limits for dormant or growing season based on P_5 are decided from Table 2.2 (Ponce, 1989; Mishra et al., 1998). In the present study, June 1 (beginning day of simulation)-October 31 is considered as the dormant season, and rest of period of the year is considered as the growing season. Thus, the variation in curve numbers based on the total rainfall in the 5-days preceding the storm under consideration (Woodward and Croshney, 1992) and CN(t) of t^{th} day which corresponds to CN_{II} is converted to CN_I or CN_{III} as given in Table 2.3 of Chapter 2 (Hawkins et al., 1985).

$$CN_I = \frac{CN_{II}}{2.3 - 0.013CN_{II}} \tag{3.8}$$

$$CN_{III} = \frac{CN_{II}}{0.43 - 0.0057CN_{II}} \tag{3.9}$$

which are valid for AMC I or AMC III. It is worth noting that the initial value of CN = CN_0 at the starting day of simulation. Since the month of May and June are usually quite hot with highest evapotranspiration, dry soils contain minimum moisture in their pores leading to availability of maximum pore space for moisture retention. Therefore, a minimum CN-value is likely to occur during this period, and designated as CN_0. The current space available for water retention (S(t)) for the first day of simulation (June 1) is based on value of CN_0, a optimized value of CN. Thus,

$$S(t)=S(0) \qquad \text{for } S(t)\geq S(0) \tag{3.10}$$

where S(0) is corresponds to CN_0 derivable from Eq. 3.6.

Now, using the CN conversion formulae (Eq. 3.8 and Eq. 3.9) from AMC II (normal) to AMC I (dry) or AMC III (wet) levels (Hawkins et al., 1985), the expressions for V_0 are derived as follows (Durbude et al., 2010):

$$\text{For AMC II } (S_{II}(t)), \qquad V_0(t)=\beta[S(t)] \tag{3.11}$$

$$\text{For AMC I}\left(S_I(t)=\left(\frac{S_{II}(t)}{2.3}\right)\right), \qquad V_0(t)=\beta\left[\frac{S(t)}{2.3}\right] \tag{3.12}$$

$$\text{For AMC III}\left(S_{III}(t)=\left(\frac{S_{II}(t)+289.56}{0.43}\right)\right), \quad V_0(t)=\beta\left[\frac{S(t)+289.56}{0.43}\right] \tag{3.13}$$

where β is coefficient of initial soil moisture store level (V_0), a fraction of S to be determined by optimization.

3.3.1.1 Routing of direct runoff

Based on the principle of continuity and storage equations, the daily direct runoff is routed to the outlet of the watershed using single linear reservoir (SLR) (Nash, 1957; Ponce, 1989). The spatially lumped form of the continuity equation for a watershed can be written as follows:

$$I-O=\frac{\Delta S}{\Delta t} \tag{3.14}$$

The simplest storage-discharge relationship used in hydrology is

$$S = KO \tag{3.15}$$

where K is coefficient (day), I is the inflow (mm/day), O is the outflow (mm/day), and S is the storage (mm), different from SCS-CN parameter 'S'. These quantities are function of time't'. Since, this model uses the input on daily basis, the time step is 1-day interval. Eq. (3.14) is also known as water budget equation or volume balance equation and it is one of the basic equations used in hydrologic analysis.

The direct runoff at time 't', RO(t) (Eqs. 3.2-3.4) is routed using a single linear reservoir to produce the surface runoff (SRO(t)) at the outlet of the basin after the number of days exceeds 5 (Nash, 1957; Mishra and Singh, 2003a) to account for catchment induced storage effects as follows:

$$SRO(t) = C_0\,RO(t) + C_1\,RO(t-1) + C_2\,SRO(t-1) \tag{3.16}$$

where

$$C_0 = \frac{(1/K)}{2+(1/K)} \tag{3.17}$$

$$C_1 = C_0 \tag{3.18}$$

$$C_2 = \frac{2-(1/K)}{2+(1/K)} \tag{3.19}$$

Here, SRO(t) is the routed direct runoff at the outlet of catchment and K is the storage coefficient to be determine through optimization. In linear reservoir routing, the amount of attenuation is a function of $\Delta t/K$. Values of $\Delta t/K$ greater than 2 can lead to negative attenuation (Ponce, 1989).

3.3.2 Evapotranspiration

Evapotranspiration (ET(t)) is the combination of evaporation from the soil surface and transpiration from the vegetation. It is the amount of water that goes back or lost to the atmosphere. The transpiration from vegetation in the unsaturated zone is considered as a function of the soil moisture available in SMS above the wilting point of the soil (Putty and Prasad 1994, 2000; Mishra et al. 2005). In the evapotranspiration process, the transpiration is considered as much more dominant factor than evaporation. Hence, in the present study, the evapotranspiration is assumed equivalent with transpiration and it is expressed as (Durbude et al., 2010):

$$ET(t) = P_1\,(\Theta(t) - \Theta_w) \tag{3.20}$$

where P_1= coefficient of transpiration from soil zone, $\Theta(t)$ = soil moisture content at time 't', Θ_w = wilting point of the soil. The soil moisture content ($\Theta(t)$) for the first day of simulation is considered as V_0. The soil moisture content for the next day of simulation is upgraded based on the soil moisture store level (V(t)), evapotranspiration (ET(t)), and drainage (DR(t)) at time 't', as described in the subsequent section.

3.3.3 Sub-surface Flow

Sub-surface flow is the flow of water beneath ground surface. It occurs when infiltrated rainfall meets the underground zone of low transmission, travels above the zone to the soil surface downhill, and appears as a seep or spring. The total stream flow consists of combination of lateral flow and base flow as a part of sub-surface flow components. After satisfying the initial demands and saturating the SMS, moisture content in excess of field capacity (Θ_f) in the unsaturated zone drain out of it (Putty and Prasad, 2000; Mishra et al., 2005). Since the moisture store in the sub-surface or in GWS is considered as non-linear, the sub-surface flow is considered to be an exponential function of available moisture only when it exceeds field capacity as (Durbude et al., 2010):

$$DR(t) = P_2\,(\Theta(t) - \Theta_f)^{Es} \tag{3.21}$$

where DR(t) = drainage rate at time 't', P_2 = subsoil drainage coefficient, $\Theta(t)$ = soil moisture content at time 't', Θ_f = field capacity of the soil in unsaturated zone, and E_s = exponent of unsaturated moisture zone. The sub-surface flow can be further partitioned into two components: (i) sub-surface flow in lateral direction as lateral flow and (ii) sub-surface flow in vertical direction as percolation into ground water zone.

3.3.3.1 Lateral flow

Part of sub-surface flow moving in lateral direction eventually joins the stream flow as lateral flow and can be considered as a fraction of the sub-surface flow (Putty and Prasad, 1994, 2000). In the present study, it is computed as:

$$THR\,(t) = P_3\,DR(t) \tag{3.22}$$

where THR(t) = lateral flow at time 't' and P_3= unsaturated soil zone runoff coefficient.

3.3.3.2 Percolation

The sub-surface flow occurring in vertical direction meets GWS due to soil permeability. The percolated amount of water is modeled as (Putty and Prasad, 1994, 2000; Mishra et al., 2005):

$$PR(t) = (1\text{-}P_3)\ DR(t) \tag{3.23}$$

where PR(t) = percolation at time 't'. GWS, a saturated store, can be considered as a non-linear reservoir and from this saturated store, outflow occurs at an exponential rate in the form of deep seepage. Since the saturated store is considered as a non-linear store, the deep seepage is taken as an exponential function of percolation.

In the formulation of deep seepage, the ground water content for the first day of simulation ($\psi(1)$) is optimized and further upgraded based on percolation (PR(t)), base flow (BF(t)) and deep percolation (DPR(t)) at time t, as explained in the subsequent section. The deep seepage will occur after satisfying the initial demand and saturating the GWS and the ground water content in excess of field capacity (Θ_f) in the saturated zone (ground water zone), as follows (Durbude et al., 2010):

$$DSP(t) = (\psi(t) - \psi_f)^{Eg} \tag{3.24}$$

where DSP(t) = deep seepage at any time 't', $\psi(t)$ = ground water at time 't', ψ_f = field capacity of the soil in the ground water zone, and E_g = exponent of ground water zone. In the present model, the initial ground water ($\psi(1)$) is taken as ψ_0, which is determined by optimization. The ground water content is updated by considering the percolation into the GWS, base flow, and deep percolation loss from GWS. Notably, the deep seepage can travel in both lateral and vertical directions through GWS and is bifurcated into two components: (i) active ground water flow (base flow) and (ii) inactive ground water flow (deep percolation) into the aquifers.

3.3.3.3 Base flow

The active ground water flow which is also known as delayed flow release from GWS travel in lateral direction in the form of base flow (BF(t)). This can be modeled as outflow from a non-linear storage as follows:

$$BF(t) = P_4 \; DSP(t) \tag{3.25}$$

where P_4=ground water zone runoff coefficient

3.3.3.4 Deep percolation

The inactive ground water flow which travel in vertical direction from the saturated GWS into aquifers is considered as a loss from the saturated store and is termed as deep percolation. This can be expressed as (Geetha et al., 2008; Durbude et al., 2010):

$$DPR(t) = (1 - P_4) \; DSP(t) \tag{3.26}$$

where DPR(t) = deep percolation at any time 't' and P_4 = ground water zone runoff coefficient.

3.3.4 Total Stream Flow

The total stream flow (TRO(t)) on day t is the sum of the surface flow and sub-surface flow in term of lateral flow and base flow (Eqs. 3.16, 3.22, and 3.25).

$$TRO(t) = RO(t) + THR(t) + BF(t) \qquad \text{if } t \le 5 \text{ days} \tag{3.27}$$

$$TRO(t) = SRO(t) + THR(t) + BF(t) \qquad \text{if } t > 5 \text{ days} \tag{3.28}$$

3.3.5 Budgeting of Soil Moisture and Ground Water Stores

Budgeting of moisture state on daily basis both in unsaturated and saturated stores is essential for a daily hydrological simulation model primarily due to mass conservation reasons. The daily ground water budget can be maintained by daily water retention storage or daily soil moisture budgeting from both stores, SMS and GWS by defining the lower and upper limits of wilting point and field capacity of soils of study watersheds using the Canadian texture triangle (http://www.pedosphere.com/resources/texture/triangle.cfm). The current space available for retention of water S(t) is upgraded on daily basis by taking into account the changes in SMS and GWS as (Durbude et al., 2010):

$$S(t+1) = S(t) + \theta(t) - \theta(t+1) + \psi(t) - \psi(t+1) \tag{3.29}$$

where S (t+1) is the next day's potential maximum retention (mm), θ(t+1) is the next day soil moisture content (mm), and ψ(t+1) is the next day ground water content (mm). The soil moisture content is updated on daily basis by considering the current soil moisture status and evapotranspiration as well as drainage losses from SMS in the previous day while the ground water content is updated by considering the current ground water status, base flow, percolation, and deep percolation losses from GWS as follows:

$$\theta(t+1) = \theta(t) + V(t) - V_0(t) - ET(t) - DR(t) \tag{3.30}$$

$$\psi(t+1) = \psi(t) + PR(t) - BF(t) - DPR(t) \tag{3.31}$$

3.4 MODEL-II: LTHS MICHEL II

As stated earlier, in the formulation of LTHS MICHEL I model, initial soil moisture depends on the AMCs as decided from Table 2.1 and Table 2.2 described in Chapter 2, which may lead to the sudden variation in the daily CN and unrealistic sudden jump in V_0 and thus, affect the performance of the model. According to Chen (1981), a discrete temporal variability of AMC (over a short span of time) may cause a serious error in the computation of CN value and hence the computed direct runoff. Mishra and Singh (2003a) proposed a model based on SCS-CN concept incorporating a non-linear continuous variation of antecedent moisture with 5 days antecedent rainfall. The antecedent moisture available in the soil prior to storm plays a vital role in the estimation of surface runoff (Mishra and Singh, 2002a) as CN variability is primarily attributed to antecedent moisture amount (AM) (SCS, 1971; Mishra and Singh, 2003a).

Therefore, in the proposed LTHS MICHEL II model, the discrete unrealistic relation of V_0 via CN and AMC, is eliminated by computing V_0 using AM instead of AMCs. This model also considers that the current space available for water retention (S(t)) for the first day of simulation (June 1) is based on value of CN_0. Afterwards, S(t) can be modified as SM(t) based on AM(t) to avoid sudden variation in daily CN that affect the model performance by using Eqs. (2.46) and (2.47) as described in previous Chapter 2, reproduced here for convenience as follows (Geetha et al., 2007).

$$SM(t) = \frac{(S(t))^2}{(AM(t) + S(t))}$$

where AM(t), an antecedent moisture amount at time't' is estimated as follows:

$$AM(t) = \delta\sqrt{P_5(t)}$$

Here, δ is the coefficient of antecedent moisture to be determined by optimization.

The value of S(t) is same as given by Eq. (3.6) for first day of simulation. After 5 days, the value of SM(t) is computed by using Eq. (2.46). As already stated, the value of S(t) is updated based on the daily changes in the SMS and GWS via the losses through evapotranspiration and deep seepage and the daily input to the soil moisture store level, in order to get the possible space for water retention as in Eq. (3.29). Since the initial soil moisture store level (V_0) is considered as fraction of S in the simplified form of Michel et al. (2005) model, it can be modified according to the modification in S. Hence, V_0 at time 't', ($V_0(t)$) can be modeled as follows to avoid unrealistic sudden jump in its computation.

$$V_0(t) = \beta\,[SM(t)] \tag{3.32}$$

where β is the coefficient of initial soil moisture store level (V_0), a fraction of SM to be determined by optimization. Thus, in this model, expressions for initial soil moisture store level (V_0) and direct runoff (RO) are modified using the expression for SM(t) (Eq. 2.46). The mathematical formulation for the computation of the various components of stream flow generating process in LTHS MICHEL II model is presented in Fig. 3.2 and further described in the following section.

3.4.1 Surface flow

As stated in the earlier section 3.3.1, the surface flow is that part of rainfall which appears in the total stream flow after satisfying the initial demands of interception, infiltration, and surface storage. It is obtained by routing the direct runoff using single linear reservoir. In this LTHS MICHEL II model, the SMA procedure proposed by Michel et al. is used for surface runoff computations with the modified expressions of V_0 to preclude the unrealistic sudden jump in its computation and further quantum jump in the computation of RO. Based on the above discussion and some theoretical arguments, the Michel et al. model is further modified by incorporating the modification in S(t) and, in turn, the modification in the formulation of V_0 (Eq. 3.32) to compute the direct runoff (RO) as follows (Durbude et al., 2010):

$$\text{If } V_0(t) \le S_a(t) - P(t), \text{ then } \quad \mathrm{RO(t)} = 0 \tag{3.33}$$

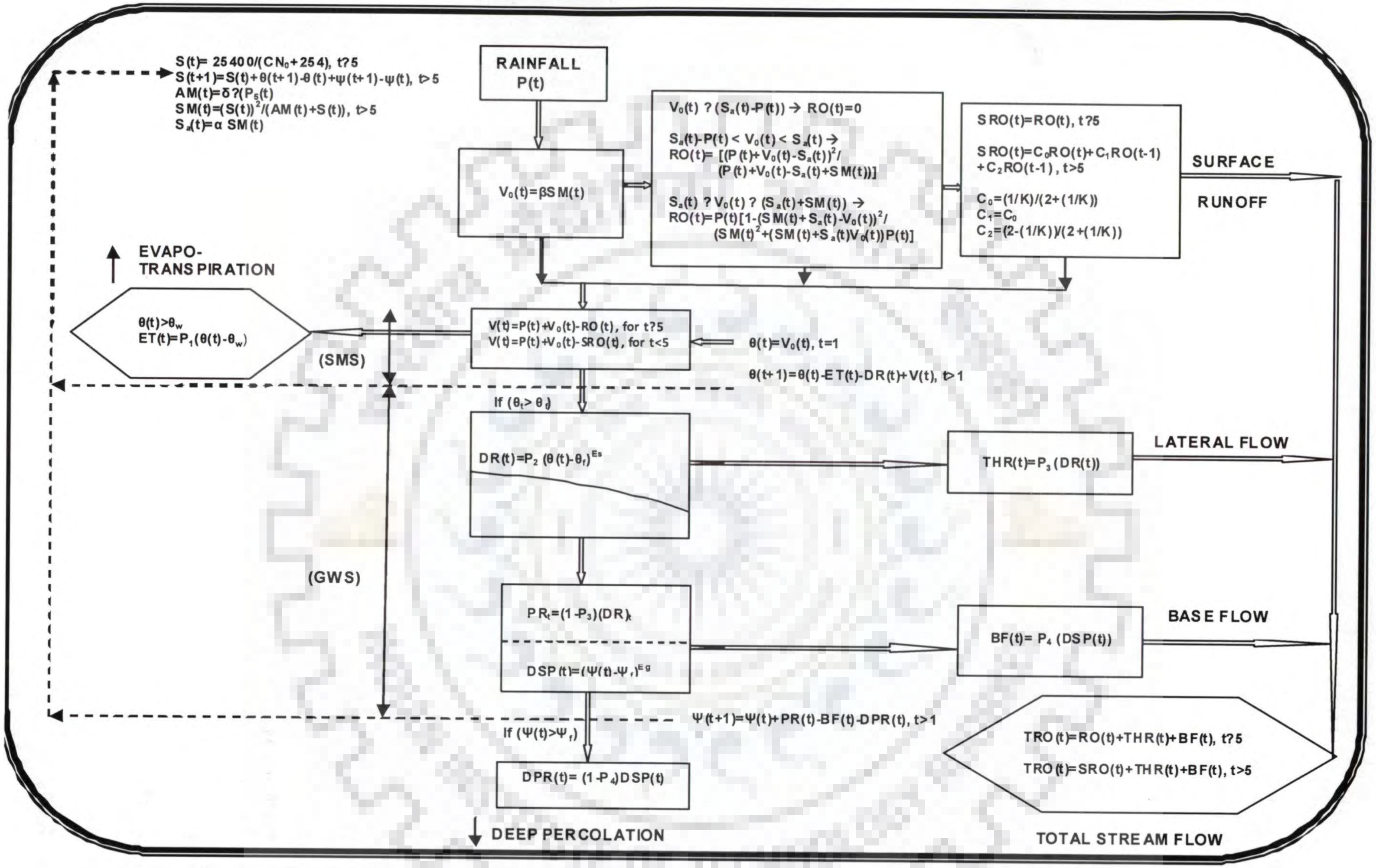


Figure 3.2 Block Diagram Showing Mathematical Formulation of Various Components of Stream Flow for the Proposed LTHS MICHEL II Model

If $S_a(t) - P(t) < V_0(t) < S_a(t)$, then

$$\text{RO(t)} = \frac{(P(t) + V_0(t) - S_a(t))^2}{P(t) + V_0(t) - S_a(t) + SM(t)} \tag{3.34}$$

If $S_a(t) \le V_0(t) \le S_a(t) + SM(t)$, then

$$\text{RO(t)} = P(t)\left[1 - \frac{(SM(t) + S_a(t) - V_0^{\,2}(t))}{SM^2(t) + (SM(t) + S_a(t) - V_0(t))P(t)}\right] \tag{3.35}$$

where $S_a(t) = \alpha\, SM(t)$ and α is model parameter, a coefficient of S_a, as stated earlier, to be determined through optimization.

The direct runoff (RO) computed by using the above expressions (Eqs. 3.33-3.35) is routed through SLR to compute surface runoff (SRO) at the outlet of the watershed using the Eqs. (3.16-3.19). Routed runoff is further used for the daily updating the SMS via daily changes in SMS ($V(t)-V_0(t)$) as given in Eq. (3.30). To this end, the surface flow component of this model is discussed while the sub-surface flow components of this model such as lateral flow and base flow are computed as per the formulation given by Model. The sub-surface drainage flow, one of components of sub-surface flow, can be computed by using Eq. (3.21). It is further partitioned into lateral flow and percolation into GWS, which can be computed using the Eq. (3.22) and Eq. (3.23), respectively. After satisfying the initial demand and saturating the GWS, the excess ground water content is converted into deep seepage, which can be computed by using Eq. (3.24). The deep seepage is further bifurcated into base flow and deep percolation and can be computed by using Eq. (3.25) and Eq. (3.26), respectively. The total stream flow (TRO(t)) on a day 't' is computed by using Eqs. (3.27) and (3.28). The current space available for retention of water S(t), which is updated on daily basis according to daily changes in SMS and GWS and can be computed by using Eq. (3.29). The daily changes in SMS and GWS can be updated using Eq. (3.30) and Eq. (3.31), respectively.

3.5 MODEL-III: LTHS ASMA I

In the model-III designated as LTHS ASMA I, the SMA procedure initially proposed by Michel et al. (2005) and further refined by Sahu et al. (2007) is re-conceptualized to derive an expression for computation of initial soil moisture store level (V_0) for daily time step based on pre-antecedent moisture level (V_{00}) before the onset of rainfall. As stated earlier, V_0 plays a vital role and prime factor responsible for the improvement in the proposed SMA procedure, there is need to derive an expression for its computation (Durbude et al., 2010). The mathematical formulations for the computation of V_0 along with other stream flow generating components are shown in Fig. 3.3 and further discussed in the subsequent sections.

3.5.1 Surface Flow

The surface flow, which is one of the components of total stream flow, is modified in this model by deriving an expression for the computation of initial soil moisture store level (V_0). Since both the original SCS-CN and Michel et al. models (in its simplified form) define three AMC levels and permit unreasonable sudden jumps in CN and V_0, respectively, a regular form of equation is necessary to compute the antecedent or initial soil moisture. Mishra and Singh (2002a) reported the antecedent moisture to be dependent on 5 days antecedent rainfall (P_5) and S and proposed an equation to estimate antecedent moisture based on the assumptions that (a) the watershed is completely dry 5 days before the onset of rainfall, which may not be true, in general. This model was valid for $P = P_5$. Since the use of I_a is discouraged by Michel et al., a refinement in the expression of initial soil moisture (V_0) (a function of P_5 and S) is desirable. The dependency of S is based on the fact that for a given P_5, the watershed with larger retention (S) must retain higher moisture than the watershed with lesser S. Therefore, the expressions for V_0, are derived based on the fact that only a fraction of water/moisture added to the soil will contribute to V_0 due to evapotranspiration losses in the previous 5 days and modified Michel et al. model is valid for 5 days antecedent rainfall (P_5). Accordingly, the assumptions are made such as the pre-antecedent moisture level (V_{00}) before the onset of rainfall is a fraction of SM and the second assumption which is based on the fact that only a fraction, in general, of moisture added to the soil will contribute to initial soil

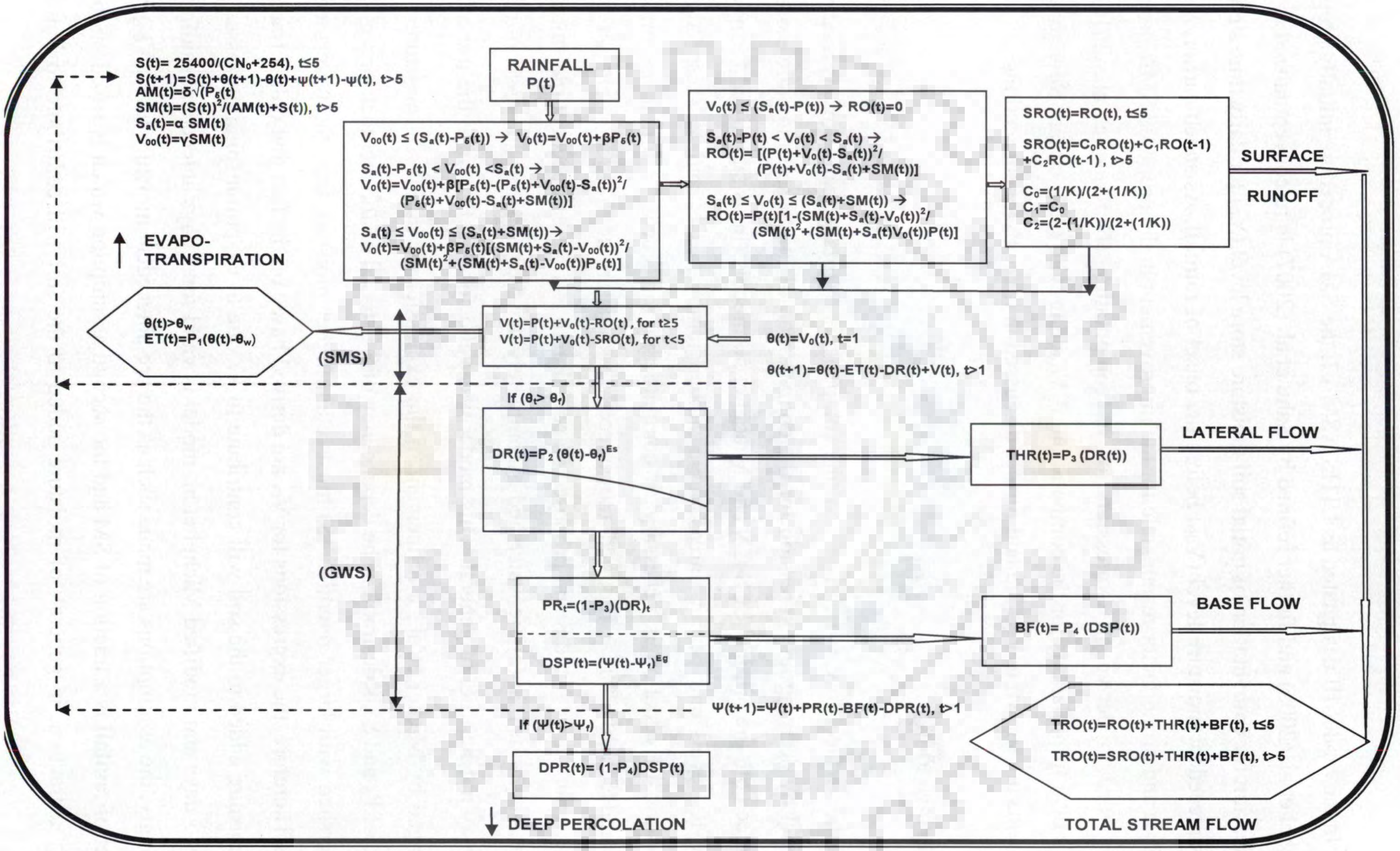


Figure 3.3 Block Diagram Showing Mathematical Formulation of Various Components of Stream Flow for the Proposed LTHS ASMA I Model

moisture store level due to evapotranspiration losses in the previous 5 days. Hence, the initial soil moisture store level (V_0) at the time of the beginning of rainfall is equal to the sum of pre-antecedent moisture level (V_{00}) and a fraction (β) of the part of rainfall, which is not transformed into runoff (P_5-Q_5) where P_5 is 5 days antecedent rainfall and Q_5 is the corresponding 5 days runoff. Thus, from the assumption that the pre-antecedent moisture level ($V_{00}(t)$) before the onset of rainfall at time t is zero or a fraction of SM(t), we have

$$V_{00}(t) = \gamma\, SM(t) \tag{3.36}$$

where γ can be considered as a coefficient of pre-antecedent soil moisture store level (V_{00}) and ranges from 0.0 to 1.0. It can be obtained by optimization.

From the second assumption, the initial soil moisture store level ($V_0(t)$) at the beginning of rainfall at time 't' is equal to the sum of pre-antecedent moisture level ($V_{00}(t)$) at time t and a fraction (β) of the part of rainfall not transformed into runoff ($P_5(t)$-$Q_5(t)$) at time t owing to 5 days antecedent rainfall ($P_5(t)$) at the time. Here, $Q_5(t)$ is the corresponding 5 days antecedent runoff at time 't'. Thus,

$$V_0(t) = V_{00}(t) + \beta\,(P_5(t) - Q_5(t)) \tag{3.37}$$

where β is coefficient of initial soil moisture store level (V_0). Here, it is considered as a fraction of rainfall that is not transformed into runoff ($P_5(t)$-$Q_5(t)$). It can be determined through optimization.

Considering Eqs. (3.33–3.35) to be valid for $P(t)=P_5(t)$ (the third assumption that modified Michel model is valid for $P(t) = P_5(t)$), the following expressions can be derived for different conditions (Durbude et al., 2010):

If $V_{00}(t) \le (S_a(t) - P_5(t))$, then $Q_5(t) = 0$; then from Eq. (3.37), we have

$$V_0(t) = V_{00}(t) + \beta(P_5(t)) \tag{3.38}$$

If (S_a(t) – P5(t)) < V00(t) < S_a(t), then

$$Q_5(t) = \frac{(P_5(t)+V_{00}(t)-S_a(t))^2}{P_5(t)+V_{00}(t)-S_a(t)+SM(t)}$$, then from Eq. (3.37), we have

$$V_0(t) = V_{00}(t) + \beta\left[P_5(t) - \frac{(P_5(t)+V_{00}(t)-S_a(t))^2}{P_5(t)+V_{00}(t)-S_a(t)+SM(t)} \right] \tag{3.39}$$

If $S_a(t) \le V_{00}(t) \le S_a(t)+SM(t)$, then

$$Q_5(t) = P_5(t)\left[1 - \frac{(SM(t)+S_a(t)-V_{00}(t))^2}{(SM(t))^2+(SM(t)+S_a(t)-V_{00}(t))P_5(t)}\right]$$, then from equation (3.37),

$$V_0(t)=V_{00}(t)+\beta P_5(t)\left[\frac{(SM(t)+S_a(t)-V_{00}(t))^2}{(SM(t))^2+(SM(t)+S_a(t)-V_{00}(t))P_5(t)}\right] \tag{3.40}$$

Using the above expression for V_0, the direct runoff (RO) is computed from Eqs. (3.33-3.35) and further routed using Eqs. (3.16-3.19). The routed surface runoff is used for updating daily SMS via daily changes in soil moisture store (V(t)-V_0(t)) as given in Eq. (3.30). The computations of other components of this model, viz., evapotranspiration, percolation, and deep percolation losses, sub-surface drainage flow, lateral flow, deep seepage, and base flow are similar to the formulations proposed for LTHS MICHEL I model, which can be computed from Eqs. (3.20-3.26). The total stream flow (TRO(t)) at time ‘t’ (Eqs. 3.27 and 3.28), is the sum of the surface runoff, lateral flow, and base flow (Eqs. 3.16, 3.22, and 3.25). The current space available for retention of water S(t) is computed by considering the changes in SMS and GWS from Eq. (3.29). Different stores considered in this model via SMS and GWS are updated on daily basis by using Eq. (3.30) and Eq. (3.31), respectively.

3.6 MODEL-IV: LTHS ASMA II

In the earlier models proposed in the present study, the main focus was to improve the surface runoff component of total stream flow by modifying the SMA procedure proposed by Michel et al. (2005) in various ways. The sub-surface flow components viz., lateral flow and base flow is modeled as conceptual behavior of different stores via daily updating SMS and

GWS as explained in the previous section 3.3.3. Thus, there is a modification in the computation of surface flow component only. Hence, there is a scope to explore the possibility of modification in the formulation of sub-surface flow components, which may further enhance the model efficiency. Therefore, in the fourth model designated as LTHS ASMA II, an effort has been made to improve the sub-surface flow components, viz., sub-surface drainage flow by means of representing the sub-surface drainage flow using a concept similar to the SCS-CN method. The modification in the SCS-CN method through theoretical analogy proposed by Yuan et al. is used to derive a relationship for sub-surface drainage flow. The conceptual frame work proposed by Yuan et al. is further developed to derive a relationship for sub-surface drainage flow. The analogy and mathematical formulations to derive an expression for sub-surface drainage flow along with others stream flow generating components are shown in Fig. 3.4 and described in the subsequent sections.

3.6.1 Surface Flow

The LTHS ASMA II model is similar to LTHS ASMA I for the computation of surface runoff. Using the expression for computation of V_0 (Eqs. 3.39-3.40), the direct runoff (RO) is computed as per the Eqs. (3.33-3.35). The computed direct runoff is routed using a single linear reservoir concept to compute the routed surface runoff (SRO) at the outlet of the watershed using the Eqs. (3.16-3.19). The routed runoff is then used for the computation of total stream flow and soil moisture store level (V(t)) at time 't' (Eq. 3.1), which is further used for sub-surface drainage flow computation. Thus, this model also considers the ASMA procedure similar to LTHS ASMA I model but differ in computation of sub-surface drainage flow and its moisture accounting.

In LTHS ASMA I and other two models, the sub-surface drainage flow is considered as exponential function of available moisture, when it exceeds field capacity of soil. While the expressions for the computation of the sub-surface drainage flow in this model is derived based on modified SCS-CN method (Yuan et al., 2001) (as described in section 2.7 of Chapter 2) as follows.

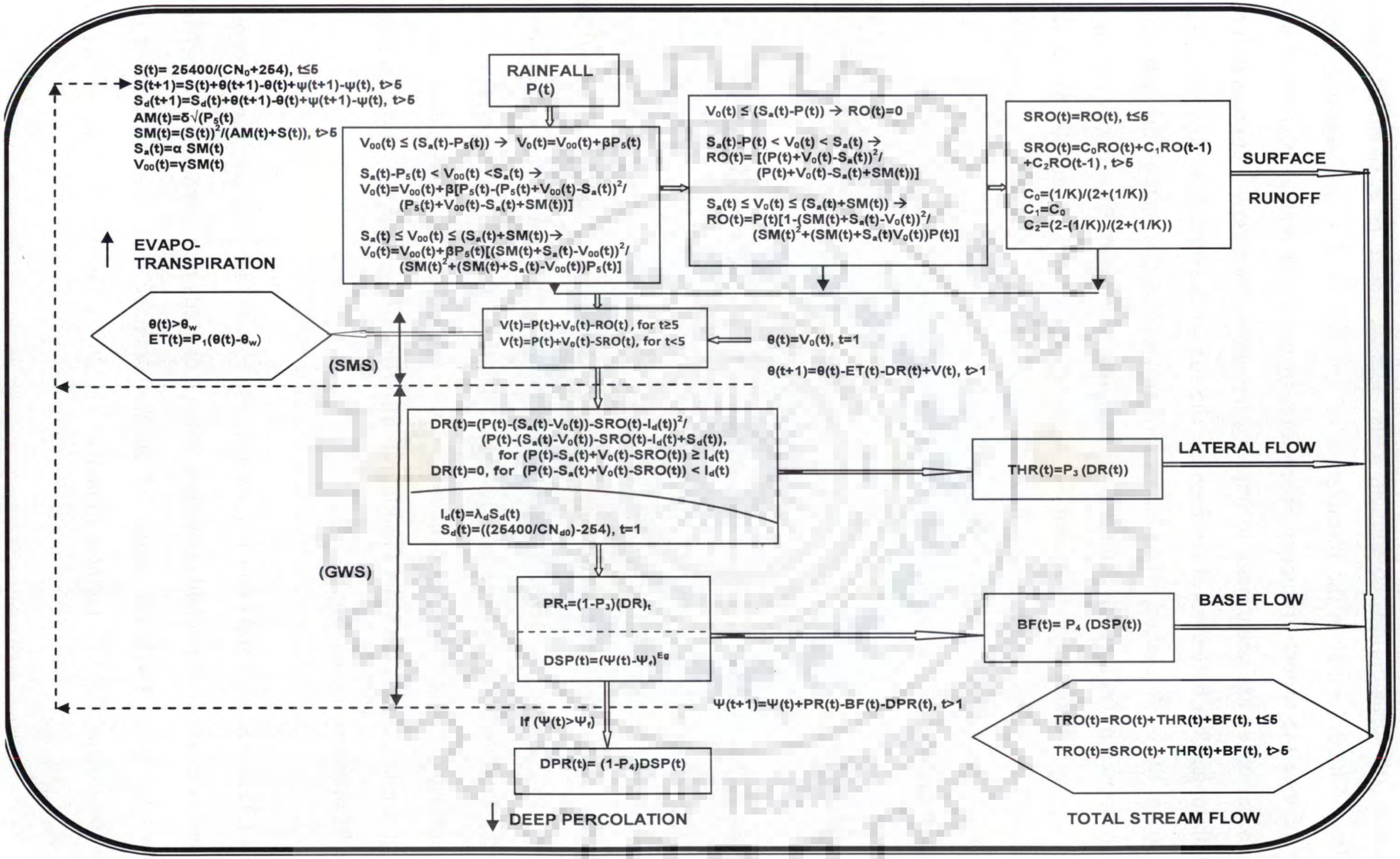


Fig. 3.4 Block Diagram Showing Mathematical Formulation of Various Components of Stream Flow for the Proposed LTHS ASMA II Model

3.6.2 Sub-surface Drainage Flow

As stated earlier, the sub-surface drainage flow occurs when infiltrated rainfall meets an underground zone of low transmission, travels above the zone to the soil surface downhill, and appears as a seep or spring. The total stream flow consists of combination of lateral flow and base flow as a part of sub-surface flow components. After satisfying the initial demands and saturating the SMS, the excess water is drained out of it. The drainage occurs when the moisture content in SMS exceeds the field capacity of the soil (Putty and Prasad, 2000; Mishra et al., 2005). In this model, the sub-surface drainage flow is computed by using the expression (Eq.2.62) based on analogy and further term re-development in the SCS-CN concept (Yuan et al., 2001). The input for surface drainage flow (P in Eq. 2. 62) is replaced by (P-I_a). Hence, Eq. (2.62) can be re-written to compute the sub-surface drainage flow at time't' (DR(t)) as follows:

$$DR(t) = \frac{(P(t) - I_a(t) - RO(t) - I_d(t))^2}{(P(t) - I_a(t) - RO(t) - I_d(t) + S_d(t))}; \text{ for } P(t) - I_a(t) - RO(t) \geq I_d(t) \quad (3.41)$$

$$= 0 \qquad \text{otherwise}$$

Since the SMA procedure proposed by Michel et al. (2005) discouraged the use of I_a and replaced by (S_a-V_0), the expression for sub-surface drainage flow (Eq. 3.41) is revised by replacing the term I_a and using the routed surface runoff (SRO) instead of RO, the following expression is obtained to compute the sub-surface drainage flow from rainfall. Thus, the sub-surface drainage flow can be modeled as:

$$DR(t) = \frac{(P(t) - (S_a(t) - V_0(t)) - SRO(t) - I_d(t))^2}{(P(t) - (S_a(t) - V_0(t)) - SRO(t) - I_d(t) + S_d(t))} \quad (3.42)$$

Eq. (3.42) is valid for $P(t) - S_a(t) + V_0(t) - SRO(t) \geq I_d(t)$; DR(t)=0, otherwise. Here,

$$I_d(t) = \lambda_d S_d(t) \quad (3.43)$$

$$S_d(t) = \frac{25400}{CNd(t)} - 254 \quad (3.44)$$

λ_d = initial abstraction for sub-surface drainage flow and CNd(t) = curve number for sub-surface drainage flow at time ‘t’. In this model, the curve number for sub-surface drainage flow, CNd(t) is considered as initial value of curve number for sub-surface drainage flow (CNd_0) for the starting day of simulation (June 1) and it varies with the advancement in time, based on the antecedent rainfall (P_5).

As stated for the earlier models, the sub-surface drainage flow is further partitioned into lateral flow and percolation into GWS, which can be computed by using Eqs. (3.22) and (3.23). After satisfying the initial demand/saturation of GWS, the excess ground water content is used to compute deep seepage using Eq. (3.24), which can be further used for the computation of base flow (Eq. 3.25) and deep percolation (Eq. 3.26). The total stream flow (TRO(t)) on day t which is the sum of surface runoff, lateral flow, and base flow can be computed using Eqs. (3.16), (3.22), and (3.25). The current space available for retention of water S(t) can be computed by considering the changes in the stores (SMS and GWS) from Eq. (3.29). Similarly, $S_d(t)$ is also upgraded on daily basis by taking into account the changes in SMS and GWS as:

$$S_d(t) = S_d(t+1) + \theta(t+1) - \theta(t) + \psi(t+1) - \psi(t) \quad (3.45)$$

where $S_d(t+1)$ is the previous day potential maximum retention (mm) for sub-surface drainage flow, $\theta(t+1)$ is the previous day soil moisture (mm), and $\psi(t+1)$ is the previous day ground water (mm) as explained earlier.

3.7 MODEL VARIABLES AND PARAMETERS

A fundamental component of the modeling process is the equation relating two or more variables. A variable is a model element whose value can vary during a simulation run whereas a parameter is a value that is held constant over a simulation run but can change from one to other (McCuen, 2003). There are two types of variables, criterion variables, and predictor variables. The criterion variables, also called as dependant variables, represent the response of the system while predictor variables, known as independent variables, are believed to cause variation in criterion variables (McCuen and Synder, 1986). Here in this analysis, hydrological components like runoff and its components, initial soil moisture, drainage, percolation, deep seepage, deep percolation, etc. are criterion variables and the input to the system, i.e. rainfall, is the predictor variable.

3.8 MODEL PARAMETERS

Performance of a hydrological model depends on selecting suitable model parameters, which are normally calibrated by using an objective function. Most operational conceptual hydrological model for simulating stream flow typically have 10 or more parameters that link transfer functions of several interconnected water stores (Vrugt et al., 2006). It is assumed that these conceptual storages correspond to physically identifiable control volumes, in real space even though the boundaries of these control volumes are not generally known. While some of the parameter values can be derived directly from the watershed characteristics, others which are not measurable in the field have to be estimated through model calibration against a measured stream flow using either trial and error approach or an automated search algorithm (Boyle, et al. 2000; Madson, 2000). The parameters which are estimated in this manner represent effective conceptual representation of spatially and temporally heterogeneous watershed properties. A model calibrated by such means can be used for simulation or prediction of hydrologic events, outside of the historical record used for model calibration, if it can be reasonably assumed that the physical characteristics of the watershed and the hydrologic/climatic conditions remain similar (Gupta et al., 2002).

In the present study, four different modified SCS-CN concept-based SMA models are proposed for long term simulation of stream flows. The description of model parameters involved in these models and the method to estimate these parameters are presented below.

3.8.1 Description of Model Parameters

The proposed models involve certain parameters relating to watershed characteristics such as soil and vegetation and climate, and thus, requiring a technique for optimization to obtain the best possible value of each of them. All four LTHS models involve different sets of model parameters. The LTHS MICHEL I model contains fourteen parameters, viz., CN_0, α, β, K, P_1, P_2, P_3, P_4, θ_w, θ_f, ψ_f, E_s, E_g, and ψ_0, and the LTHS MICHEL II model has fifteen parameters viz., CN_0, α, β, δ, K, P_1, P_2, P_3, P_4, θ_w, θ_f, ψ_f, E_s, E_g, and ψ_0. The LTHS ASMA I model involves sixteen parameters, CN_0, α, β, δ, γ, K, P_1, P_2, P_3, P_4, θ_w, θ_f, ψ_f, E_s, E_g, and ψ_0, while LTHS ASMA II model involves fifteen parameters, viz., CN_0, δ, α, β, γ, K, P_1, P_3, P_4, θ_w, ψ_f, E_g, ψ_0, CNd_0, λ_d. The description of various parameters involved in the formulation of these models is given in Table 3.1.

Table 3.1 Description of Model Parameters

Sr. No.	Model Parameter	Description
1	CN_0	Initial curve number (starting day of simulation)
2	α	Coefficient of S_a, parameter of SMA procedure
3	β	Coefficient of initial soil moisture store level (V_0)
4	K	Storage coefficient
5	P_1	Coefficient of transpiration from soil zone
6	P_2	Subsoil drainage coefficient
7	P_3	Unsaturated soil zone runoff coefficient
8	P_4	Ground water zone runoff coefficient
9	θ_w	Wilting point of the soil
10	θ_f	Field capacity of the soil in unsaturated zone
11	ψ_f	Field capacity of the soil in the ground water zone
12	E_s	Exponent of unsaturated moisture zone
13	E_g	Exponent of ground water zone
14	ψ_0	Initial ground water content
15	δ	Coefficient of antecedent moisture
16	γ	Coefficient of pre-antecedent soil moisture store level (V_{00})
17	CNd_0	Initial curve number for sub-surface flow (starting day of simulation)
18	λ_d	Initial abstraction for sub-surface drainage flow

The parameter CN_0 represents the curve number on the first day of simulation, i.e. June 1, assuming that the maximum pore space is available in the soil for the water storage or retention on the first day of simulation. The value of CN_0 can vary from 0 to 100. The model parameter α, β are the coefficients of the parameters of SMA procedure proposed by

Michel et al., namely S_a and V_0. As stated earlier, the parameter S_a is a parameter of SMA procedure based on which different conditions for the value of V_0 were set to compute surface runoff. These parameters are assumed as a fraction of S, and hence, the model parameters α and β can vary from 0 to 1. The single linear reservoir routing (Mishra and Singh, 2004a) is carried out to compute the direct surface runoff, which involves a parameter storage coefficient, K (day). This parameter is also to be optimized. The coefficients such as coefficient of transpiration from soil zone, subsoil drainage coefficient, unsaturated soil zone runoff coefficient, and ground water zone runoff coefficient can vary between 0 and 1.

As already stated, the daily water balance can be maintained by daily water retention storage or soil moisture budgeting from both SMS and GWS by defining their lower and upper limits of wilting point (θ_w) of different soil characteristics of the study watersheds, field capacity of the soil in unsaturated zone (θ_f) and field capacity (ψ_f) of the soil and initial water content (ψ_0) in ground water zone. The ranges for these model parameters are decided based on soil characteristics of the study watersheds using the Canadian texture triangle (http://www.pedosphere.com/resources/texture/triangle.cfm). The exponent of unsaturated moisture zone (E_s) and ground water zone (E_g) are the routing parameters which represent the exponential decay of sub-surface flow components and can be obtained through optimization.

In the LTHS MICHEL II model, a coefficient of antecedent moisture (δ) is used to compute the antecedent moisture amount (AM) from the antecedent 5-days rainfall (P_5) prior to the day under consideration, to modify the potential retention of the watersheds (S). This can be obtained through optimization. To express V_0 in the mathematical form, LTHS ASMA I model introduce the coefficient (γ) of pre-antecedent soil moisture store level (V_{00}), which can vary from 0 to 1. Likewise LTHS ASMA II uses the parameters CNd_0 and λ_d to formulate the sub-surface flow components of this model. Similar to parameter CN_0, the parameter CNd_0 also represents the curve number for sub-surface drainage flow on the first day of simulation, i.e. June 1, assuming that the maximum pore space is available in the soil for water storage or retention on the first day of simulation. The value of CNd_0 also varies from 0 to 100.

3.8.2 Estimation of Model Parameters

The values of model parameters can be estimated by using an appropriate optimization technique. The optimization is carried out to arrive at their best possible value for each of these parameters to produce an acceptable model output. Here, in these models, the number of parameters is relatively large, but it is at the gain of significant higher efficiency and these generate not only total stream flow but also its components satisfactorily. The model parameters are optimized using non-linear Marquardt (1963) algorithm and trial and error approach utilizing the objective function of minimizing the sum of square of errors between the computed and observed data. Selecting an appropriate and powerful objective function is one of keys to successful modeling. The goal of the optimization is to see that the error involved in the analysis is minimum or acceptably small, and then it would be possible to rely on the output predicted. The non-linear Marquardt algorithm of the least squares of the Statistical Analysis System has the advantages of yielding a unique set of parameters' values (Mishra and Singh, 2003a). This algorithm chooses a suitable range for each parameter and also needs to have initial guess of each parameter. In a specific run, if the computed value of a parameter equals its lower or upper limit on either side, the range can be widened. The final estimates of parameters are derived using the goodness-of-the-fit described in terms of model efficiency.

3.9 MODEL EVALUATION

The performance evaluation of the models having unequal number of parameters is compared by using the various evaluation criteria like model efficiency (E) and the error criterion such as standard error (SE), percent bias or percent relative error (RE). On the other hand, the other error criteria like root mean square error (RMSE), coefficient of determination (r^2) along with model efficiency (E) criteria were used for comparative performance evaluation of models with equal number of parameters. The model efficiency is generally known as the Nash-Sutcliffe (1970) coefficient of efficiency (NSE) and the same is used in the present study. The various evaluation criteria are discussed in the subsequent section.

3.9.1 Model Efficiency

To evaluate the performance of model, the model efficiency (NSE) is determined. NSE is perhaps the best and most widely used objective function to measure the performance of a model (WMO, 1975, 1992; Refsgaard and Knudsen, 1996; El-Sadek et al., 2001; Fentie et al., 2002; Michel et al., 2005; Jain and Singh, 2005; Jain and Sudheer, 2008, etc.). It expresses the fraction of the measured stream flow variance that is reproduced by the model, as follows:

$$NSE = \left[1 - \frac{\sum_{i=1}^{N} (QO_i - QC_i)^2}{\sum_{i=1}^{N} (QO_i - Q_{ave})^2} \right] \tag{3.46}$$

where QO_i is the observed runoff for day i (mm), QC_i is the computed runoff for day i (mm), Q_{avg} mean observed stream flow (mm) during the evaluation period, N is the total number of days in evaluation period, and i is an integer varying from 1 to N.

NSE varies from minus infinity (-∞) to 1. It can also assume a negative value if $\sum_{i=1}^{N}(QO_i - QC_i)^2 > \sum_{i=1}^{N}(QO_i - Q_{ave})^2$, implying that the variance in the observed and computed values is greater than the model variance, which indicates that the average observed value is a better estimate than the model predicted. In the present study, simulation results are considered to be very good for values of NSE > 0.75 whereas for values of NSE between 0.75 and 0.36 these are considered as good to satisfactory (Motovilov et al., 1999). The efficiency of 1 implies that the computed values are the same as the observed ones, which is the perfect fit.

3.9.2 Error Criteria

As stated earlier, various error criteria, viz., root mean square error (RMSE), standard error (SE), and percent bias or percent relative error (RE), were used to evaluate and compare the performance of the proposed models. These are described below.

RMSE, and SE can be computed as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(QO_i - QC_i)^2} \tag{3.47}$$

$$SE = \sqrt{\frac{1}{N-m+1}\sum_{i=1}^{N}(QO_i - QC_i)^2} \tag{3.48}$$

where QO_i is the observed runoff for day i (mm), QC_i is the computed runoff for day i (mm), Q_{avg} mean observed stream flow (mm) during the evaluation period, N is the total number of days in evaluation period, m is the number of model parameters, and i is an integer varying from 1 to N.

RMSE and SE describe the proportion of the total variance in the observed data that can be explained by the model. A lower value of SE and RMSE indicates better model performance, and vice versa. SE = 0 or RMSE = 0 exhibits a perfect fit. The works of Madsen et al. (2002), Mishra et al. (2003a, 2004a), and Itenfisu et al. (2003) are but a few examples among many others to cite the wide usage of SE and RMSE. SE is a better goodness-of-fit measure as it has the same dimension as QO_i, accounts for the degrees of freedom N-m, and is valid for nonlinear as well as linear models (McCuen, 2003). The unit of RMSE or SE here is mm.

Another error criterion used in this study is the percent relative error (RE). This is a measure of the average tendency of the simulated flows to be larger or smaller than their observed values. RE=0.0 indicates overall results to have been neither over-estimated nor under-estimated. A positive value indicates model bias towards underestimation whereas a negative value of RE indicates bias towards overestimation (Gupta et al., 1999). RE is expressed as:

$$RE(\%) = \frac{\sum_{i=1}^{n}(QO_i - QC_i)}{\sum_{i=1}^{n}(QO_i)} \times 100 \qquad (3.49)$$

where RE is the deviation of stream flow discharge expressed as percent, QO_i is the observed runoff for day i (mm), QC_i is the computed runoff for day i (mm), Q_{avg} mean observed stream flow (mm) during the evaluation period, N is the total number of days in evaluation period, m is the number of model parameters, and i is an integer varying from 1 to N.

The performance of the model is considered "very good" if the absolute RE is <10%, "good" if the absolute RE lies between 10 and 15%, and "fair" if the absolute RE lies between 15 and 25%, and unsatisfactory if absolute RE > 25% for calibration and validation periods (Donigian et al., 1983; Harmel et al., 2006).

3.10 REMARKS

In this Chapter, four new/modified continuos long term hydrologic simulation (LTHS) models are proposed based on the SCS-CN method and modified concept given by Michel et al. (2005) for SMA procedure for the computation of surface flow component and the conceptual frame work proposed by Yuan et al. (2001) for sub-surface flow components to simulate the daily stream flow. Developed models incorporate modules to simulate major hydrologic phenomena that control the water movement in a watershed, such as surface runoff, initial soil moisture store level, evapotranspiration, sub-surface drainage flow, percolation, lateral flow, deep seepage, base flow and deep percolation. Various evaluation criteria used to evaluate the performance of the proposed LTHS models are also discussed. The proposed models employ the modified SMA procedure proposed by Michel et al. (2005) in the SCS-CN method to compute the surface runoff and conceptual frame-work of Yuan et al. (2001) for sub-surface drainage flow computation and appropriate mathematical expressions are provided to simulate various stream flow generating processes.

CHAPTER 4

STUDY AREA AND DATA AVAILABILITY

4.1 GENERAL

To test the performance of the proposed models described in Chapter 3, data from 17 watersheds varying in size/shape, and physical characteristics and located in different agro-climatic sub-zones of India (http://www.krishisewa.com/ krishi/Azone.html) were collected and used. The topographical features, soil, annual rainfall, and cropping pattern of sub-zones vary from each other. The daily rainfall and runoff data of the selected watersheds have been collected from Water Resources Development Organization (WRDO), Bangalore, Karnataka (India) and Central Water Commission (CWC). The topographical features such as watershed boundary, drainage and contour network, raingauge and stream gauge locations of each watershed lying in various basins, viz., Tungabhadra, Narmada, Malaprabha, Hemavathi and West Flowing river basins, etc. were delineated using ILWIS GIS software. The capability of ILWIS GIS was used for estimating the weighted rainfall of each watershed using Theissan weights. Details about name, topography, watershed characteristics, climate, etc. of selected watersheds under each basin are presented in Table 4.1. The locations of various basins/sub-basins in India map is shows in Fig. 4.1 and the basin wise description of watersheds is explained in the subsequent sections.

4.2 WATERSHEDS UNDER TUNGABHADRA SUB-BASIN

The Tungabhadra River is one of the major tributaries of river Krishna and is formed by the union of the twin rivers Tunga and Bhadra, which rise together in the Western Ghats at Gangamula at an elevation of 1196 m above mean sea level (amsl). The study watersheds namely, Attigundi, Sagar, Sorab, Amachi, and Hirehalla fall under this sub-basin, and lie in Hilly agro-climatic sub-zone of Karnataka state and a part of Southern Plateau and Hills

Table 4.1 Details of Watersheds and Data used for Model Calibration and Validation

Sr. No.	Watershed Characteristics	Name of Watershed								
		Hemavathi	**Hridaynagar**	**Mohegaon**	**Manot**	**Amachi**	**Anthrolli**	**Attigundi**	**Barchi**	**Khanapur**
		1	2	3	4	5	6	7	8	9
1	Basin	Cauvery	Narmada	Narmada	Narmada	Tungabhadra	Kalinadi	Tungabhadra	Kalinadi	Krishna
2	River	Hemavathi	Banjar	Burhner	Narmada	Mavinhole	Dusginala	Honnamana	Barchinala	Malaprabha
3	State	Karnataka	Chhattisgarh	Chhattisgarh	Chhattisgarh	Karnataka	Karnataka	Karnataka	Karnataka	Karnataka
4	District	Chikmanglur	Durg	Mandla	Shadol	Shimoga	Uttar Kanada	Chikamagalur	Uttar Kanada	Belgaum
5	Area (sq. km.)	600	3370	4661	5032	87	503	4.51	14.5	320
6	Latitude	12^{0}55' to 13^{0}11' N	21^{0}42' to 22^{0}36' N	22^{0}32' to 22^{0}56' N	22^{0}46' to 23^{0}18' N	14^{0}10' to 14^{0}16' N	15^{0}20' to 15^{0}34' N	13^{0}23' to 13^{0}25' N	15^{0}18' to 15^{0}24' N	15^{0}20' to 15^{0}40' N
7	Longitude	75^{0}29' to 75^{0}51' E	80^{0}28' to 81^{0}36' E	80^{0}41' to 81^{0}38' E	80^{0}34' to 81^{0}47' E	75^{0}04' to 75^{0}11' E	74^{0}35' to 74^{0}55' E	75^{0}43' to 75^{0}45' E	74^{0}36' to 74^{0}39'E	74^{0}20' to 74^{0}30' E
8	Topography	Low land, semi hilly and hilly	Flat, undulating land	Flat , undulating land	Hilly (Maikala range)	Hilly (Western Ghats)	Hilly (Western Ghats)	Hilly (Baba Budan hills)	Hilly (Western Ghats)	Hilly (Hill crest & valley bottom)
9	Agro-climatic sub-zone	Hilly zone of Karnataka	Northern hill region of Chhattisgarh	Northern hill region of Chhattisgarh	Northern hill region of Chhattisgarh	Southern Transition zone of Karnataka	Hilly zone of Karnataka	Hilly zone of Karnataka	Hilly zone of Karnataka	Northern Transition zone of Karnataka
10	Land Use/Cover	Forest, Coffee plantation, Agriculture	Forest, Agriculture, Degraded land	Forest, Agriculture	Forest, Agriculture, Waste land	Dense mixed jungle (Forest)	Forest, Agriculture, Wasteland	Reserved Forest	Forest, Agriculture	Forest , Agriculture
11	Soil	Red loamy and red sandy	Black to mixed red	Silty loam and silty clay loam	Red, yellow and medium black	Red loamy	Red loamy	Red loamy	Brownish & fine grained	Red loamy & Medium Black
12	Elevation (m) (amsl)	1240-890	600-372	900-509	1110-450	800-576	778-532	1627-1439	734-480	792-646
13	Avg. annual rainfall (mm)	2972	1178	1547	1596	1655	1099	1833	1536	1113
14	Calibration Period	1975-1978 (3 years)	1981-1986 (5 years)	1981-1986 (5 years)	1981-1986 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1989-1992 (3 years)	1985-1990 (5 years)
15	Validation Period	1978-1980 (2 years)	1986-1990 (4 years)	1986-1990 (4 years)	1986-1990 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1992-1994 (2 years)	1990-1994 (4 years)

Table 4.1 continued……

Sr. No.	Watershed Characteristics	Name of Watershed							
		Hirehalla	**Sagar**	**Sorab**	**Dasanakatte**	**Haladi**	**Jadkal**	**Kokkarne**	**Halkal**
		10	11	12	13	14	15	16	17
1	Basin	Tungabhadra	Tungabhadra	Tungabhadra	Haladi	Haladi	Kollur	Sitanadi	Kollur
2	River	Hirenadi	Varda	Dandavathi	Dasankatte	Varahi	Jadkalhole	Sitanadi	Halkalhole
3	State	Karnataka	Karnataka	Karnataka	Karnataka	Karnataka	Karnataka	Karnataka	Karnataka
4	District	Koppal	Shimoga	Shimoga	Dakshina Kanada	Dakshina Kanada	Dakshina Kanada	Dakshina Kanada	Dakshina Kanada
5	Area (sq. km.)	1296	75	96	135	505	90	343	108
6	Latitude	15^{0}20' to 15^{0}43 N	13^{0}48' to 14^{0}01'N	13^{0}38' to 13^{0}46' N	13^{0}31' to 13^{0}38' N	13^{0}35' to 13^{0}46' N	13^{0}47' to 13^{0}56' N	13^{0}20' to 13^{0}35' N	13^{0}49' to 13^{0}55' N
7	Longitude	75^{0}44' to 76^{0}17' E	74^{0}50' to 75^{0}10' E	74^{0}58' to 75^{0}16' E	74^{0}52' to 75^{0}03' E	74^{0}52' to 75^{0}10' E	74^{0}45' to 74^{0}48' E	74^{0}49' to 75^{0}10' E	74^{0}42' to 74^{0}53' E
8	Topography	Both flat and undulating land	Semihilly, Hilly	Hilly (Western Ghats)	Hilly (Western Ghats)	Hilly (Western Ghats)	Hilly (Western Ghats)	Hilly (Western Ghats)	Hilly (Western Ghats)
9	Agro-climatic zone	Northern Dry zone of Karnataka	Southern Transition zone of Karnataka	Southern Transition zone of Karnataka	Coastal zone of Karnataka	Coastal zone of Karnataka	Coastal zone of Karnataka	Coastal zone of Karnataka	Coastal zone of Karnataka
10	Land Use/ Cover	Agriculture, Degraded land	Dense mixed jungle (Forest)	Dense mixed jungle (Forest)	Reserved Forest (Ballimane)	Tombattu Reserved Forest	Reserved Forest (Madi Bare)	Fairly dense mixed jungle	Megani Valley Reserved Forest
11	Soil Type	Black	Red Loamy	Red and gravelly Loamy	Laterite	Laterite	Laterite	Laterite	Laterite
12	Elevation (m) (amsl)	648-498	577-685	567-833	870-1.0	969-1.0	1143-0.7	1153-6.3	1102-0.7
13	Average annual rainfall (mm)	579	1963	1368	4687	5021	5436	5161	5436
14	Calibration Period	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)	1985-1990 (5 years)
15	Validation Period	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)	1990-1994 (4 years)

Fig. 4.1 India Map Showing Locations of Basins/Sub-basins under Study

Region of India. Fig 4.2 shows the drainage maps of selected watersheds in Tungabhadra sub-basin. Brief descriptions of the watersheds under this sub-basin are given below:

4.2.1 Attigundi Watershed

Attigundi watershed falls under the Hilly agro-climatic zone of Karnataka State, a part of the Southern Plateau and Hills Region of India. It is situated in the Western Ghats region of Tungabhadra sub-basin. The watershed is drained out by the river Honnamanahallahole (hole means river in Kannada, the regional language of India), which is originating from the Baba Budan hills of the Western Ghats at an altitude of 1627 m amsl and nearly 6 km from the Attigundi village in the Chickamagalur district of Karnataka State, India. The stream gauge site is maintained by WRDO, Bangalore, at an altitude of 1439 m amsl near Attigundi village.

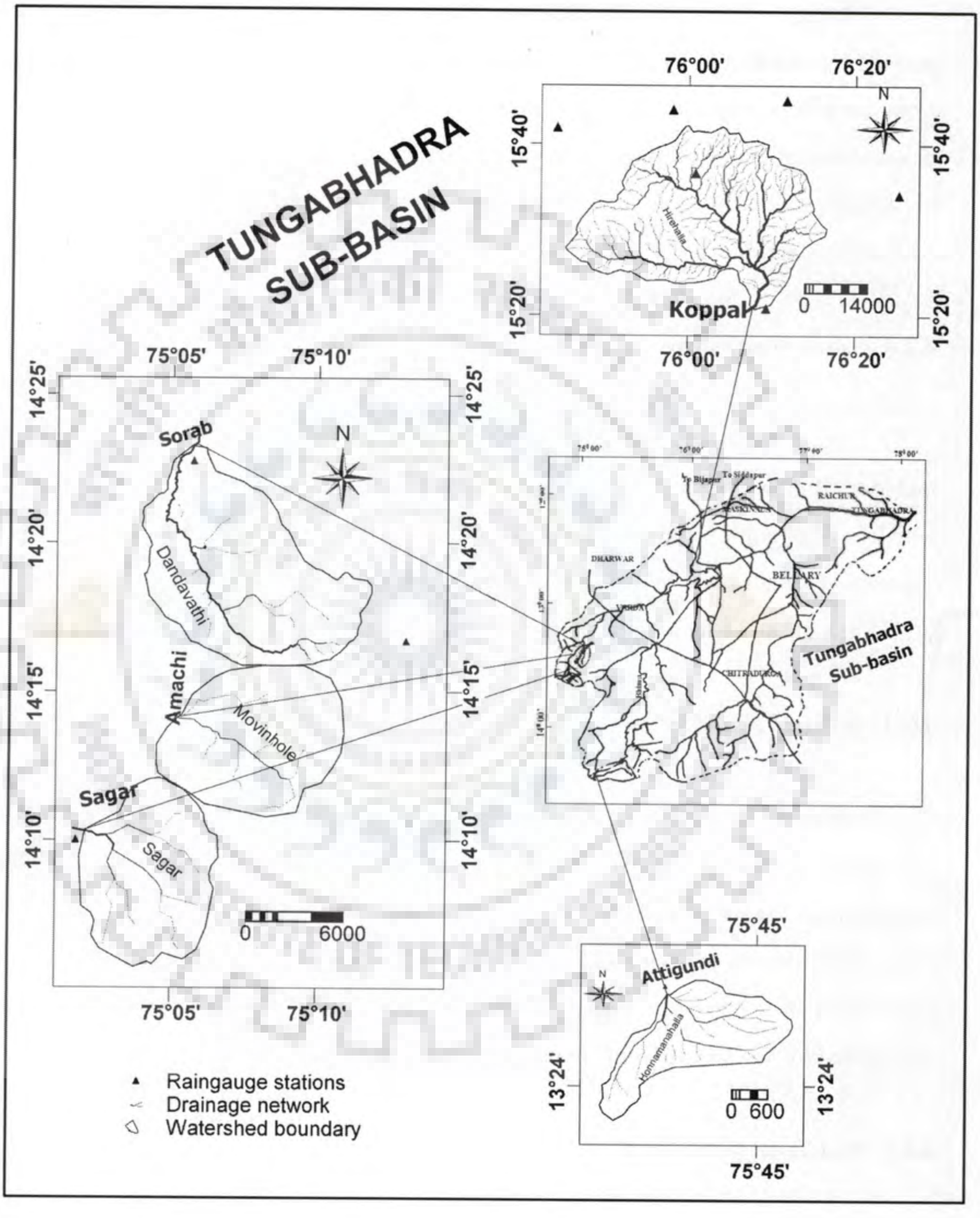


Fig. 4.2 Drainage Maps of Selected Watersheds in Tungabhadra Sub-basin

4.2.2 Amachi Watershed

Amachi watershed falls under the Southern Transition zone of Karnataka (India) and drained by Mavinhole River, a tributary of Varda River. The river, Mavinhole is originating from the dense mixed jungle of Western Ghats at an altitude of 800 m amsl and 2.5 km downstream of Baruru village in Shimoga district of Karnataka State. The stream gauge site of WRDO is located at an altitude of 576 m amsl at Amachi village in Shimoga district of Karnataka State, India.

4.2.3 Sagar Watershed

Sagar watershed also falls under the Southern Transition zone of Karnataka (India) and located in the Western Ghats region of India. The watershed is drained by the river Varda, which is originating from the foothill of Western Ghats, nearly 10 km from the Sagar in the Shimoga district of Karnataka, India. The stream gauge site is located at Sagar at an altitude of 577 m amsl and is being maintained by WRDO.

4.2.4 Sorab Watershed

Sorab watershed also falls under the Southern Transition zone of Karnataka (India) and darined by Dandavati River, a tributary of river Varda. River Dandavati originates from dense mixed jungle of Western Ghats, near Karjikoppa village in the foot-hills of Western Ghats at an altitude of about 833 m amsl in Shimoga district of Karnataka State in India. The river flows in a northerly direction and joins the Varada River. The stream gauge site is maintained by WRDO at Sorab at an elevation of 567 m amsl.

4.2.5 Hirehalla Watershed

Hirehalla watershed falls under the Northern Dry zone of Karnataka state in India and drained by Hirenadi which merge into the Tungabhadra reservoir in the downstream of Koppal. River Hirenadi originates from the upstream of Yelburga taluka of Koppal district of

Karnataka State, India, at an altitude of 648 m amsl. The stream gauge site is maintained by WRDO at Koppal (Karnataka State).

4.3 WATERSHEDS UNDER WEST FLOWING RIVER BASINS

There exist a large number of rivers in the Western coast, viz., coastal Maharashtra and Karnataka and entire Kerala, which are small in length but carry a significant amount of water due to very high rainfall in Western Ghats. They drain only 3% of the India's land area but carry about 11% of India's total river flows. The study watersheds in west flowing river basin are: Kokkarne, Halkal, Jadkal, Haladi, Dasanakatte, Barchi, and Anthrolli; falling under the coastal Karnataka, a part of hilly agro-climatic sub-zone of India and situated in the Western Ghats. These rivers flow in westward direction towards the Arabian Sea. The details of these watersheds are presented in Table 4.1 and boundaries and drainage maps are shown in Fig. 4.3.

4.3.1 Kokkarne Watershed

The Kokkarne watershed is drained by the river Sitanadi, a west flowing river originating from Talavanti village in the Someshwar reserved forest in Udupi district of Karnataka state at an altitude of 1153 m amsl. The watershed is situated in the hills of the Western Ghats and falls under the coastal Karnataka agro-climatic sub-zone of India. The stream gauge site of WRDO is located on Sitanadi River at Kokkarne Bridge in Udupi taluka of Dakshina Kannada district of Karnataka State, India.

4.3.2 Halkal Watershed

Halkal watershed is drained by Halkalhole, a west flowing river falling under the coastal Karnataka agro-climatic sub-zone of India. River Halkalhole originates from Chalkin Bare of Megani valley reserved forest in Udupi district of Karnataka state at an altitude of 1102 m amsl. The watershed is situated in the dense mixed jungle of Western Ghats region. The stream gauge site is located on Halkalhole at Halkal Bridge in Dakshina Kannada district of Karnataka, India, and is being maintained by WRDO.

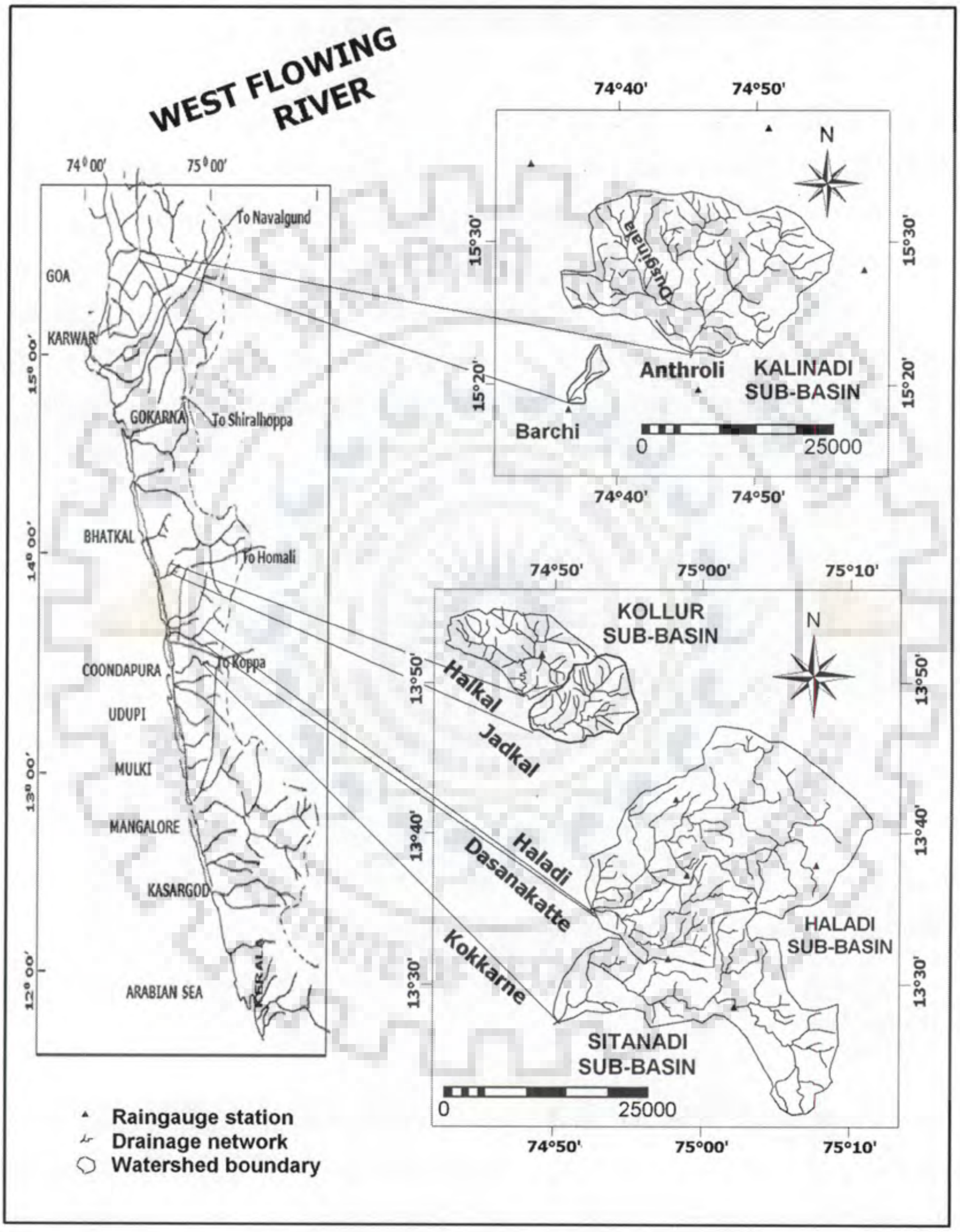


Fig. 4.3 Drainage Maps of Selected Watersheds in West Flowing Rivers Basin

4.3.3 Jadkal Watershed

This watershed is drained out by Jadkalhole, which originates from the hills of the Western Ghats, 3 km upstream of Jadkal village in the Dakshina Kanada district of Karnataka, India. It is a sub-catchment of Kollur River flowing in westward direction towards the Arabian Sea and falls under the Coastal Karnataka agro-climatic sub-zone of India. The stream gauge site maintained by WRDO is located on Jadkalhole at Jadkal Bridge in Dakshina Kannada district of Karnataka, India.

4.3.4 Haladi Watershed

Haladi watershed is drained by the Varahi River, a tributary of Haladi River. River Varahi originates from Kavaledurga at an altitude of 969 m amsl in Udupi district of Karnataka State, India. The watershed is situated in the Tombattu reserved forest with open mixed jungle in the hills of the Western Ghats and falls under the Coastal Karnataka agro-climatic sub-zone of India. The stream gauge site maintained by WRDO is located on Haladi river at Haladi Bridge in Dakshina Kannada district of Karnataka, India.

4.3.5 Dasanakatte Watershed

Dasanakatte watershed is drained by Dasanakatte River, a tributary of Haladi River, which originates from Ballimane reserved forest at an altitude of 870 m amsl, 3 km upstream of Amashebail village in the Western Ghats in Udupi district of Karnataka state, India. The watershed is situated in open mixed jungle of bamboo and falls under the Coastal Karnataka agro-climatic sub-zone of India. The stream gauge site maintained by WRDO is located on Dasanakatte river near Haladi Bridge in Dakshina Kannada district of Karnataka, India.

4.3.6 Barchi Watershed

Barchi watershed is located in the leeward side of Western Ghats and falls under the Hilly agro-climatic zone of the Karnataka State in India. It is drained by Barchinala, a tributary of Kali River, which originates from Thavargatti in Belgaum district at an altitude of about 734 m amsl, 20 km north of Dandeli and flows through North Kannada district of Karnataka State, India. The watershed is relatively short in width and the river flows in southerly direction and joins the main Barchi river near the gauging site. It consists of steep hills and valleys intercepted with thick vegetation. The slopes of the Western Ghats are covered with dense deciduous forest. The stream gauge site of WRDO is located at an elevation of 480 m, where the river crosses Dandeli-Thavargatti road, about 5 km from Dandeli.

4.3.7 Anthrolli Watershed

Anthrolli watershed upstream of Teregaon Bridge is also located in the leeward side of Western Ghats. It falls under the Hilly agro-climatic zone region of the Karnataka State (India). The watershed is drained by Dusginala, a tributary of Kali River. The Dusginala river originates from Deogaon village in Khanapur taluka of Belgaum district at an altitude of about 778 m amsl, 5 km south of Kittur village in Belgaum district and flows through Dharwar and North Kannada district of Karnataka State, India. The watershed is elongated in shape with broader width and river flows in southerly direction and joins the main Dusginala near the gauging site. The stream gauge site of WRDO is located on bridge where Dusginala crosses Khanapur -Haliyal road, about 6 km from Haliyal at an elevation of 532 m amsl.

4.4 WATERSHED UNDER MALAPRABHA SUB-BASIN (KHANAPUR)

The Malaprabha river rises in the Western Ghats, at an altitude of about 793 m amsl about 16 km west of Jamboti in the Belgaum district of Karnataka. The river flows first in an easterly and then in a north-easterly direction and joins the Krishna at an elevation of about 488 m amsl, about 306 km from its source. The stream gauge site maintained by WRDO is located at an elevation of 646 m amsl, where the Belgaum-Goa road crosses river at Khanapur. The other details about location, topography, catchment characteristics and climate etc. are given in Table 4.1. Fig. 4.4 shows drainage map of Khanapur watershed.

Fig. 4.4 Drainage Maps of Malaprabha and Hemavathi Watersheds

4.5 WATERSHED UNDER CAUVERY BASIN (HEMAVATHI)

The Hemavathi river is a tributary of river Cauvery, originating in Ballaiarayanadurga in the Western Ghats in Mundgiri taluk of Chikmanglur district in Karnataka State, India. It traverses a total length of about 55.13 km up to gauging site at Sakleshpur. Forest, agriculture and coffee plantation are the major land use of the basin. Soils in the forest area and coffee plantations are greyish due to high humus content. The details about location, topography, catchment characteristics, climate, etc. are given in Table 4.1. Fig. 4.4 shows the drainage map of Hemavathi watershed.

4.6 WATERSHEDS UNDER NARMADA BASIN

Narmada River originates in the Amarkantak plateau in the Shahdol district of Madhya Pradesh. It flows about 1300 km towards west through Sal and teak forests, through gorges and broad valleys to merge with the waters of the Arabian Sea in the Bharuch district of Gujarat. With many short tributaries flowing into it from north and south, the Narmada basin forms a very important topographic feature of peninsular India. The study watersheds namely, Manot, Mohegaon, and Hridaynagar fall under this basin and in the central plateau and hills agro-climatic region of India. The details of watersheds under this basin are given in the Table 4.1. Drainage maps of watersheds situated in Narmada basin are shown in Fig. 4.5.

4.6.1 Manot Watershed

Manot watershed is drained out by River Narmada, which rises from Amarkantak plateau of Maikala range in Shahdol district of Madhya Pradesh at an elevation of about 1059 m amsl. The length of the Narmada river from its origin up to Manot is about 269 km. It has continental type of climate classified as sub-tropical and sub-humid. It is very hot in summer and cold in winter. The stream gauging site is located at Manot in Shahdol district of Madhya Pradesh, India, and maintained by CWC, India.

4.6.2 Hridaynagar Watershed

Hridaynagar watershed is drained by the Banjar River, a tributary of Narmada River. The river Banjar originates from the Satpura range in Durg district of Madhya Pradesh near Rampur village at an elevation of 600 m. The elevation drops from 600 to 372 m amsl at Hridaynagar gauging site of CWC (Table 4.1). Climate of the basin can be classified as subtropical sub-humid and about 90% of the annual rainfall is received during monsoon season (June–November).

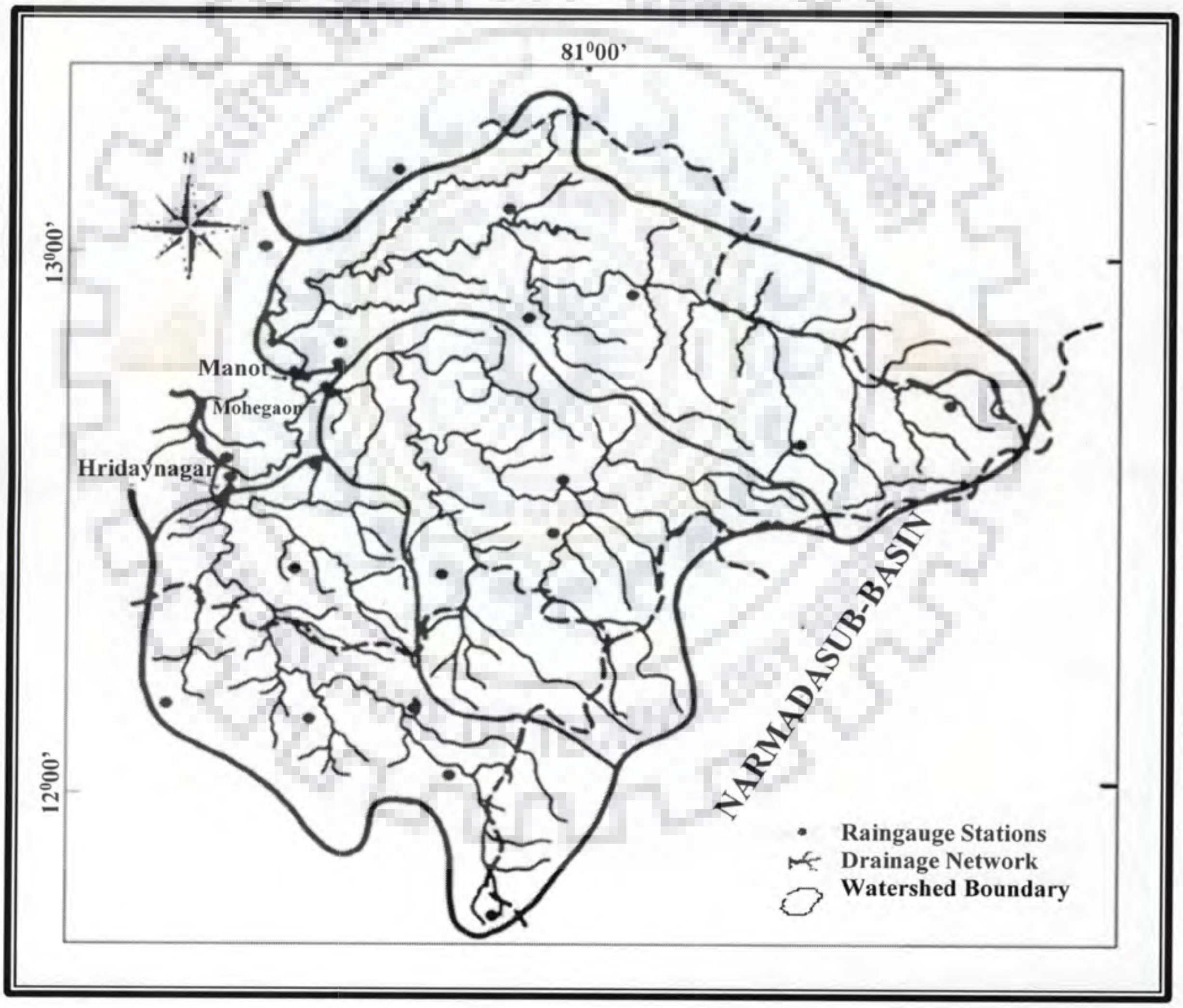


Fig. 4.5 Drainage Maps of Selected Watersheds in Narmada Sub-basin

4.6.3 Mohegaon Watershed

The Burhner river which drains the Mohegaon watershed is a tributary of Narmada river and rises in the Maikala range, south-east of Gwara village in the Mandla district of Madhya Pradesh at an elevation of about 900 m amsl. It flows in westerly direction for a total length of 177 km to join the Narmada near Manot. The elevation at Mohegaon gauging site drops to 509 m amsl and climate of the basin can be classified as sub-tropical and sub-humid. The other details of the watershed are given in Table 4.1.

CHAPTER 5

MODEL APPLICATION AND EVALUATION

5.1 GENERAL

The long term hydrological simulation (LTHS) models described in Chapter 3 employ the SCS-CN concept incorporating various sets of soil moisture accounting (SMA) procedures to calculate the space available for water retention. The water retention store is updated based on the daily changes in Soil Moisture Store (SMS) and Ground Water Store (GWS). These proposed models along with the existing SCS-CN based continuous models such as generalized continuous Michel et al. (2005) sub-model and Geetha et al. (2008) lumped conceptual rainfall-runoff (LCRR) model were applied to the daily data of rainfall and stream flow of the selected watersheds from different agro-climatic zones of India as detailed in Chapter 4. This chapter discusses various aspects related to (i) application and performance evaluation of the proposed lumped, conceptual long term hydrologic simulation models for simulating the daily stream flow of selected watersheds under different agro-climatic set up; (ii) identification of the dormant/dominant processes and mechanism involved in the generation of stream flow from each watershed; and (iii) inter-comparison of performance among various proposed LTHS models and with existing models of Michel at al. (2005) and Geetha et al. (2008).

As stated above, the selected watersheds lie in different agro-climatic zones of India and exhibit widely varied runoff generating characteristics. Therefore, for evaluating the performance of the developed and existing models, these watersheds are grouped into three different categories depending on the runoff coefficient (Gan et al., 1997; Geetha et al, 2008) as detailed in Table 5.1. The watersheds having runoff coefficient (C) below or equal to 0.36 ($C \leq 0.36$) are categorized as dry, those having runoff coefficient between 0.36 and 0.65 ($0.36 < C \leq 0.65$) as average, and the watersheds having runoff coefficient more than 0.65

(C>0.65) are categorized as wet. Accordingly, five watersheds namely, Hirehalla, Hridaynagar, Amachi, Mohegaon, and Barchi are categorized as dry; and eight watersheds namely, Hemavathi, Attigundi, Kokkarne, Dasanakatte, Haladi, Halkal, Jadkal, Sorab as wet and the remaining three watersheds as average watersheds (Table 5.1). It can be seen from Table 5.1 that Hirehalla watershed shows lowest average annual runoff Coefficient of 0.11 and average seasonal runoff Coefficient of 0.13, and it is the driest watershed among the selected watersheds in the present study.

Table 5.1 Runoff Coefficient and Condition of Study Watersheds

Sr. No.	Name of the Watershed	Average Annual		Average Seasonal	
		Runoff Coefficient	Watershed Condition	Runoff Coefficient	Watershed Condition
1	Hemavathi	0.78	Wet	0.81	Wet
2	Hridayanagar	0.24	Dry	0.26	Dry
3	Mohegaon	0.35	Dry	0.36	Dry
4	Manot	0.45	Average	0.47	Average
5	Amachi	0.29	Dry	0.31	Dry
6	Anthrolli	0.37	Average	0.41	Average
7	Attigundi	0.72	Wet	0.78	Wet
8	Barchi	0.35	Dry	0.36	Dry
9	Khanapur	0.60	Average	0.62	Average
10	Hirehalla	0.11	Dry	0.13	Dry
11	Sagar	0.66	Wet	0.67	Wet
12	Sorab	0.58	Average	0.63	Average
13	Dasanakatte	0.90	Wet	0.89	Wet
14	Haladi	0.93	Wet	0.84	Wet
15	Jadkal	0.92	Wet	0.93	Wet
16	Kokkarne	0.79	Wet	0.80	Wet
17	Halkal	0.89	Wet	0.90	Wet

5.2 MODEL CALIBRATION AND VALIDATION

For a conceptual model to be useful for simulating response from a watershed, its parameters need to be calibrated. It is well known that conceptually realistic models may produce erroneous results if they are not properly calibrated. The calibration of a model is performed to determine the parameters of the model such that an acceptable match is obtained between the observed behavior of the watershed and model predicted behavior (Jain, 1993, McCuen, et al. 2006). In the present study, this involves obtaining the best match between the observed and computed stream flows. Two approaches are generally followed for the calibration of a conceptual model, (i) manual fitting of parameter using trial and error and (ii) automatic fitting using an optimization algorithm. The parameter values obtained from an automatic calibration may be further fine-tuned manually to achieve an improved match between observed and computed stream flows.

Conceptual models are difficult to calibrate by means of fully automatic methods; one major reason for this is the inability of conventional procedures to locate the global optimal set of parameters (Sorooshian and Gupta, 1983). Hence, various parameters involved in the model are calibrated using appropriate optimization techniques and then a validation test is performed on an independent data set. Validation tests the calibrated model against the additional set of field data to further examine the range of validity of the calibrated model. It is a more stringent evaluation of a model because parameter values are not allowed to be adjusted during the process of validation on independent data set. The validation assesses the ability of the model to simulate in periods and areas outside the range of data used in calibration. Various statistical measures such as Nash and Sutcliffe measure (NSE) and the relative error (RE) (Chapter 3) are used to evaluate quantitatively models' performance both during calibration and validation periods. The error statistics such as root mean square error (RMSE) and standard error (SE) are used for inter-comparison of models. Since there is nearly equal number of parameters involved in the proposed models in the present study, there is not much significant difference in the values of RMSE and SE calculated in calibration and validation of these models. However, SE is a better goodness-of-fit measure as it has the same dimension as observed runoff, accounts for the degrees of freedom (*N-m*), and it is valid for nonlinear as well as linear models (McCuen, 2003). Therefore, the only one error criterion, SE, is considered instead of RMSE and SE both for inter-comparison of the proposed LTHS models.

As stated in Chapter 3, the proposed LTHS models in the present study involve certain parameters relating to climate, vegetation and soil, which are to be optimized. The non-linear Marquardt (1963) optimization algorithm in FORTRAN program, coupled with trial and error, utilizing the objective function of minimizing errors between the computed and observed daily stream flow is used for optimizing these parameters. Though the trial and error has drawbacks, it involves qualitative hydrologic reasoning in comparing the simulated and observed runoff values, for minimizing the errors. The parameter values obtained from an automatic calibration are further fine-tuned manually to achieve an improved match between the computed and observed data. The non-linear Marquardt algorithm used in the present study requires a priori estimates of initial, lower, and upper limits of values of parameters to be optimized. The range of each parameter is selected appropriately and an initial estimate of each parameter is supplied to determine the optimal values using Marquardt algorithm. The initial values and range of variation of parameters of proposed models used for optimization for each of the watershed under study are presented in Table 5.2.

To test the performance of the proposed models, the available observed data of study watersheds is split into two groups as detailed in Table 4.1. Data for one group is used to calibrate the parameters of the proposed and existing models and performance of these models is evaluated by using the other group of data not used in the calibration of models. The performance evaluation of all the proposed models is studied using (a) yearly data and (b) seasonal (monsoon) data (June to November) series of study watersheds. The daily rainfall and stream gauge records of all watersheds except Hemavathi and Barchi during annual and seasonal periods for 5 years out of 9 years are used in calibration and the remaining 4 years in validation as detailed in Table 4.1. The daily rainfall and stream gauge records of annual and seasonal periods of Hridaynagar, Manot, and Mohegaon watersheds during the period (1981-1986) are used for model calibration, while the data of remaining period (1986-1990) are used for validation. In case of Amachi, Anthrolli, Attigundi, Khanapur, Hirehalla, Sagar, Sorab, Dasanakatte, Haladi, Jadkal, Kokkarne, and Halkal watersheds, the daily rainfall and stream flow records of 5 years (1985-1989) are used for calibration, and the remaining 4 years of data for the period (1989-94) for validation. The daily rainfall and stream gauge records of 3 years (1975-1978) out of 5 years (1975-1980) of annual and monsoon periods of Hemavathi watershed are used to calibrate the model, and remaining two years data (1978-1980) for validation. Similarly, 3 years (1989-1992) out of 5 years (1989-1993) of daily annual and seasonal rainfall and stream flow of Barchi watersheds are used for calibration, and remaining data for validation.

Table 5.2 Lower and Upper Limits of Parameters and Initial Values used in Calibration of the Proposed LTHS Models

Sr. No.	Model Parameter		Name of Watershed								
			Hemavathi	Hridaynagar	Mohegaon	Manot	Amachi	Anthrolli	Attigundi	Barchi	Khanapur
1	CN_0	Range	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100
		Initial value	60	60	60	60	60	60	60	60	60
2	δ	Range	0-5.00	0-1.00	0-1.00	0-1.00	0.-1.00	0.-1.00	0.-1.00	0.-1.00	0.-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
3	α	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.3	0.5	0.5	0.5	0.2	0.5	0.5	0.5	0.5
4	β	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
5	γ	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
6	K	Range	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0
		Initial value	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45
7	P_1	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
8	P_2	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.2	0.5	0.5	0.3	0.5	0.5	0.5	0.5
9/10	P_3/P_4	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
11	θ_w	Range	40-150	200-300	80-120	200-300	60-180	60-200	100-140	60-180	60-180
		Initial value	100	250	100	250	100	100	120	100	100
12/13	θ_f/ψ_f	Range	100-400	300-450	250-400	300-500	200-400	200-400	200-400	200-350	200-400
		Initial value	150	400	300	400	250	250	250	250	250
14	Es	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
15	E_g	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-2.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16	ψ_0	Range	150-1000	300-1000	150-1000	350-1000	150-500	200-1000	150-1000	150-1000	200-1000
		Initial value	400	400	400	400	400	400	400	400	400
17	CNd_0	Range	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100
		Initial value	60	60	60	60	60	60	60	60	60
18	λ_d	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 5.2 continued..............

Sr. No.	Model Parameter		Name of Watershed							
			Hirehalla	Sagar	Sorab	Dasankatte	Haladi	Jadkal	Kokkarne	Halkal
1	CN_0	Range	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100
		Initial value	60	60	60	60	60	60	60	60
2	δ	Range	0-1.00	0-1.00	0-1.00	0.-1.00	0.-1.00	0.-1.00	0.-1.00	0.-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
3	α	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.2	0.5	0.5	0.5	0.5
4	β	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
5	γ	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
6	K	Range	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0	0.5-5.0
		Initial value	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45
7	P_1	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
8	P_2	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.2	0.5	0.5	0.3	0.5	0.5	0.5	0.5
9/10	P_3/P_4	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
11	θ_w	Range	200-300	80-120	200-300	60-180	60-200	100-140	60-180	60-180
		Initial value	250	100	250	100	100	120	100	100
12/13	θ_f/ψ_f	Range	300-450	250-400	300-500	200-400	200-400	200-400	200-350	200-400
		Initial value	400	300	400	250	250	250	250	250
14	E_s	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
15	E_g	Range	0-2.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16	ψ_0	Range	300-1000	150-1000	350-1000	150-500	200-1000	150-1000	150-1000	200-1000
		Initial value	400	400	400	400	400	400	400	400
17	CNd_0	Range	0-100	0-100	0-100	0-100	0-100	0-100	0-100	0-100
		Initial value	60	60	60	60	60	60	60	60
18	λ_d	Range	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00	0-1.00
		Initial value	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

5.3 MODIFIED SCS-CN CONCEPT BASED MODEL-I (LTHS MICHEL I)

The model LTHS MICHEL I (Model-I) is modification of the discrete formulations of the Michel et al. (2005) model by incorporating an expression for soil moisture store level prior to rainfall occurrence (V_0) to make it continuous long term hydrologic simulation model (Durbude et al., 2010). It uses the expression for computing direct runoff based on V_0 for various AMCs proposed by Michel et al. (2005), and sub-surface flow computation based on the conceptual behavior of soil moisture store (SMS) and ground water store (GWS) as given by Putty and Prasad (2000). Model-I has fourteen parameters, viz., CN_0, α, β, K, P_1, P_2, P_3, P_4, θ_w, θ_f, ψ_f, E_s, E_g, and ψ_0. The range of variation of these parameters is detailed in Chapter 3 and presented in Table 5.2. The model application by using annual and seasonal data series, which include both calibration and validation data sets and the results are described in the subsequent sections.

5.3.1 Application of Model-I on Annual Data

The optimal values of the set of parameters of Model-I estimated using the non-linear Marquardt algorithm for various watersheds is presented in Table 5.3. Using this optimal set of parameter values (Table 5.3), the performance of the model was tested for data marked for validation. The model efficiency in terms of NSE values in both calibration and validation of Model-I is given in Table 5.4. The range of NSE obtained in calibration and validation is shown in Fig. 5.1 for wet and dry categories of watersheds. As seen from Table 5.4 and Fig 5.1, NSE varies from 0.70 to 0.88 for all high yielding (wet) watersheds in calibration indicating satisfactory to very good model performance (Motovilov et al., 1999) in daily stream flow simulation (Durbude et al., 2010). For low yielding (dry) watersheds, the NSE varies from 0.38 to 0.52 in calibration (excluding most dry watershed, Hirehalla) indicating satisfactory model response for these watersheds (Fig. 5.1). The model yields the maximum NSE of 0.88 in calibration for Hemavathi watershed and 0.89 in validation for Jadkal watershed, while the minimum efficiency of 0.52 in calibration is seen for Hridaynagar watershed and 0.34 in validation for Anthrolli watershed excluding most dry watershed Hirehalla, for which the model efficiency is very poor (NSE = -0.001). Thus, Model-I yield high efficiency for wet watersheds and relatively low efficiency for dry watersheds indicating

Table 5.3 Optimized Values of Parameters of LTHS MICHEL I Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter													
		CN_0	α	B	K	P_1	P_2	P_3	P_4	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	30.0	0.33	0.10	1.43	0.03	0.08	0.10	0.85	122.0	250.6	130.1	0.31	1.94	206.2
2.	Hridaynagar	48.8	0.92	0.98	2.35	0.06	0.60	0.42	0.72	201.3	411.2	364.5	0.18	0.90	311.1
3.	Mohegaon	30.1	0.32	0.10	0.50	0.02	0.97	0.40	0.30	150.0	376.3	400.0	0.40	0.37	576.4
4.	Manot	30.0	0.10	0.10	0.50	0.01	0.83	0.59	0.10	200.0	405.3	332.8	0.37	0.43	801.4
5.	Amachi	50.8	0.10	0.41	5.00	0.10	0.91	0.10	0.59	180.0	321.4	330.4	0.34	1.22	260.4
6.	Anthrolli	14.0	0.02	0.10	0.50	0.02	0.10	0.45	0.12	198.1	249.5	200.0	0.32	0.72	809.0
7.	Attigundi	58.1	0.10	0.39	2.50	0.01	0.10	0.27	0.95	160.0	350.0	247.5	0.39	1.22	231.2
8.	Barchi	15.0	0.11	0.06	0.50	0.02	0.38	0.60	0.57	71.1	220.0	346.1	0.15	0.57	411.6
9.	Khanapur	16.0	0.19	0.10	1.80	0.05	0.54	0.10	0.65	116.6	353.4	364.7	0.41	1.27	679.9
10.	Hirehalla	33.2	0.48	0.51	0.50	0.05	0.10	0.10	0.50	100.0	214.7	314.9	0.30	1.25	320.0
11.	Sagar	42.0	0.10	0.06	0.50	0.05	0.50	0.60	0.19	180.0	200.0	400.0	0.60	0.58	642.2
12.	Sorab	68.8	0.10	0.03	0.50	0.06	0.20	0.10	0.91	180.0	220.0	400.0	0.40	0.90	740.7
13.	Dasanakatte	22.9	0.39	0.10	0.50	0.07	0.99	0.30	0.99	150.0	200.0	300.0	0.37	0.78	250.0
14.	Haladi	21.6	0.39	0.12	0.50	0.06	0.99	0.10	0.99	160.0	230.0	248.8	0.35	0.85	251.8
15.	Jadkal	23.0	0.31	0.13	0.50	0.04	0.99	0.30	0.99	140.0	260.0	320.0	0.36	0.72	300.0
16.	Kokkarne	23.2	0.56	0.16	0.50	0.04	0.98	0.30	0.99	180.0	249.1	309.5	0.35	0.65	312.1
17.	Halkal	20.6	0.38	0.12	0.50	0.07	0.61	0.30	0.99	150.0	180.0	400.0	0.38	0.82	250.0

Table 5.4 NS Efficiency and Absolute RE in Calibration and Validation of the Proposed LTHS Models (Annual Data)

Sr. No.	Name of Watershed	Calibration								Validation							
		NS Efficiency				Absolute RE (%)				NS Efficiency				Absolute RE (%)			
		M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV
1.	Haladi	0.86	0.87	0.88	0.89	16.3	11.4	11.4	0.3	0.66	0.63	0.65	0.68	13.5	8.5	8.2	20.0
2.	Jadkal	0.83	0.84	0.85	0.87	18.5	6.3	2.6	1.5	0.89	0.87	0.87	0.89	9.7	1.3	5.1	9.7
3.	Dasanakatte	0.81	0.82	0.84	0.87	14.9	13.2	3.8	2.1	0.77	0.76	0.77	0.79	12.8	8.0	0.0	3.8
4.	Halkal	0.88	0.88	0.89	0.90	7.9	5.1	7.1	4.9	0.82	0.84	0.84	0.86	8.0	6.6	6.7	0.4
5.	Kokkarne	0.87	0.87	0.88	0.92	0.7	0.1	3.6	1.7	0.86	0.85	0.86	0.85	2.3	5.0	0.5	4.9
6.	Hemavathi	0.88	0.90	0.90	0.91	9.4	7.8	5.3	7.8	0.63	0.89	0.90	0.90	19.2	8.0	4.9	16.1
7.	Attigundi	0.76	0.78	0.79	0.81	11.4	9.0	3.3	4.4	0.52	0.54	0.53	0.53	1.9	8.1	6.2	0.0
8.	Sagar	0.70	0.71	0.76	0.79	15.6	12.6	3.9	1.2	0.56	0.53	0.66	0.68	25.8	16.1	14.7	16.6
9.	Khanapur	0.73	0.77	0.79	0.77	1.0	2.3	4.0	5.2	0.70	0.70	0.72	0.73	29.5	33.9	30.8	24.1
10.	Sorab	0.64	0.72	0.74	0.75	14.0	12.3	12.6	3.7	0.59	0.58	0.56	0.47	10.7	0.8	1.5	3.9
11.	Manot	0.65	0.70	0.72	0.79	5.7	3.7	3.6	5.3	0.54	0.55	0.61	0.68	7.5	10.3	5.7	21.5
12.	Anthrolli	0.60	0.68	0.70	0.75	0.7	16.2	5.7	1.7	0.34	0.38	0.49	0.39	6.7	19.3	12.2	7.3
13.	Mohegaon	0.55	0.59	0.60	0.65	21.5	15.3	13.2	13.4	0.46	0.49	0.49	0.54	34.1	24.6	8.5	29.8
14.	Barchi	0.56	0.60	0.62	0.65	0.2	6.0	5.2	5.4	0.52	0.59	0.59	0.61	1.6	19.2	13.3	15.4
15.	Amachi	0.55	0.62	0.63	0.63	10.5	9.8	2.0	5.7	0.38	0.43	0.43	0.50	25.3	2.0	0.8	5.2
16.	Hridaynagar	0.52	0.54	0.58	0.59	12.3	10.9	10.7	9.5	0.41	0.49	0.49	0.50	57.1	54.3	56.5	55.8
17.	Hirehalla	0.07	0.15	0.16	0.17	68.8	7.9	13.7	8.9	-0.001	0.36	0.36	0.45	48.5	24.5	25.4	7.8

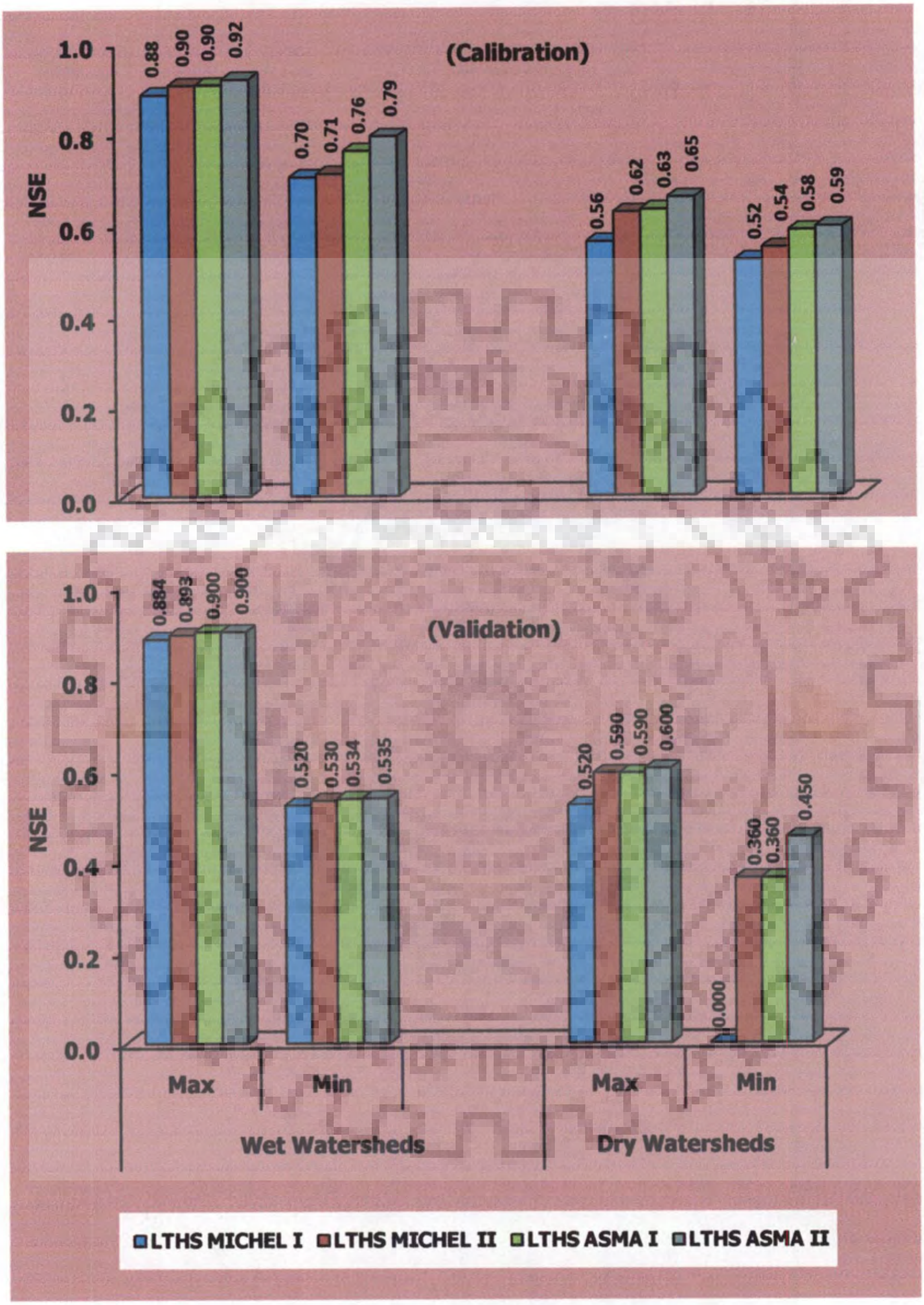


Fig. 5.1 Range of NSE Obtained in Calibration and Validation of the Proposed LTHS Models on Annual Data of Wet and Dry Watersheds

a very good model response for wet watersheds and good to satisfactory model response for dry watersheds, and poor response to most dry Hirehalla watershed having lowest value of average runoff coefficient (Durbude et al., 2010). This is apparent from the trend analysis presented in Fig. 5.2 by plotting ascending order of runoff Coefficient of various watersheds under study against NSE values in calibration and validation. The NSE increase with watershed wetness in terms of runoff coefficient as shown in Fig. 5.2.

The other evaluation criterion is RE, a measure of the average tendency of the simulated flows to be larger or smaller than their observed values. The absolute value of RE (%) computed for calibration and validation periods for Model-I is listed in Table 5.4. As seen from Table 5.4, the absolute values of RE varies from 0.6% to 18.5% in calibration for all high yielding watersheds, which can be considered as a very good to satisfactory model performance to simulate the total stream flow (Donigian et al., 1983; Harmel et al., 2006). In case of dry watersheds, RE varies from 10.5% to 21.5% except Hirehalla watershed, which can be ascribed to good to satisfactory performance. The performance of the model is unsatisfactory in the most dry watershed, Hirehalla where RE = 68.8%. The performance of model is also very good for all watersheds under average condition except for the Sorab watershed (14%).

The performance of the model is also evaluated on the basis of annual values of observed and computed runoff. The computed values and annual average values of rainfall, observed runoff, simulated runoff, and RE for each year are shown in Appendix A. The annual average values of rainfall, observed runoff, simulated runoff, and absolute RE of annual data series are presented separately in Table 5.5. The trend analysis on the plot of annual average values of absolute RE for study watersheds is also performed, as shown in Fig. 5.3, to evaluate the performance of Model-I for watershed wetness conditions defined in terms of average runoff coefficient.

As seen from Fig. 5.3, the values of RE decrease with watershed wetness indicating very good performance of model for wet watersheds, good to satisfactory performance for dry watersheds, and poor performance for most dry Hirehalla watershed. The yearly values of RE

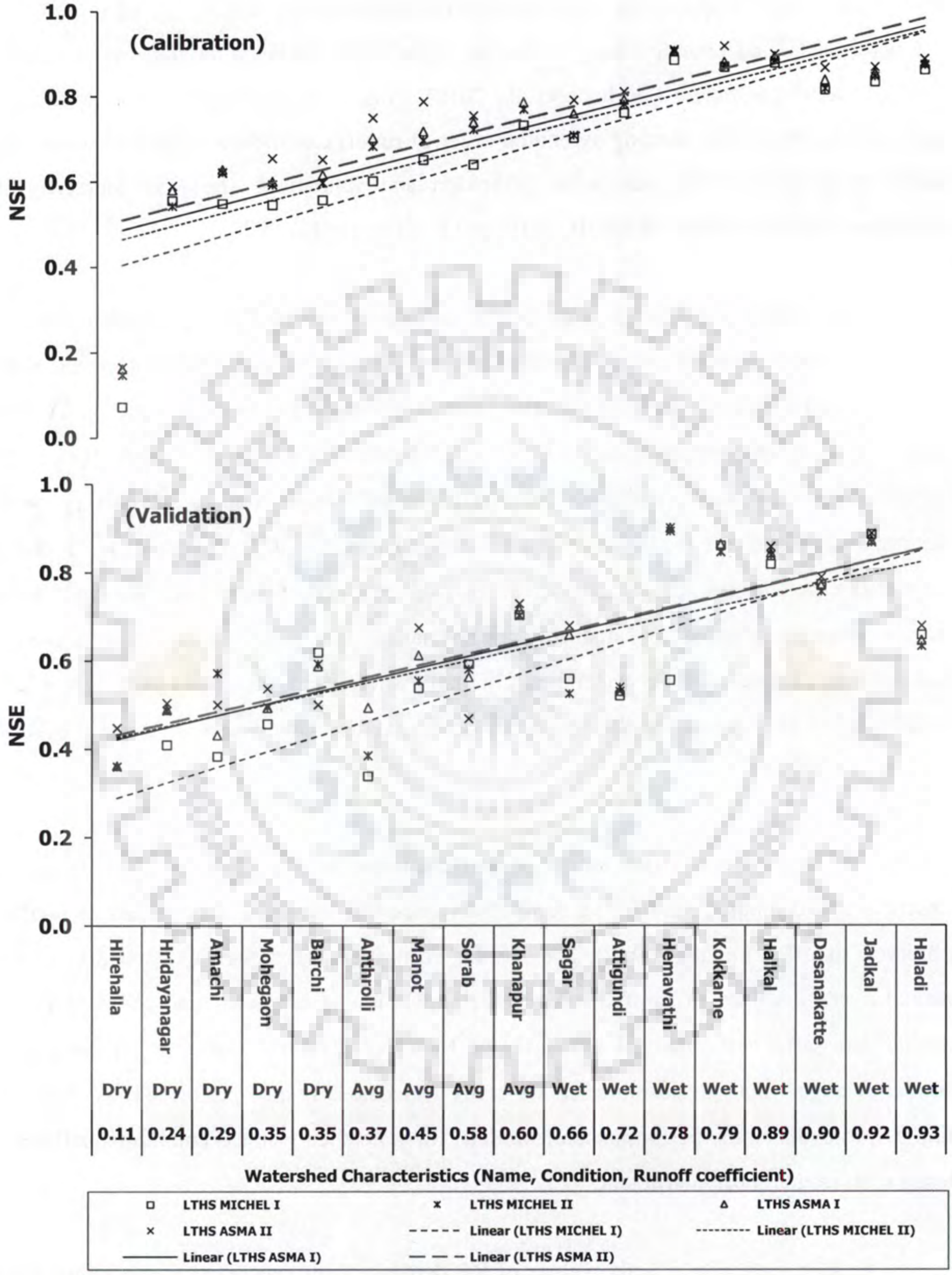


Fig. 5.2 Performance of the Proposed LTHS Models on Annual Data of Study Watersheds

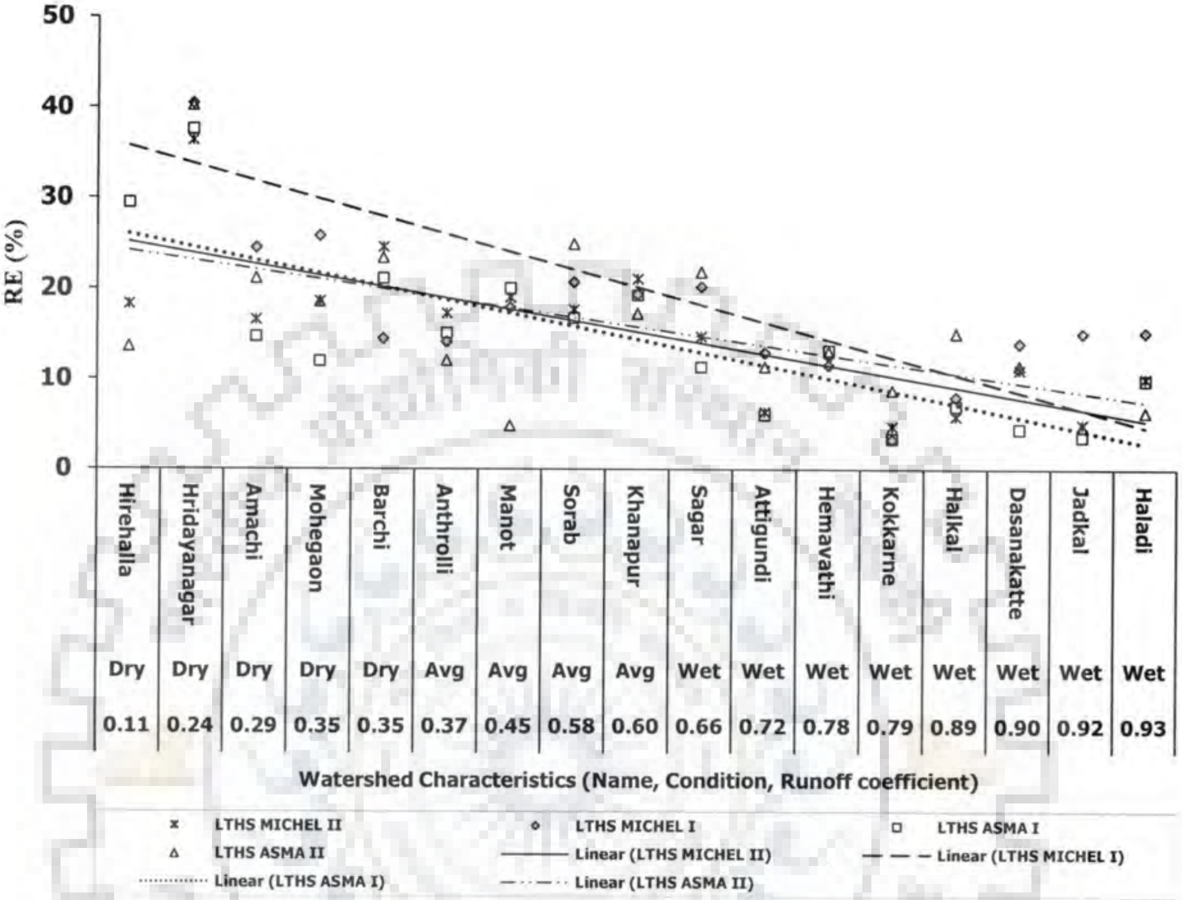


Fig. 5.3 Annual Average of Absolute Values of RE (Percent) Obtained for the Proposed LTHS Models on Annual Data of Study Watersheds

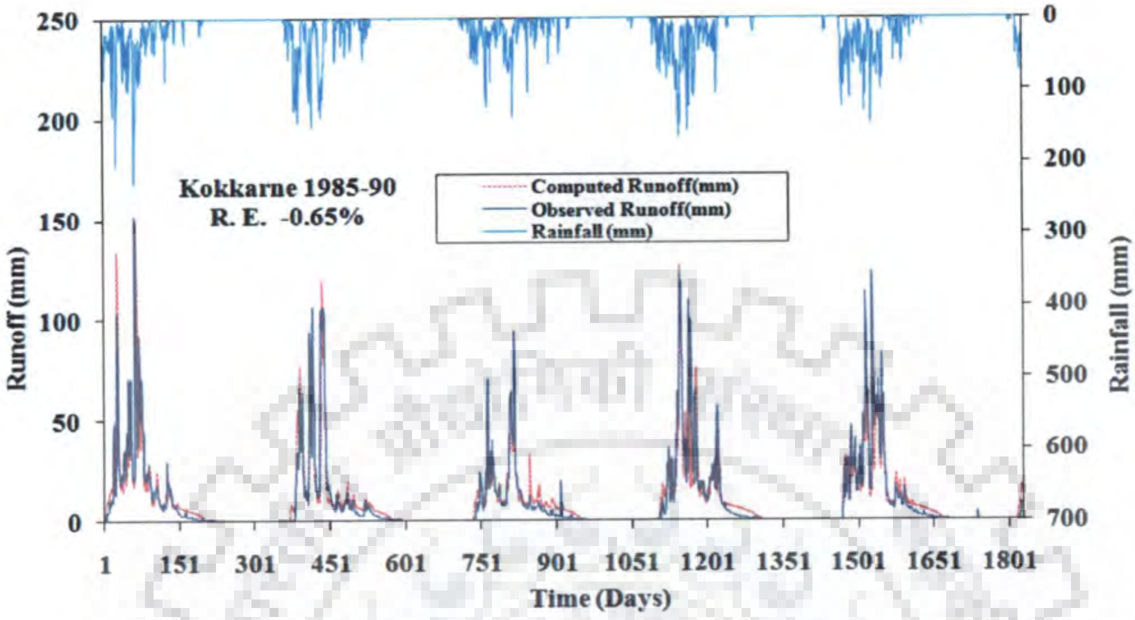
obtained for study watersheds shown in Table 5.5 indicate that the model performance is fair and very good in some years (Gupta et al., 1999), which may be attributed to high rainfall. A positive RE indicates that the model did not respond well to high rainfall or bias towards underestimation of stream flow whereas a negative RE indicates bias towards overestimation during some years.

Table 5.5 Annual Average Values of Rainfall, Observed Runoff, Simulated Runoff and Absolute RE for the Proposed LTHS Models

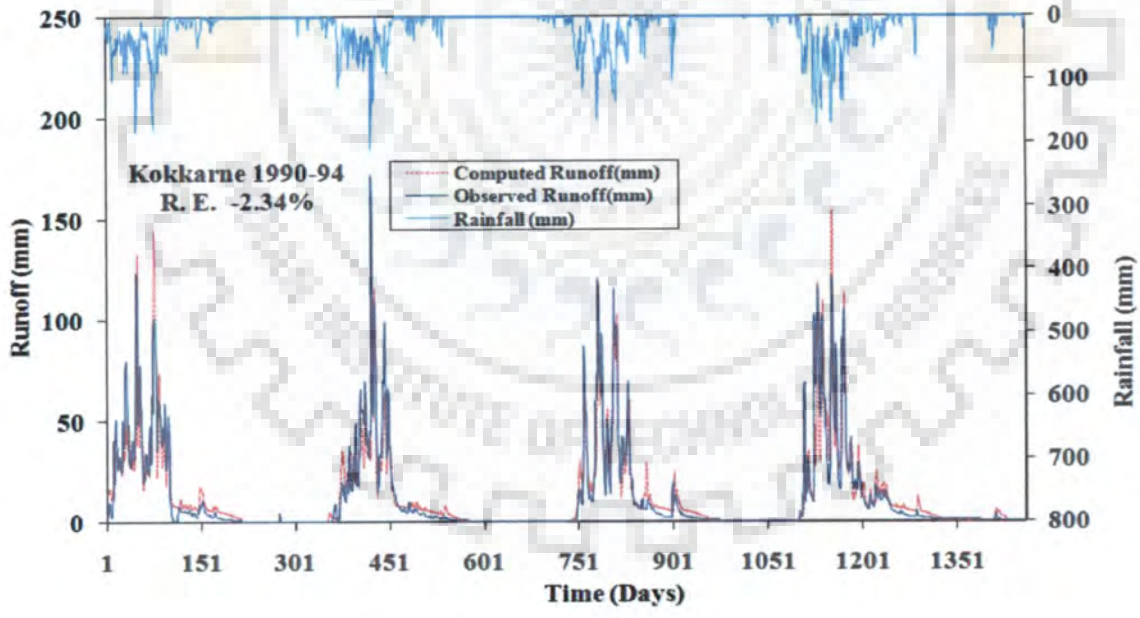
Sr. No.	Name of Watershed	Rainfall	Observed Runoff	LTHS MICHEL I (M-I)		LTHS MICHEL II (M-II)		LTHS ASMA I (M-III)		LTHS ASMA II (M-IV)	
				Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE
		(mm)	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
1	Hemavathi	2858.7	2232.7	1935.3	11.6	2033.7	12.0	2091.7	13.2	1949.4	13.6
2	Hridaynagar	1441.8	351.8	227.9	40.4	235.4	36.4	231.8	37.6	235.1	40.2
3	Mohegaon	1231.5	431.1	315.7	25.8	348.3	18.6	382.8	12.0	343.6	21.1
4	Manot	1263.6	564.8	527.6	17.9	526.3	19.1	569.5	20.1	491.4	18.6
5	Amachi	1707.3	491.7	401.7	24.5	463.8	16.6	494.3	14.7	351.8	28.9
6	Anthrolli	998.9	365.2	350.8	14.1	298.9	17.3	329.4	15.1	346.2	12.1
7	Attigundi	1960.6	1404.2	1337.6	8.6	1282.0	10.8	1336.3	8.8	1431.3	7.2
8	Barchi	1419.4	497.7	494.0	14.5	478.1	24.6	539.5	21.1	355.0	35.7
9	Khanapur	3980.3	2398.8	2001.2	19.4	1954.2	21.1	2013.9	19.3	2119.2	17.3
10	Hirehalla	594.5	67.8	29.4	65.3	56.2	18.3	54.1	29.5	67.6	21.8
11	Sagar	1864.4	1222.0	960.2	20.2	1043.7	14.8	1098.5	11.4	1099.6	11.4
12	Sorab	1321.2	766.4	673.5	20.7	722.3	17.7	718.4	16.8	770.9	13.1
13	Dasanakatte	4628.7	4166.5	3589.4	14.0	3723.9	11.1	4087.3	4.4	4044.9	8.8
14	Haladi	4718.2	4400.6	3745.1	15.2	3962.5	10.1	3971.1	9.9	3953.7	15.1
15	Jadkal	5209.3	4815.1	4114.3	15.1	4692.7	5.0	4875.6	3.6	4548.3	11.5
16	Kokkarne	5061.6	4010.6	4070.4	3.3	4111.9	4.8	3956.9	3.4	4074.7	4.7
17	Halkal	5239.9	4650.2	4279.8	8.0	4376.3	5.9	4650.2	7.0	4552.5	6.3

To analyze the model performance on the basis of subjective assessment through visual comparison between the observed and computed runoff, the daily variation of rainfall, observed runoff, and computed runoff for Model-I for all years for all study watersheds along with RE (%) in calibration and validation are plotted and shown in Appendix B for calibration and Appendix C for validation. Figs. 5.4(a, b, c, d) depict some of the plots given in Appendix B and Appendix C at larger scales for better visualization of the results. As seen from these figures and other figures shown in Appendices (B and C), match between observed and model simulated runoff hydrographs is better for high yielding watersheds (for example, Hemavathi and Kokkarne watersheds etc.) compared to other relatively drier watersheds (for example, Hridaynagar watershed) in both calibration and validation. It is more apparent from the plots of the sample calibration and validation results yielding very good and poor performance of Model-I for sample years as shown in Figs. 5.5 (a, b, c, d). Notably, the resulting RE also reveals the degree of model performance on a watershed. The higher the RE, the poorer the model performance, and vice versa. Overall, this model exhibits a close match of the computed stream flow with the observed one, except for some deviation in simulating the peaks in both calibration and validation (Durbude et al., 2010).

The annual average values in terms of percentage of rainfall of various stream flow generating components, viz., surface runoff, evapotranspiration, sub-surface drainage, lateral flow, percolation, base flow, deep percolation, etc. are also estimated and presented in Table 5.6. The model also distinguishes the dormant and dominant components/processes of hydrologic cycle involved in it. Here, the process yielding less than 10% runoff contribution is termed as the dormant, it is dominant, otherwise (Geetha et al., 2007). To analyse the dormancy/dominancy of these components graphically, annual average values of these components were plotted against annual average runoff coefficient and separate trend lines were fitted as shown in Fig. 5.6. It is apparent from Fig. 5.6 that the surface runoff is predominant in most of the watersheds studied and more significant in wet watersheds as compared to lateral flow and base flow. It can also be seen from Fig. 5.6 that the base flow is significant in high runoff producing coastal watersheds than low runoff producing watersheds, while the evapotranspiration shows reverse trends. All other components except deep percolation show linearly increasing trends with respect to runoff coefficient. Deep percolation is dormant in high runoff producing watersheds.

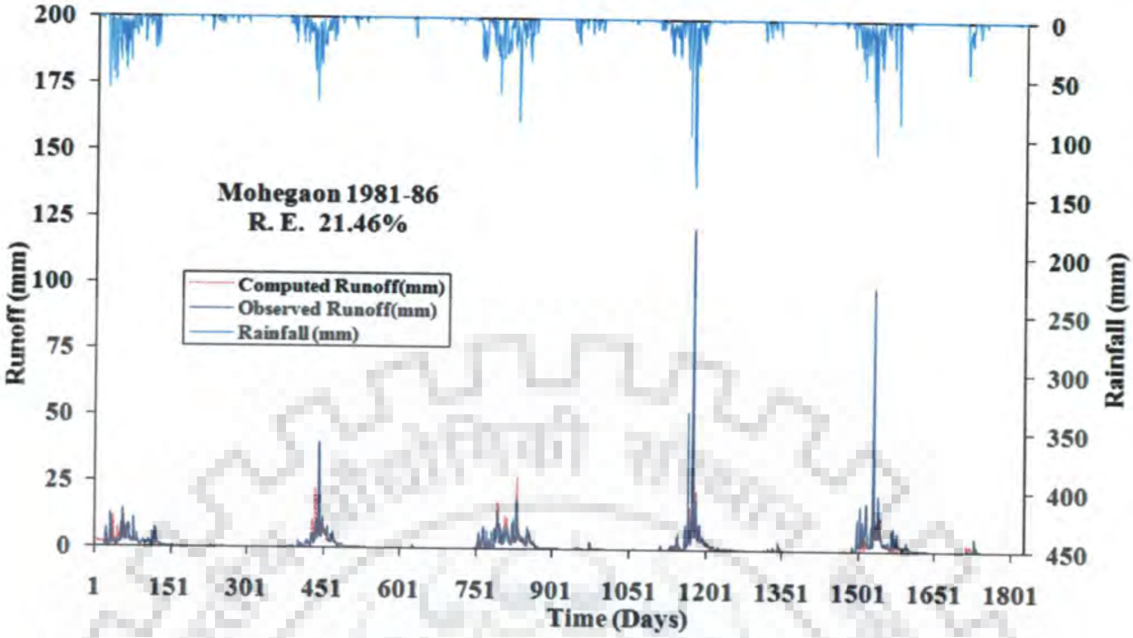


(a) Calibration (Kokkarne Watershed)

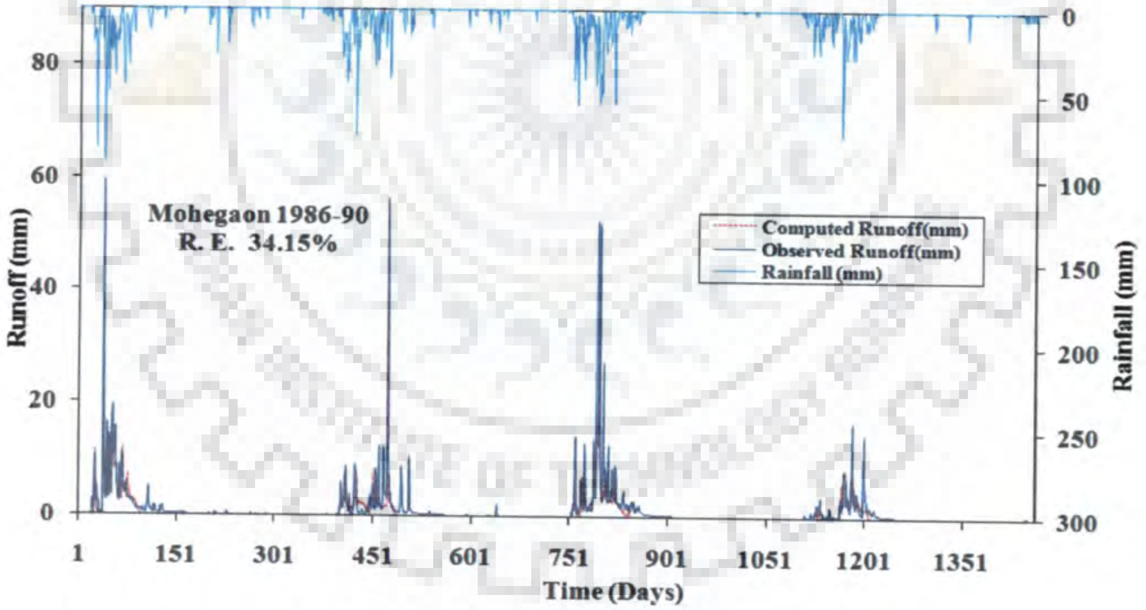


(b) Validation (Kokkarne Watershed)

Fig. 5.4 (a, b) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) of Kokkarne (Wet) Watershed in (a) Calibration and (b) Validation of LTHS MICHEL I Model (Day 1 represnets June 1)

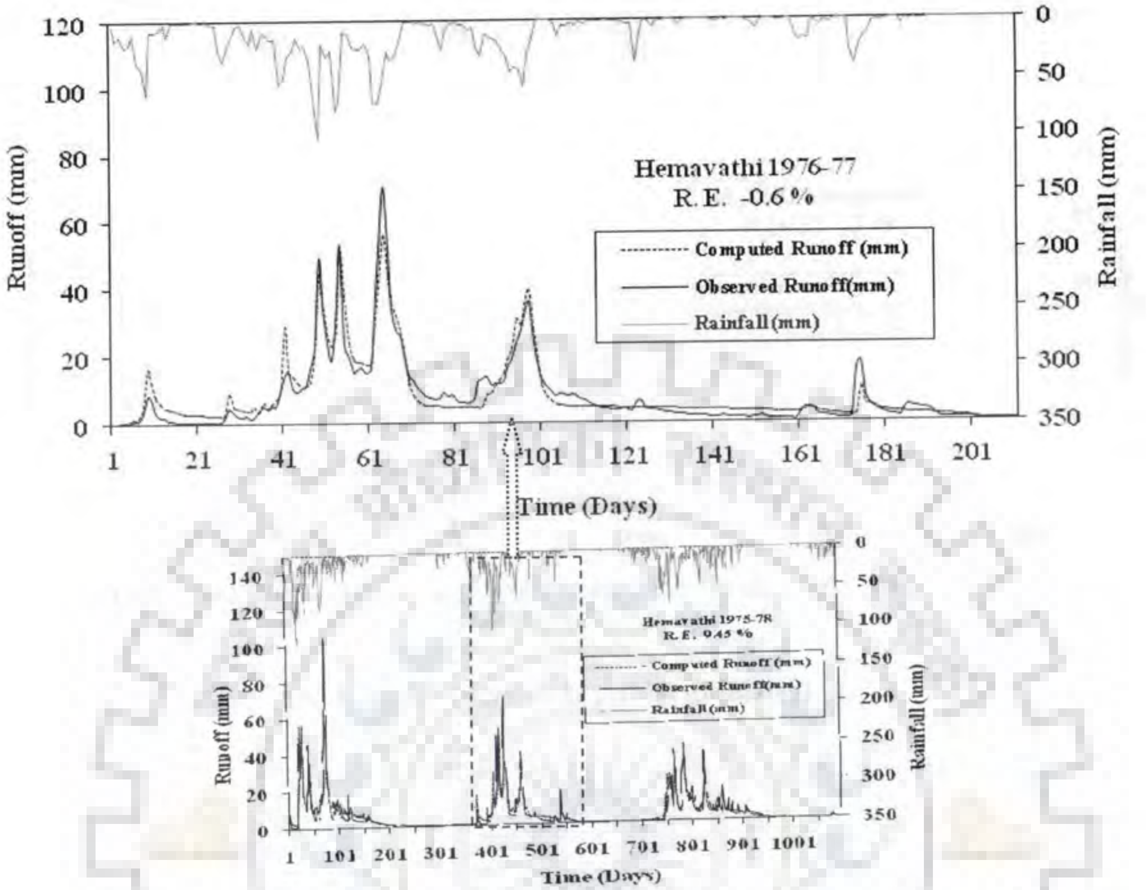


(c) Calibration (Mohegaon Watershed)

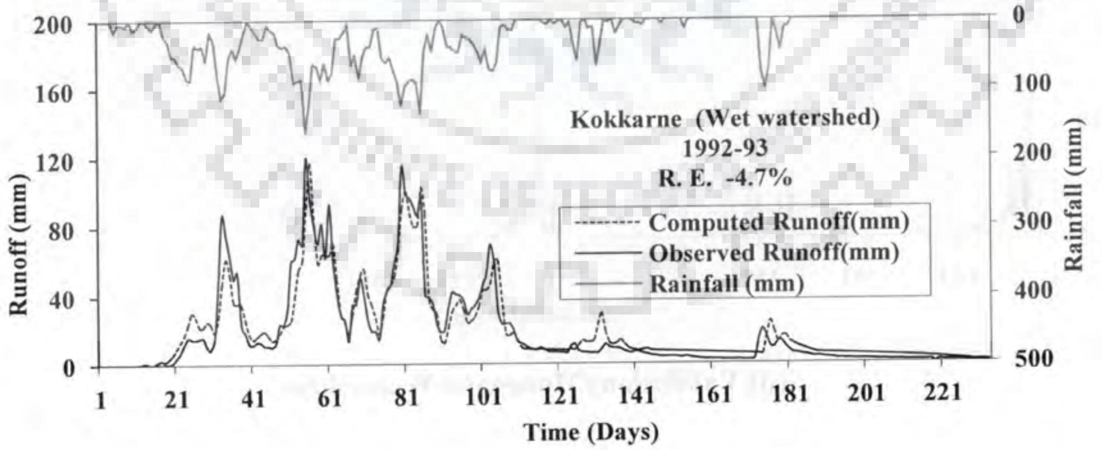


(d) Validation (Mohegaon Watershed)

Fig. 5.4 (c, d) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) of Mohegaon (Dry) Watershed in (c) Calibration and (d) Validation of LTHS MICHEL I Model (Day 1 represents June 1)

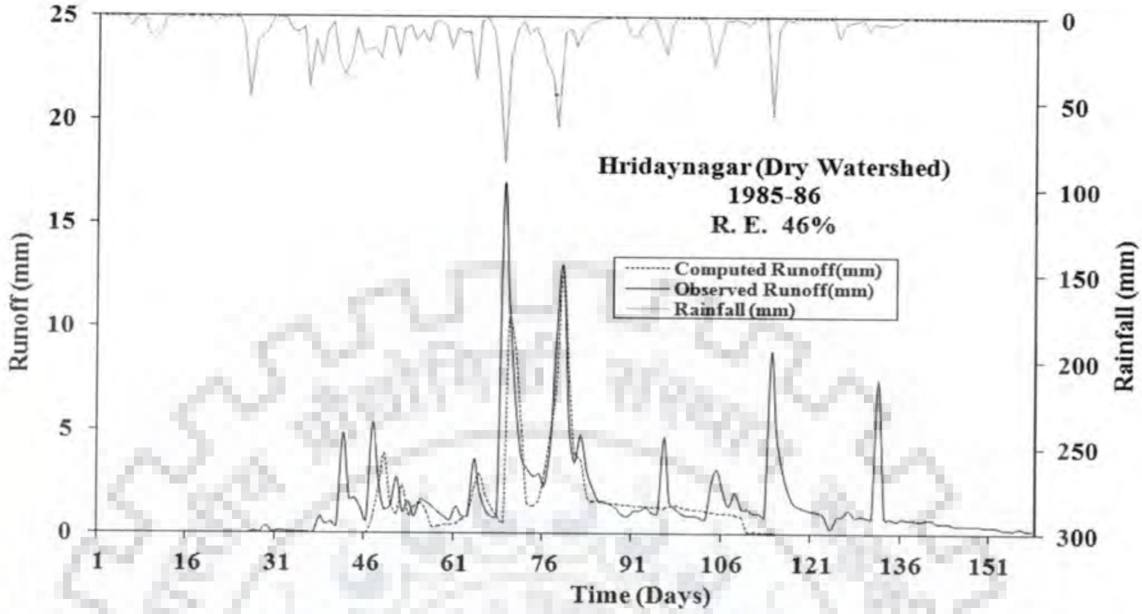


(a) Calibration (Hemavathi)

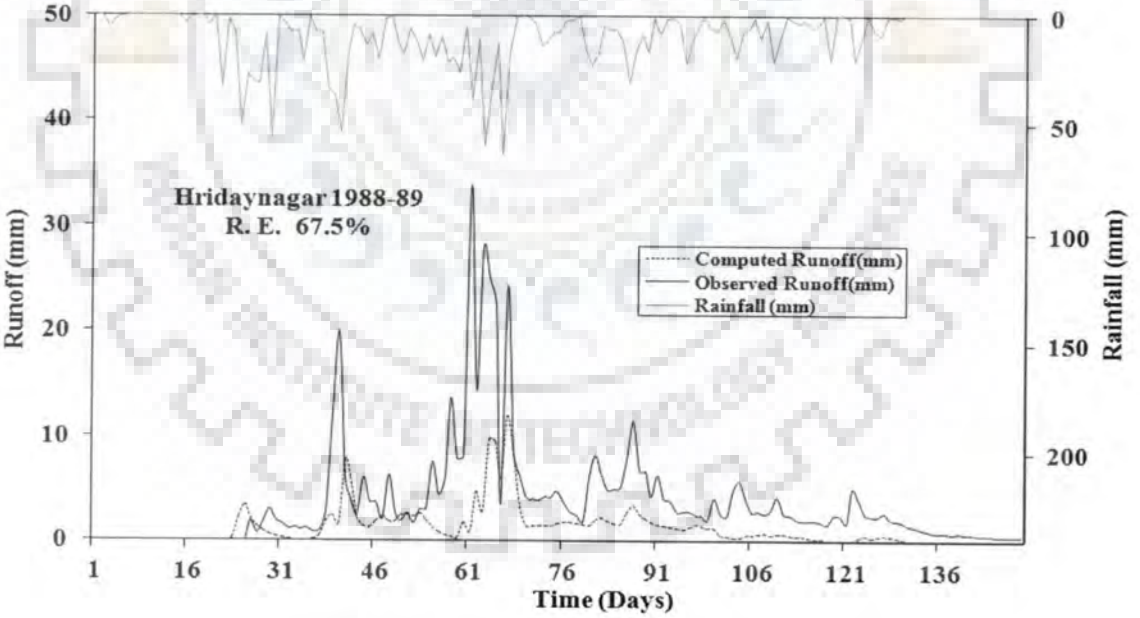


(b) Validation (Kokkarne Watershed)

Fig. 5.5 (a, b) Very Good Performance in (a) Calibration and (b) Validation of LTHS MICHEL I Model on Wet Watershed (Day 1 represents June 1)



(c) Calibration (Hridaynagar Watershed)



(d) Validation (Hridaynagar Watershed)

Fig. 5.5 (c, d) Poor Performance in (c) Calibration and (d) Validation of LTHS MICHEL I Model on Dry Watershed (Day 1 represents June 1)

Table 5.6 Percent Estimates of Hydrological Components of LTHS MICHEL I Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotran-spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	35.1	26.5	37.1	3.7	33.4	28.8	5.1	67.6	77.9
2.	Hridaynagar	100	3.1	81.8	14.2	5.9	8.2	5.6	2.2	14.7	24.3
3.	Mohegaon	100	13.2	65.3	19.9	8.0	11.9	4.1	9.5	25.2	34.7
4.	Manot	100	22.1	45.3	30.1	17.8	12.3	1.7	15.2	41.6	44.2
5.	Amachi	100	13.7	69.6	15.6	1.6	14.0	8.0	5.6	23.2	28.7
6.	Anthrolli	100	18.0	50.2	29.1	13.1	15.9	2.9	22.0	34.1	36.6
7.	Attigundi	100	13.0	29.4	56.1	15.0	41.1	38.9	2.1	66.9	71.6
8.	Barchi	100	7.4	59.8	31.4	18.8	12.5	7.9	6.0	34.1	35.1
9.	Khanapur	100	23.1	38.3	38.4	3.8	34.6	23.0	12.4	49.9	59.4
10.	Hirehalla	100	1.2	93.7	4.9	0.6	4.3	2.5	1.9	4.3	11.2
11.	Sagar	100	24.3	35.3	39.1	23.5	15.6	3.3	14.0	51.0	65.5
12.	Sorab	100	16.9	48.7	31.7	3.2	28.5	30.0	3.1	50.1	58.4
13.	Dasanakatte	100	30.4	22.3	47.1	14.1	33.0	32.5	0.3	77.1	90.0
14.	Haladi	100	42.0	20.5	37.3	3.7	33.6	33.2	0.3	78.9	93.0
15.	Jadkal	100	50.6	21.1	28.0	8.4	19.6	19.4	0.2	78.5	92.5
16.	Kokkarne	100	41.3	19.4	39.1	11.7	27.4	27.1	0.3	80.1	79.2
17.	Halkal	100	42.4	17.8	39.4	11.8	27.6	26.9	0.3	81.2	88.3

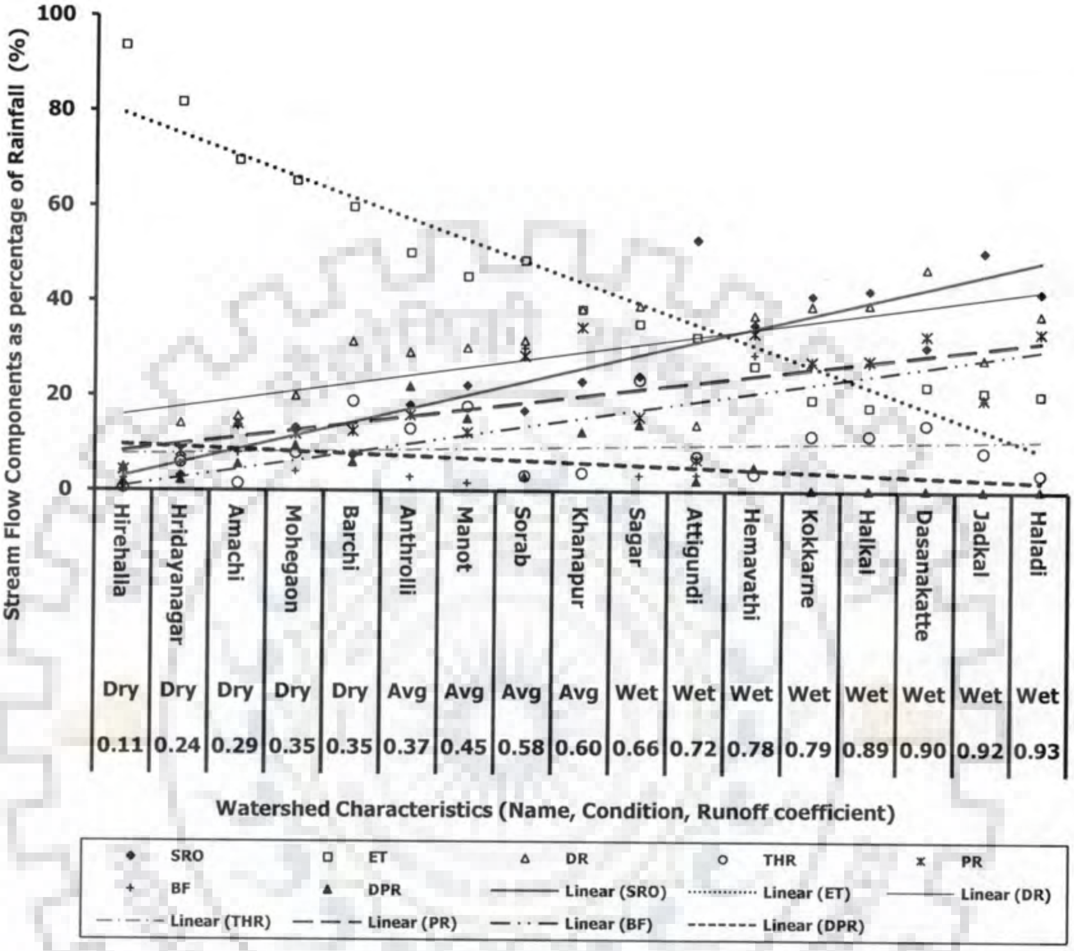


Fig. 5.6 Trend Analysis of Average Annual Variations in Stream Flow Generating Components of LTHS MICHEL I Model

5.3.2 Application of Model-I on Seasonal Data

For evaluating the performance of Model-I, the analysis is also performed on seasonal data detailed in Chapter 4. As stated previously, the season is taken for monsoon months starting from 1st June to 30th November. The assumption is made that the curve number on the first day of each year (1st June) is same and equal to the optimized value of CN_0 as the hydrologic data is used only during monsoon period. As the initial conditions of the soil retention capacity are computed on this assumption, a different set of optimal values of parameters is obtained for seasonal data and presented in Table 5.7. The performance of Model-I in term of NSE and RE during calibration and validation is given in Table 5.8. As seen from Table 5.8, the model yields a maximum NSE of 0.86 in calibration for Hemavathi watershed and 0.84 in validation for Jadkal watershed (Fig. 5.7), while the minimum efficiency of 0.38 in calibration is found for Amachi watershed and 0.27 in validation for Anthrolli watershed (excluding most dry Hirehalla watershed for which efficiency is very poor). It is evident from the plot of seasonal average runoff coefficient of various watersheds in ascending order of NSE values in calibration and validation (Fig. 5.8) that the model exhibits similar trends as for annual data series, i.e. yields higher efficiency for wet watershed than for dry watershed. The trend line drawn on Fig. 5.8 shows that NSE increases with watershed wetness in terms of seasonal average runoff coefficient as similar with model application using annual data series. However, the model efficiency is comparatively better for both calibration and validation of Model-I using annual data series than seasonal data series for all study watersheds as evident from Fig. 5.9; which could be ascribed to proper accounting of soil moisture in annual data series.

The model is further evaluated for error criteria, RE. The absolute values of RE in calibration and validation by using seasonal data of study watersheds are listed in Table 5.8. As seen from Table 5.8, RE varies from 0.9 to 13.6% in calibration for all high yielding watersheds which can be categorized as very good to satisfactory performance of the model to simulate the total stream flow except for Sagar watershed for which the model performance is poor (RE=29%) according to criteria recommended by Donigian et al. (1983) and Harmel et al. (2006). The values of RE in case of dry watershed vary from 5.4 to 8.0% (excluding most dry Hirehalla watershed), indicating a very good performance

Table 5.7 Optimized Values of Parameters of LTHS MICHEL I Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter													
		CN_0	α	β	K	P_1	P_2	P_3	P_4	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	30.0	0.02	0.02	1.20	0.01	0.99	0.07	0.98	40.0	219.2	264.5	0.35	0.52	276.9
2.	Hridaynagar	48.4	0.87	0.93	2.00	0.06	0.79	0.38	0.74	205.7	400.0	430.7	0.18	0.90	379.4
3.	Mohegaon	29.3	0.10	0.03	0.50	0.01	0.54	0.41	0.10	120.0	367.5	318.9	0.58	0.51	439.2
4.	Manot	33.3	0.10	0.02	0.50	0.03	0.10	0.42	0.99	205.1	300.0	495.7	0.87	0.78	496.0
5.	Amachi	64.0	0.41	0.50	2.53	0.02	0.31	0.60	0.66	148.5	332.6	348.3	0.60	0.49	338.9
6.	Anthrolli	49.6	0.01	0.01	0.50	0.06	0.70	0.57	0.15	160.0	200.0	303.6	0.34	0.43	436.7
7.	Attigundi	30.0	0.001	0.01	0.83	0.03	0.99	0.31	0.75	140.0	200.0	202.0	0.38	0.59	465.8
8.	Barchi	53.1	0.30	0.99	4.32	0.11	0.90	0.60	0.99	150.0	220.0	314.3	0.30	0.56	230.7
9.	Khanapur	16.0	0.24	0.10	0.50	0.05	0.70	0.33	0.60	70.0	209.8	340.6	0.40	0.70	473.8
10.	Hirehalla	32.4	0.49	0.52	0.50	0.05	0.10	0.26	0.31	101.5	223.6	259.5	0.10	1.13	354.6
11.	Sagar	65.4	0.10	0.06	0.50	0.05	0.99	0.60	0.10	150.0	220.0	357.2	0.67	0.48	840.9
12.	Sorab	30.6	0.10	0.02	0.51	0.01	0.20	0.60	0.99	180.0	359.1	204.4	0.40	0.60	208.2
13.	Dasanakatte	22.1	0.45	0.11	0.50	0.05	0.99	0.40	0.99	170.0	220.0	320.0	0.36	0.72	250.0
14.	Haladi	20.2	0.49	0.14	0.50	0.04	0.55	0.33	0.99	170.0	210.0	360.2	0.35	0.79	267.3
15.	Jadkal	21.9	0.32	0.13	0.50	0.02	0.46	0.40	0.99	180.0	330.0	320.0	0.32	0.81	355.7
16.	Kokkarne	20.7	0.65	0.19	0.50	0.04	0.99	0.30	0.99	180.0	259.4	400.0	0.35	0.64	253.0
17.	Halkal	20.3	0.64	0.19	0.50	0.07	0.99	0.40	0.99	180.0	190.0	400.0	0.38	0.70	250.0

Table 5.8 NS Efficiency and Absolute RE in Calibration and Validation of the Proposed LTHS Models (Seasonal Data)

Sr. No.	Name of Watershed	Calibration								Validation							
		NS Efficiency				Absolute RE (%)				NS Efficiency				Absolute RE (%)			
		M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV
1.	Jadkal	0.80	0.80	0.80	0.83	11.9	3.4	3.9	2.1	0.84	0.82	0.84	0.86	3.2	4.6	3.0	7.6
2.	Halkal	0.84	0.84	0.84	0.87	4.8	0.5	1.5	0.5	0.76	0.77	0.78	0.73	6.1	1.6	3.6	12.9
3.	Dasanakatte	0.75	0.76	0.77	0.79	9.1	0.3	0.6	1.4	0.70	0.62	0.67	0.63	9.0	1.3	1.5	18.0
4.	Haladi	0.81	0.82	0.83	0.84	7.5	4.9	3.4	1.3	0.56	0.53	0.54	0.67	7.6	10.2	11.8	5.9
5.	Hemavathi	0.86	0.87	0.87	0.87	2.1	2.1	4.0	4.6	0.45	0.88	0.88	0.88	9.3	4.9	6.3	7.8
6.	Kokkarne	0.83	0.83	0.83	0.86	0.9	0.5	0.4	2.8	0.81	0.80	0.81	0.84	0.7	3.3	1.1	9.9
7.	Attigundi	0.57	0.59	0.67	0.69	18.2	18.5	2.1	2.3	0.30	0.31	0.34	0.34	20.7	17.8	6.7	8.5
8.	Sagar	0.64	0.65	0.73	0.74	29.4	8.4	1.5	0.5	0.34	0.40	0.51	0.51	33.9	14.8	6.1	21.5
9.	Sorab	0.61	0.69	0.70	0.74	14.4	14.5	11.5	4.3	0.50	0.51	0.52	0.51	2.8	1.6	0.1	7.4
10.	Khanapur	0.70	0.70	0.70	0.72	2.0	0.6	2.0	1.9	0.63	0.64	0.62	0.65	34.0	31.9	32.5	29.8
11.	Manot	0.66	0.68	0.68	0.76	6.8	1.8	2.1	3.2	0.55	0.55	0.55	0.66	13.2	9.7	14.0	15.1
12.	Anthrolli	0.63	0.66	0.67	0.70	18.8	11.7	5.8	6.3	0.27	0.33	0.39	0.33	24.3	18.8	15.8	16.5
13.	Mohegaon	0.55	0.56	0.57	0.63	8.0	11.7	5.3	6.7	0.43	0.44	0.45	0.52	15.0	25.9	11.9	25.4
14.	Barchi	0.47	0.52	0.52	0.61	10.0	3.7	2.9	2.7	0.42	0.56	0.57	0.51	11.1	10.0	10.6	9.3
15.	Amachi	0.38	0.49	0.52	0.54	5.4	3.6	6.5	1.1	0.31	0.39	0.26	0.42	7.7	1.1	4.1	5.6
16.	Hridaynagar	0.48	0.53	0.54	0.55	8.3	13.3	1.8	7.7	0.37	0.44	0.47	0.41	51.3	55.5	45.1	57.4
17.	Hirehalla	0.05	0.16	0.17	0.17	61.6	8.2	14.7	11.6	-0.01	0.38	0.39	0.48	66.2	24.8	32.0	6.2

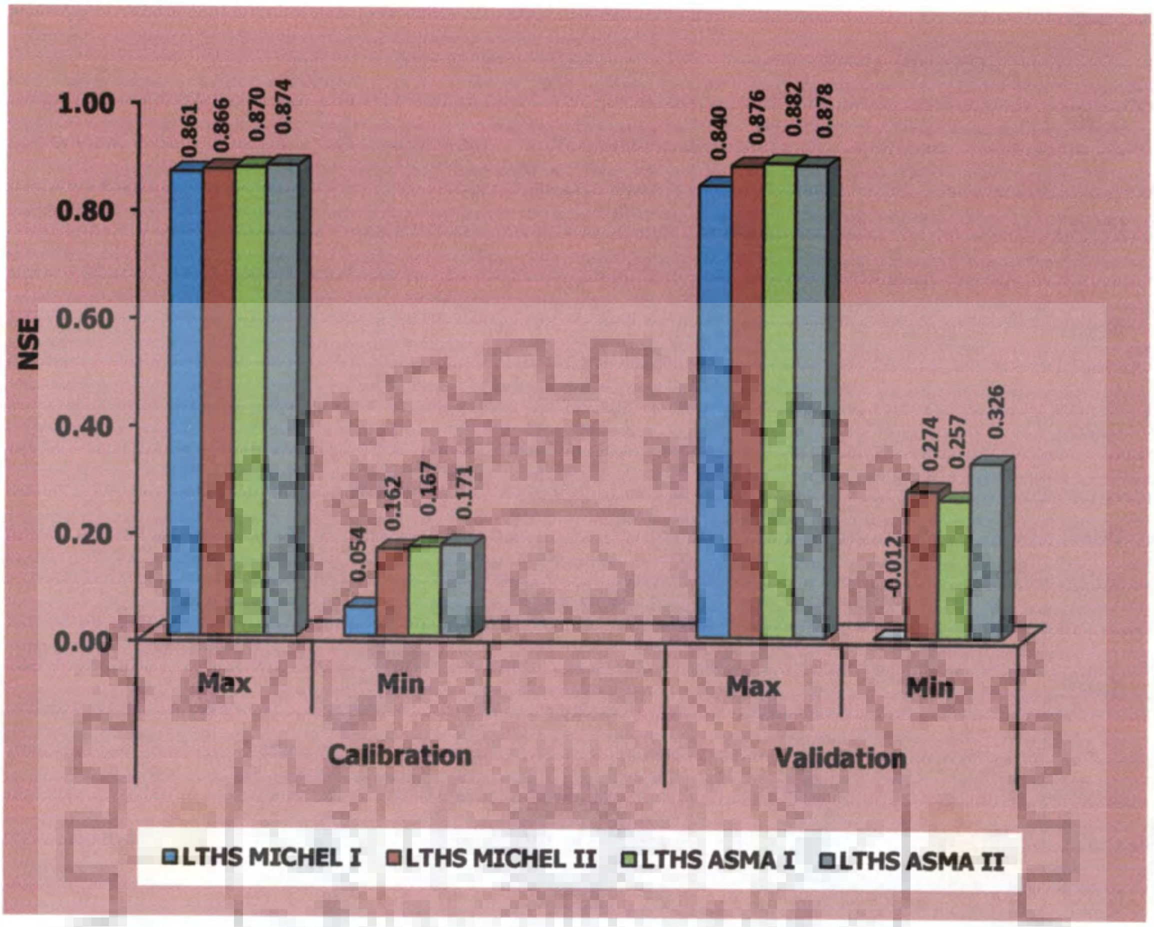


Fig. 5.7 Range of NSE Obtained in Calibration and Validation of the Proposed LTHS Models on Seasonal Data of Study Watersheds

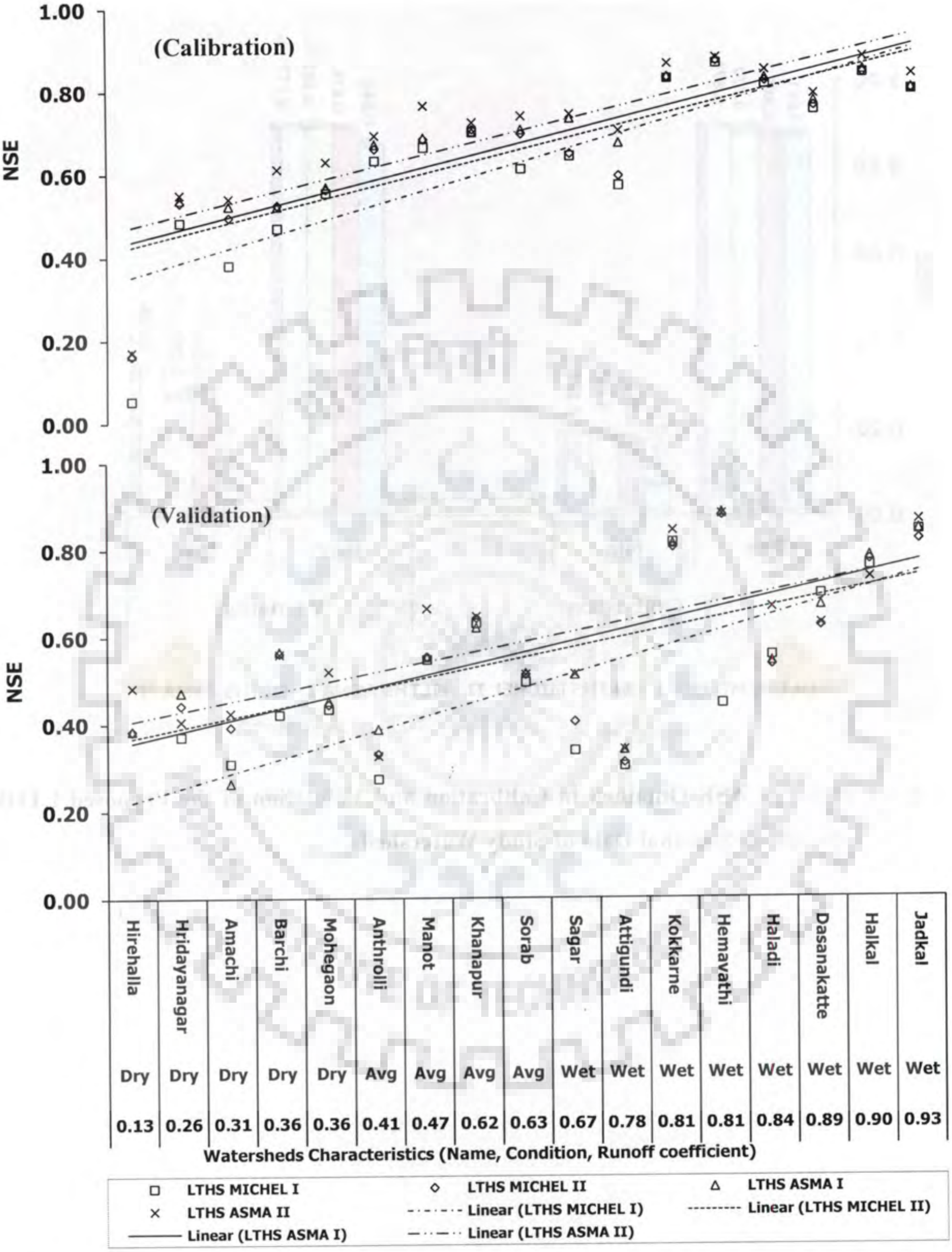


Fig. 5.8 Performance of the Proposed LTHS Models on Seasonal Data of Study Watersheds

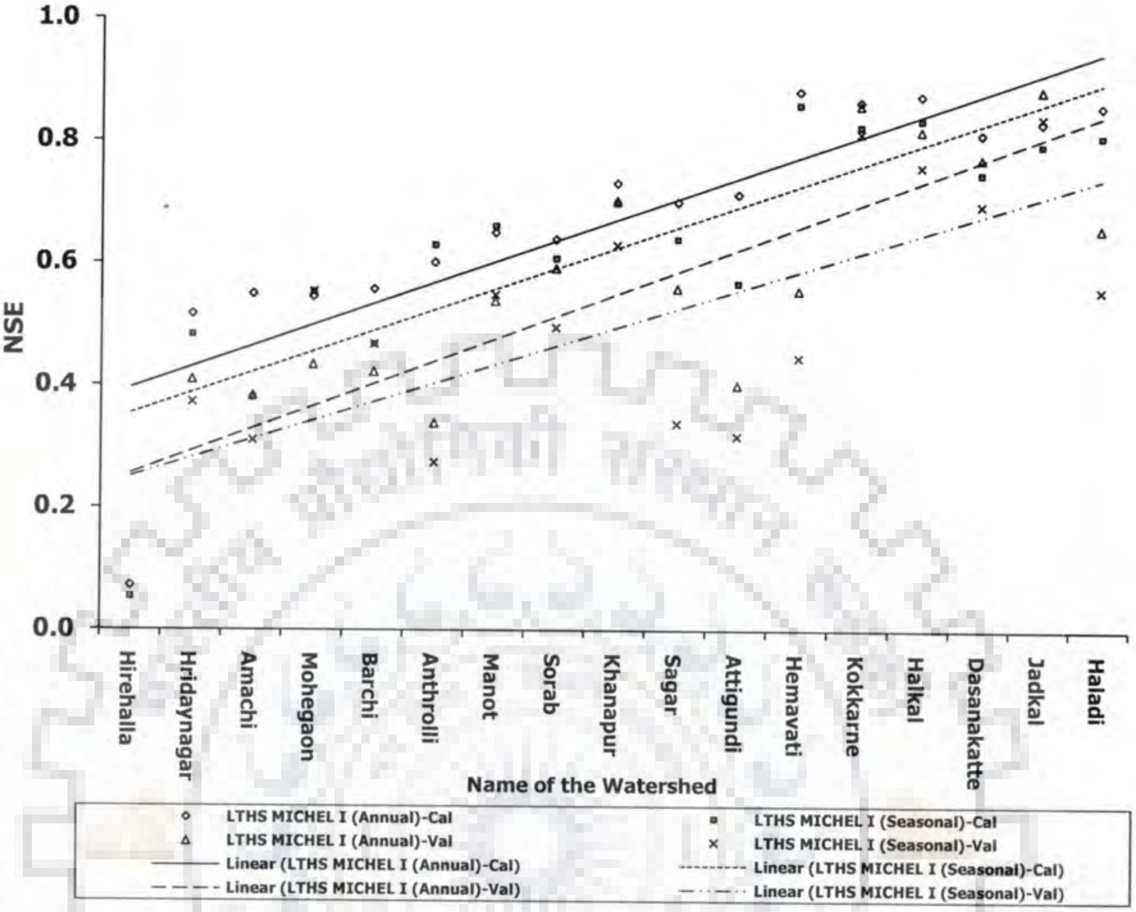


Fig. 5.9 Comparative Performance of LTHS MICHEL I Model on Annual and Seasonal Data Series of Study Watersheds

(Donigian et al., 1983; Harmel et al., 2006). The model yield unsatisfactory performance to simulate the total stream flow of most dry Hirehalla watershed (RE = 62.0%). The model performance is also very good for all watersheds under average condition except the Sorab and Anthrolli watersheds (RE>10.0%). The seasonal values of rainfall, observed runoff, simulated runoff and relative error for each year is also analyzed and shown in Appendix D. The seasonal average values of absolute RE for each study watersheds is presented in Table 5.9. The trend analysis on the plot of ascending order of runoff coefficient of study watersheds against seasonal average values of absolute RE (Table 5.9) as presented in Fig. 5.10 indicate a similar trend, i.e. the reverse trend of RE with watershed wetness in terms of average runoff coefficient as observed for annual average values of the absolute RE.

Table 5.9 Seasonal Average Values of Rainfall, Observed Runoff, Simulated Runoff, and Absolute RE for the Proposed LTHS Models

Sr. No.	Name of Watershed	Rainfall	Observed Runoff	LTHS MICHEL I (M-I)		LTHS MICHEL II (M-II)		LTHS ASMA I (M-III)		LTHS ASMA II (M-IV)	
				Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE	Simulated Runoff	Absolute RE
		(mm)	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
1	Hemavathi	2644.0	2130.1	2078.9	11.3	2039.7	10.2	1999.0	9.5	2077.3	9.9
2	Hridaynagar	1312.7	344.1	239.4	37.3	223.5	38.2	261.2	30.2	229.5	41.1
3	Mohegaon	1148.4	408.1	371.3	12.0	343.1	17.6	383.3	11.7	355.9	19.3
4	Manot	1147.2	544.8	491.1	20.0	514.7	19.9	502.5	20.4	496.7	18.9
5	Amachi	1582.5	485.0	452.9	11.2	474.1	13.3	489.8	13.4	473.3	21.6
6	Anthrolli	879.9	360.3	281.9	20.9	304.1	16.5	318.8	16.0	316.6	15.3
7	Attigundi	1785.2	1384.1	1114.3	19.5	1133.3	18.8	1323.4	5.8	1304.8	8.9
8	Barchi	1364.8	497.7	445.8	12.3	489.4	21.2	485.9	21.3	478.2	19.8
9	Khanapur	3881.9	2396.1	1907.1	20.4	1962.0	19.5	1966.8	20.5	2003.4	18.5
10	Hirehalla	481.9	64.4	23.0	63.7	53.0	19.2	48.6	27.0	65.3	20.0
11	Sagar	1737.1	1158.8	789.2	31.8	1019.8	11.8	1126.8	5.7	1017.1	17.0
12	Sorab	1217.2	764.9	705.2	20.5	724.1	17.7	726.7	18.1	718.7	14.5
13	Dasanakatte	4498.0	4003.7	3638.9	9.0	4035.9	3.8	4021.0	4.4	3616.6	10.6
14	Haladi	4565.1	3846.9	3830.0	7.8	3929.2	7.3	3990.2	7.8	3713.7	9.7
15	Jadkal	5065.0	4702.6	4345.6	8.0	4728.3	3.9	4678.8	3.4	4475.4	8.7
16	Kokkarne	4880.7	3938.7	3934.3	4.1	4014.4	5.4	3953.1	4.2	3689.2	7.1
17	Halkal	5095.6	4586.8	4335.6	5.2	4535.6	2.4	4466.6	2.6	4264.2	10.3

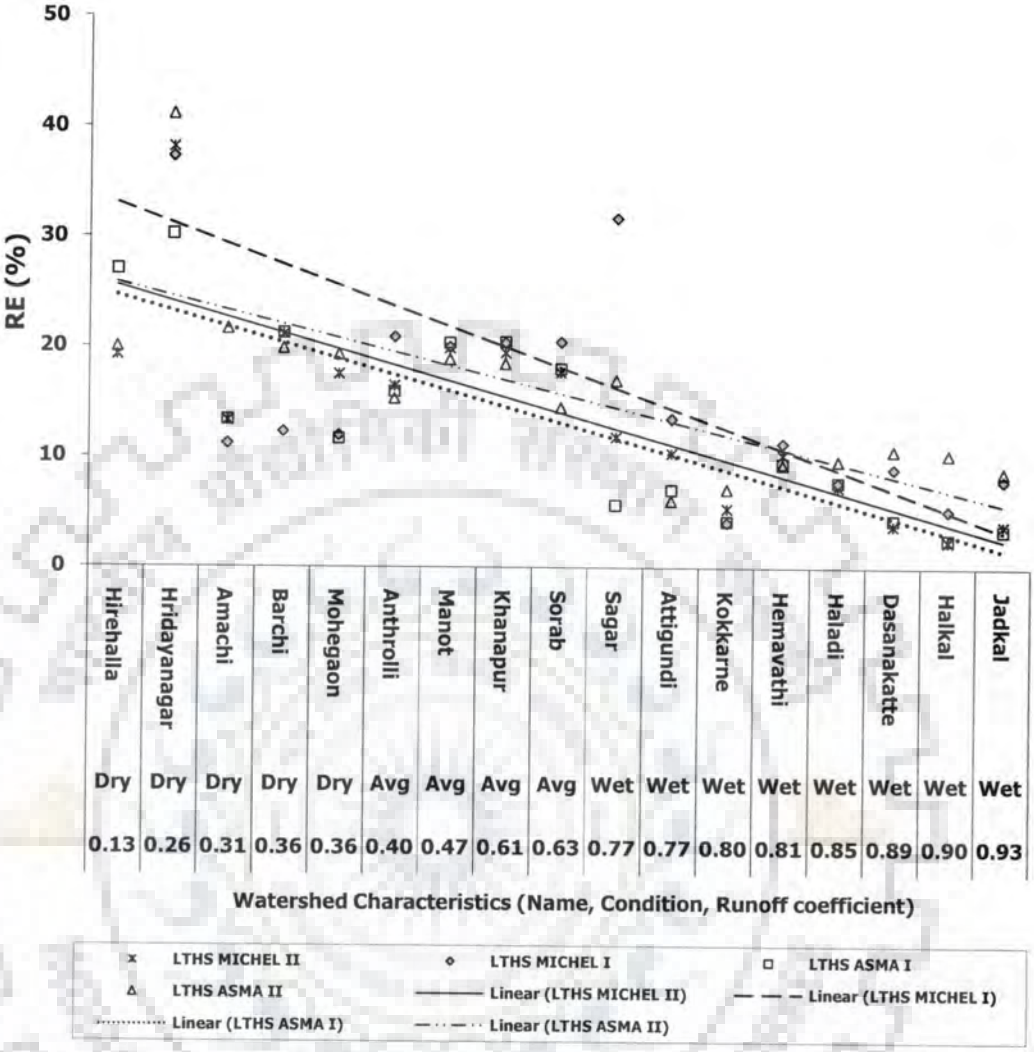


Fig. 5.10 Annual Average of Absolute Values of RE (%) Obtained for the Proposed LTHS Models on Seasonal Data Series of Study Watersheds

The annual average values in terms of percentage of rainfall of various stream flow generating components are also estimated and presented in Table 5.10. It is apparent from Table 5.10 that the surface runoff is more prominant than lateral flow and base flow as seen in application of this model to annual data series. Similarly, the other components of stream flow generation process, except losses such as evapotranspiration and deep percolation, are more significant/dominant in high runoff producing coastal watersheds than low runoff producing watersheds.

Table 5.10 Percent Estimates of Hydrological Components of LTHS MICHEL I Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)								
		Rainfall (%)	Surface Runoff	Evapotran -spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	35.5	19.1	44.3	3.1	41.2	39.3	0.8	78.0	80.9
2.	Hridaynagar	100	3.2	79.3	16.6	6.3	10.4	7.4	2.6	16.9	25.9
3.	Mohegaon	100	13.3	42.9	41.4	16.9	24.6	2.6	23.2	32.7	36.9
4.	Manot	100	18.6	55.6	24.1	10.2	13.9	13.7	0.1	42.5	47.0
5.	Amachi	100	3.9	65.9	28.5	17.1	11.4	7.5	3.9	28.5	30.7
6.	Anthrolli	100	13.7	56.9	26.5	15.0	11.5	2.1	11.6	30.8	40.6
7.	Attigundi	100	11.1	27.3	60.7	18.6	42.1	32.7	10.9	62.4	77.6
8.	Barchi	100	19.7	64.4	14.8	8.8	6.0	4.5	0.1	33.0	36.3
9.	Khanapur	100	17.3	39.7	42.9	14.1	28.8	17.5	11.7	48.9	61.6
10.	Hirehalla	100	1.2	93.6	4.6	1.2	3.4	2.0	4.4	4.4	13.1
11.	Sagar	100	24.9	43.3	30.7	18.4	12.3	1.6	14.1	44.9	66.5
12.	Sorab	100	17.8	40.9	37.3	22.4	14.9	14.8	0.2	55.0	63.4
13.	Dasanakatte	100	30.2	18.4	51.2	20.5	30.7	30.0	0.3	80.6	88.8
14.	Haladi	100	37.2	15.3	47.4	15.6	31.7	31.1	0.3	83.9	84.4
15.	Jadkal	100	52.5	13.8	33.2	13.3	19.9	19.7	0.2	85.5	93.0
16.	Kokkarne	100	43.4	18.8	37.7	11.3	26.4	25.6	0.3	80.3	80.3
17.	Halkal	100	40.6	14.4	44.8	17.9	26.9	26.3	0.3	84.8	89.6

5.4 MODIFIED SCS-CN CONCEPT BASED MODEL-II (LTHS MICHEL II)

The model LTHS MICHEL II (Model-II) is a modified form of LTHS MICHEL I model by refinement in SMA procedure to represent improved watershed behavior. This long term daily stream flow Model-II has been improved over conventional SCS-CN technique and Model-I in two aspects (i) by introducing a factor known as antecedent moisture (AM), to modify daily maximum potential water retention (S) values and then S is updated based on daily changes in SMS and GWS via the losses through evapotranspiration and deep seepage and the daily input to the soil moisture store level in order to get the possible space for water retention; and (ii) deriving the mathematical expression for computing the initial soil moisture (V_0) and direct runoff (RO). The basic difference in LTHS MICHEL I and this model is in the computation of V_0 and RO. As stated earlier, the LTHS MICHEL I model computes CN based on various AMC levels decided from Table 2.1 and Table 2.2, CN depends on the 5 days antecedent rainfall prior to the day under consideration, while this model computes V_0 based on AM by taking into account 5 days antecedent rainfall prior to the day under consideration. The computation of V_0 using AMC levels in Model-I may however lead to sudden variation in V_0 and thus affect the model performance. The demerit of LTHS MICHEL I model is eliminated in this model by varying initial soil moisture using AM instead of AMCs. This model has been developed using appropriate mathematical expressions and consist of fifteen parameters, i.e. one more parameter δ, a coefficient of antecedent moisture, than LTHS MICHEL I model as detailed in Chapter 3. This model is also tested for its performance on annual and seasonal data series as described in subsequent sections.

5.4.1 Application of Model-II on Annual Data

The optimal set of model parameters obtained through calibration using annual data marked for calibration is presented in Table 5.11. The model efficiency in terms of NSE values is presented in Table 5.4 for both calibration and validation. As seen from Table 5.4, Model-II yields maximum NSE of 0.90 and 0.89 in calibration and validation respectively for Hemavathi watershed, which is found to be better than Model-I. The minimum efficiency of 0.54 in calibration is found for Hridaynagar watershed and 0.38 in validation for Anthrolli watershed (excluding most dry watershed Hirehalla). In case of high yielding watersheds,

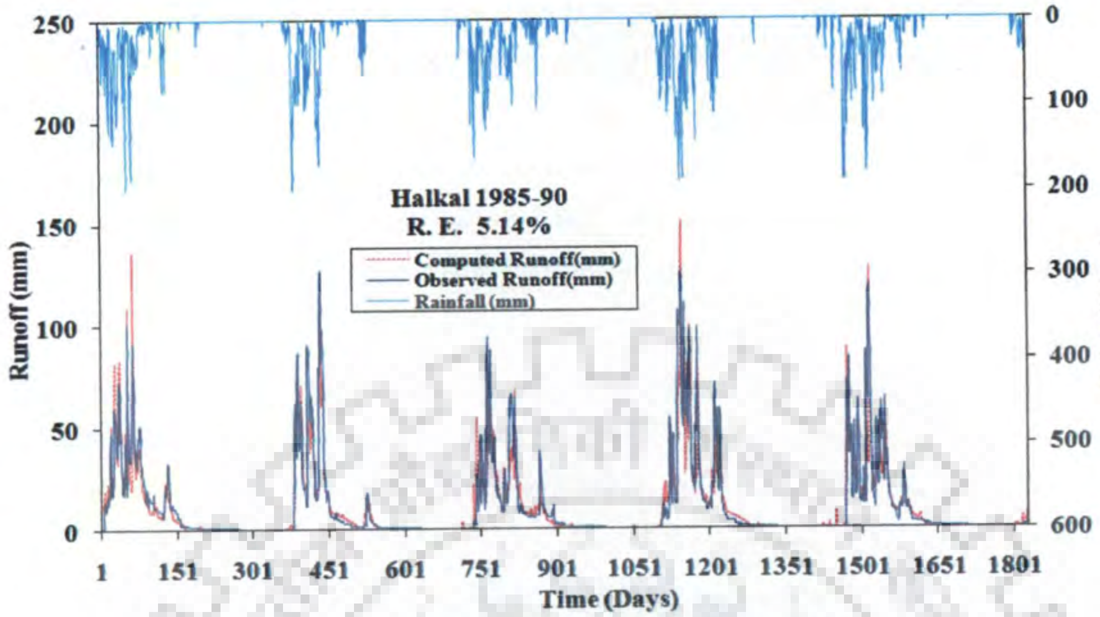
Table 5.11 Optimizes Values of Parameters of LTHS MICHEL II Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	α	β	K	P_1	P_2	P_3	P_4	δ	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	33.1	0.44	0.53	1.32	0.01	0.50	0.40	0.99	1.02	80.1	290.9	400.0	0.30	0.47	230.2
2.	Hridaynagar	33.4	0.13	0.10	1.07	0.09	0.10	0.24	0.99	0.10	200.0	301.5	274.6	0.19	0.86	300.0
3.	Mohegaon	33.7	0.50	0.55	0.50	0.02	0.73	0.10	0.57	0.05	99.3	368.2	342.5	0.55	0.57	159.6
4.	Manot	39.1	0.38	0.38	0.50	0.07	0.10	0.34	0.99	0.95	293.7	331.1	382.0	0.36	0.89	350.0
5.	Amachi	21.6	0.21	0.21	0.57	0.01	0.10	0.34	0.80	0.20	81.6	425.1	308.1	0.90	0.65	305.8
6.	Anthrolli	49.8	0.49	0.54	0.50	0.05	0.80	0.10	0.40	0.99	129.1	200.0	262.7	0.60	0.57	259.1
7.	Attigundi	27.5	0.44	0.50	1.93	0.05	0.64	0.01	0.99	0.06	140.0	200.0	300.0	0.40	0.95	200.0
8.	Barchi	25.7	0.42	0.49	0.59	0.02	0.10	0.10	0.87	0.01	126.3	350.0	350.0	0.90	0.75	344.1
9.	Khanapur	15.0	0.23	0.28	0.50	0.02	0.99	0.31	0.48	0.10	60.0	400.0	200.0	0.45	0.71	207.2
10.	Hirehalla	15.0	0.47	0.50	0.50	0.03	0.10	0.10	0.10	0.99	180.2	224.2	350.0	0.57	0.44	250.6
11.	Sagar	35.9	0.47	0.62	0.50	0.01	0.90	0.60	0.99	0.72	60.1	255.5	380.0	0.10	0.06	201.8
12.	Sorab	43.1	0.49	0.61	0.57	0.02	0.96	0.60	0.99	0.10	109.5	231.1	400.0	0.40	0.29	285.6
13.	Dasanakatte	23.6	0.40	0.40	0.50	0.02	0.99	0.30	0.99	0.99	180.0	358.3	400.0	0.38	0.69	220.0
14.	Haladi	23.1	0.45	0.46	0.50	0.01	0.37	0.60	0.99	0.99	170.0	315.5	500.0	0.28	0.69	200.0
15.	Jadkal	30.0	0.46	0.58	0.50	0.01	0.87	0.30	0.99	0.99	179.6	366.9	400.0	0.38	0.71	390.7
16.	Kokkarne	18.9	0.17	0.22	0.50	0.01	0.10	0.60	0.87	0.99	180.0	379.5	399.8	0.10	0.89	200.2
17.	Halkal	27.0	0.67	0.72	0.50	0.01	0.73	0.50	0.99	0.99	120.2	400.0	400.0	0.38	0.68	200.0

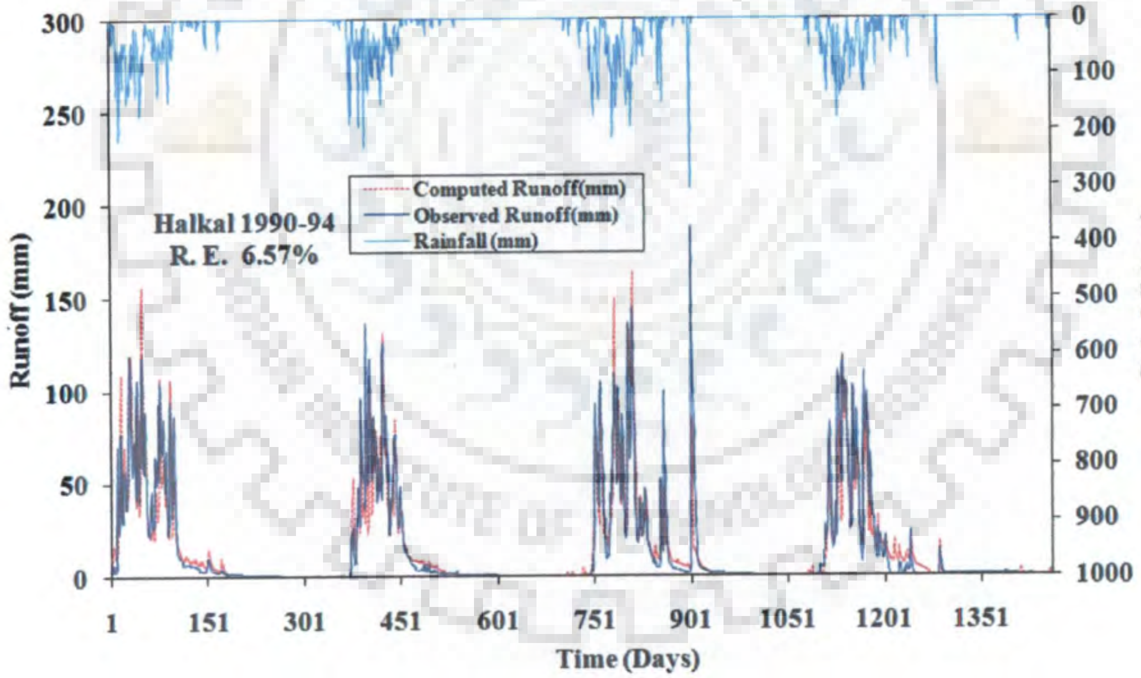
NSE varies from 0.71 to 0.90 in calibration (Fig. 5.1) indicating very good to satisfactory model response (Motovilov et al., 1999). As similar with the results obtained for LTHS MICHEL I model, this model also yields high efficiency for high yielding (wet) watersheds and comparatively lower efficiency for low yielding (dry) watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry watershed of Hirehalla. It is evident from the trend line shown in Fig. 5.2 for calibration and validation, the NSE increases with increase in watershed wetness in terms of average runoff coefficient. It can also be observed that there is improvement in the efficiency of Model-II compared to Model-I for high yielding wet watersheds as shown in Fig. 5.1. The NSE for the most dry watershed, Hirehalla also improved from 0.07 to 0.15 in calibration and -0.001 to 0.36 in validation (Table 5.4) for Model-II compared to Model-I on annual data of study watersheds. General improvement in model efficiency for Mode-II is mainly attributed to the modification in SMA procedure.

Model-II is further evaluated based on relative error obtained in calibration and validation periods. The values of RE obtained for calibration and validation periods are listed in Table 5.4. As seen from Table 5.4, the value of RE varies from 0.07 to 13.22% in calibration for all coastal watersheds and 5.98 to 15.33% for dry watersheds indicating very good to satisfactory model performance to simulate the stream flow. The model performance is also very good for Manot and Khanapur watersheds under average condition (Donigian et al., 1983; Harmel et al., 2006). It is apparent from the trend analysis presented in Fig. 5.3 for annual average values of absolute RE (Table 5.5 and Appendix A) that RE decreases with watershed wetness in terms of average runoff coefficient.

The performance of Model-II is also analyzed based on subjective assessment through visual comparison between observed and computed runoff for calibration and validation periods using annual data series of study watersheds. The plots of daily variations of rainfall, observed, and computed values of runoff for all watersheds are shown in Appendix B for calibration, and Appendix C for validation for this model. Figs. 5.11 (a, b, c, d) 5.12 (a, b, c, d) depicts sample plots of watersheds extracted from these Appendices (B and C) at larger scale for better visualization of the simulation results. It is seen from these figures that the model fit in simulation of daily stream flows for high yielding and watersheds (for example,

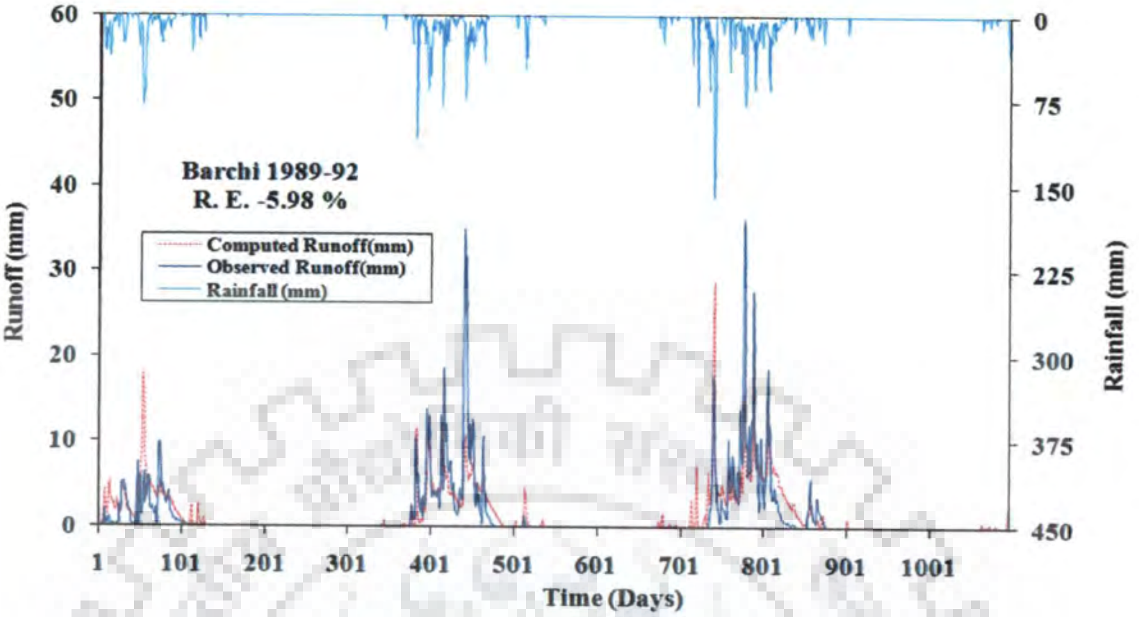


(a) Calibration (Halkal Watershed)

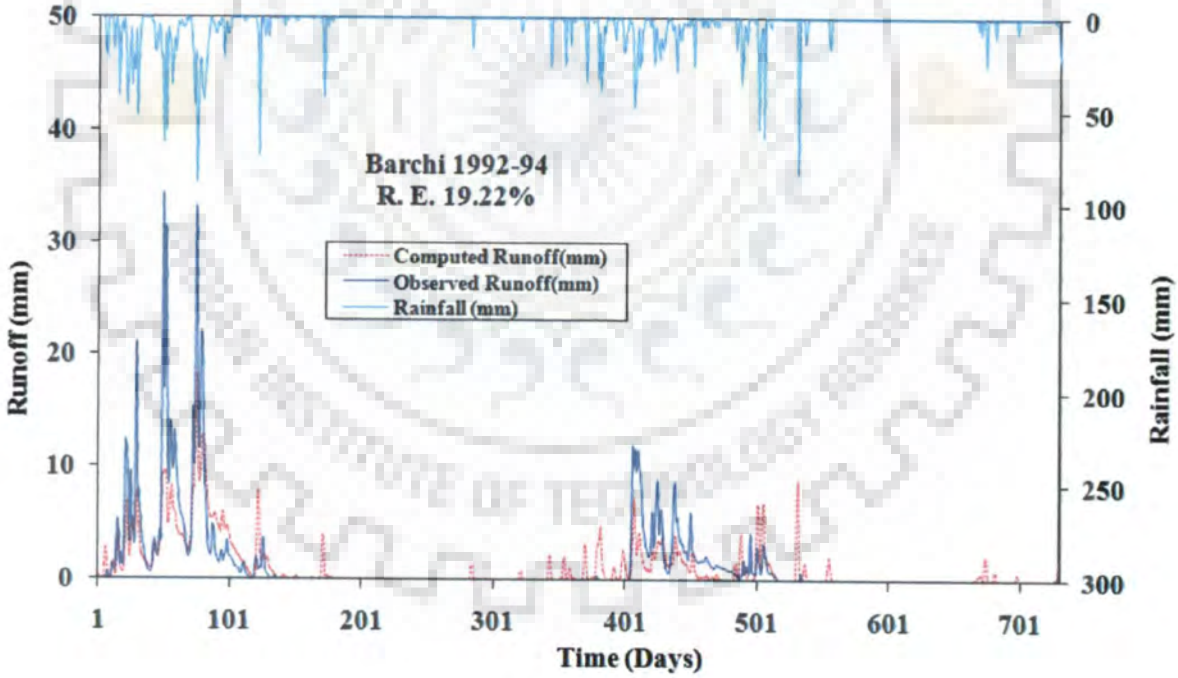


(b) Validation (Halkal Watershed)

Fig. 5.11 (a, b) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) of Halkal (Wet) Watershed in (a) Calibration and (b) Validation of LTHS MICHEL II Model (Day 1 represents June 1)

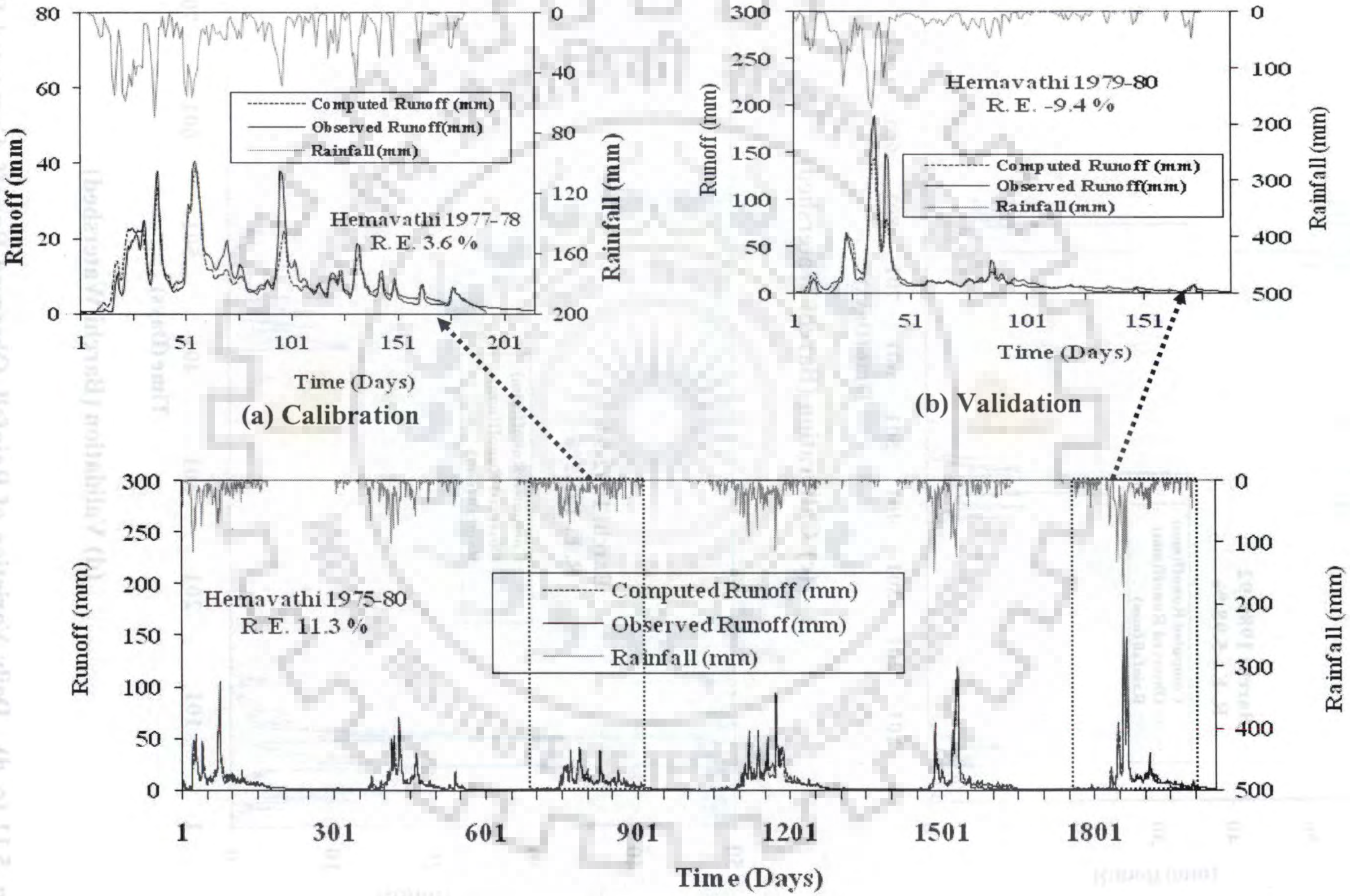


(c) Calibration (Barchi Watershed)



(d) Validation (Barchi Watershed)

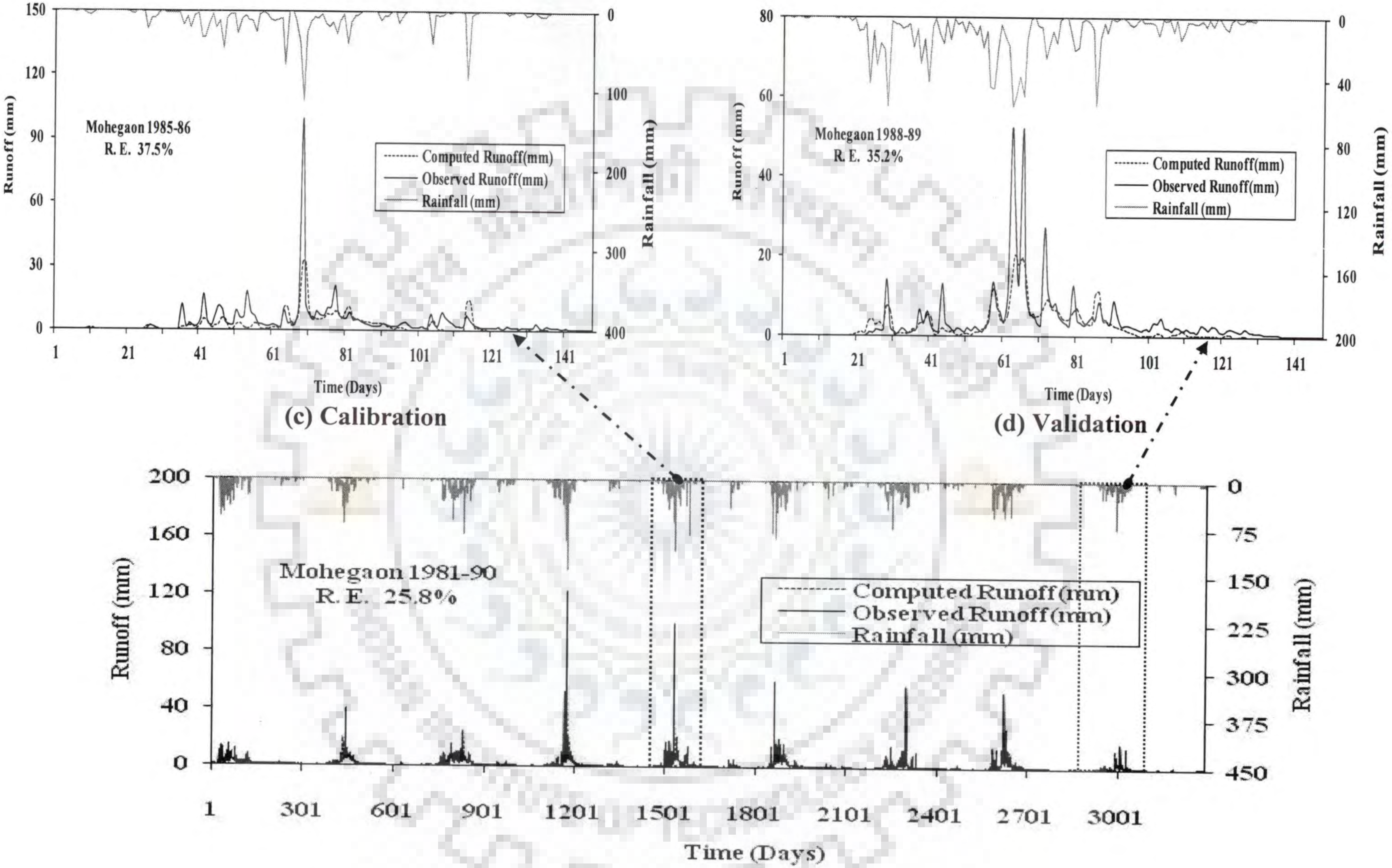
Fig. 5.11 (c, d) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) of Barchi (Dry) Watershed in (a) Calibration and (b) Validation of LTHS MICHEL II Model (Day 1represents June 1)



(a) Calibration

(b) Validation

Fig. 5.12 (a, b) Very Good Performance in a) Calibration and b) Validation of LTHS MICHEL II Model on Hemavathi (Wet) Watershed (Day 1 represents June 1)



(c) Calibration

(d) Validation

Fig. 5.12 (c, b) Poor Performance in c) Calibration and d) Validation of LTHS MICHEL II Model on Mohegaon (Dry) Watershed (Day 1 represents June 1)

Table 5.12 Percent Estimates of Hydrological Components of LTHS MICHEL II Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotranspiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	44.3	29.4	28.1	11.2	16.8	15.5	0.2	71.0	77.9
2.	Hridaynagar	100	6.9	83.6	8.2	2.0	6.3	6.4	0.1	15.2	24.3
3.	Mohegaon	100	18.7	66.1	16.4	1.6	14.8	7.5	5.6	27.9	34.7
4.	Manot	100	20.7	57.2	21.2	7.2	14.0	13.6	0.1	41.5	44.2
5.	Amachi	100	5.5	70.2	24.2	8.3	15.9	12.7	3.2	26.5	28.7
6.	Anthrolli	100	20.9	61.6	17.1	1.7	15.4	6.1	9.3	28.8	36.6
7.	Attigundi	100	17.6	34.3	49.1	0.5	48.6	47.5	0.5	65.5	71.6
8.	Barchi	100	16.4	68.3	19.1	1.9	17.2	14.9	2.2	33.2	35.1
9.	Khanapur	100	15.9	33.4	51.5	16.0	35.6	17.1	18.5	48.9	59.4
10.	Hirehalla	100	7.2	92.9	13.1	1.3	11.8	0.9	8.4	9.4	11.2
11.	Sagar	100	44.6	45.7	11.5	6.9	4.6	3.3	0.0	54.8	65.5
12.	Sorab	100	34.4	47.2	19.5	11.7	7.8	6.1	0.1	52.3	58.4
13.	Dasanakatte	100	32.7	21.0	47.7	14.3	33.4	32.7	0.3	79.7	90.0
14.	Haladi	100	34.8	16.2	49.7	29.8	19.9	19.0	0.2	83.6	93.0
15.	Jadkal	100	53.7	11.0	36.3	10.9	25.4	25.1	0.3	89.7	92.5
16.	Kokkarne	100	47.4	17.8	36.5	21.9	14.6	11.6	1.7	80.9	79.2
17.	Halkal	100	40.7	16.9	43.0	21.6	21.4	20.7	0.2	83.1	88.3

Halkal, Hemavathi watersheds, etc.) is better than other low yielding watersheds (for example, Barchi, Mohegaon watersheds, etc.) in calibration and validation. Overall, this model also exhibits a close match of the computed runoff with the observed runoff, except for some deviation in simulating some high peaks similar to Model-I.

The dormancy and dominancy of various components of stream flow generating processes involved in the present model are also analysed. The annual average of these components in terms of percentage of rainfall is presented in Table 5.12. To distinguish the dormancy/dominancy of these components, annual average values of these components are plotted against annual average runoff coefficient, and separate trend lines fitted as shown in Fig. 5.13. Similar to previous model (Model-I), this model also reflects the dominancy of surface runoff compared to lateral flow and base flow and significance of base flow in high runoff producing coastal watersheds. All other components of stream flow generation process show the trend similar to Model-I.

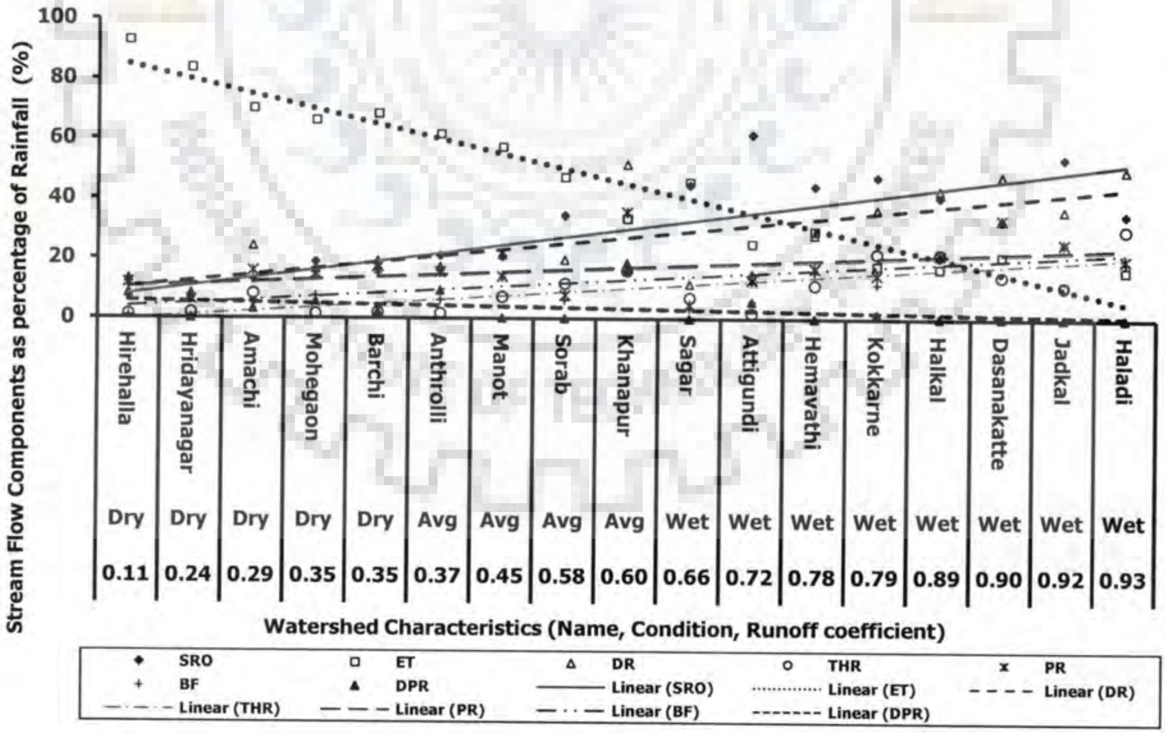


Fig. 5.13 Trend Analysis of Average Annual Variation in Various Stream Flow Generating Components of LTHS MICHEL II Model

5.4.2 Application of Model-II on Seasonal Data

The performance of Model-II is also evaluated on seasonal data series of study watersheds. The optimal set of model parameters obtained through calibration on seasonal data series is presented in Table 5.13. The performance of model in term of NSE and RE in calibration and validation are presented in Table 5.8. As seen from Table 5.8, the model yields maximum NSE of 0.87 in calibration and 0.88 in validation for Hemavathi watershed, which is more than the NSE obtained for Model-I using the seasonal data of study watersheds (Fig. 5.7). The minimum NSE of 0.49 in calibration is seen for Amachi watershed (excluding Hirehalla watershed) and 0.27 in validation for Attigundi watershed (Table 5.8). The trend analysis performed on the plot of seasonal average runoff coefficient of study watersheds in ascending order of NSE values during calibration and validation (Fig. 5.8) shows that Model-II exhibits similar trend as obtained for annual data series i.e. high efficiency for wet watersheds and comparatively low efficiency for dry watersheds. But the model efficiency is better for annual data series than seasonal data series (Fig. 5.14), which could be ascribed to proper accounting of soil moisture in annual data series as observed earlier in case of application of Model-I using seasonal data series of study watersheds.

Similarly, the model is also evaluated for errors based on absolute percent RE in calibration and validation using seasonal data as shown in Table 5.8. As seen from Table 5.8, the value of RE goes up to 8.4 % in calibration for all high yielding watersheds, which can be categorized as very good performance of Model to simulate the total stream flow, while the value of RE in case of dry watersheds varies from 3.6 to 13.3% for dry watersheds yield a very good to good performance of Model-II (Donigian et al., 1983; Harmel et al., 2006). The performance of Model-II is also satisfactory when tested with the seasonal data of all watersheds under average condition. The trend analysis presented in Fig. 5.10 for annual average values of absolute RE for seasonal data (Table 5.9 and Appendix D) indicates the reverse trend of RE with watershed wetness in terms of average runoff coefficient.

The annual average values in terms of percentage of rainfall of various runoff generating components are also estimated and presented in Table 5.14. Similar results are

Table 5.13 Optimized Values of Parameters of LTHS MICHEL II Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	α	β	K	P_1	P_2	P_3	P_4	δ	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	34.0	0.53	0.63	1.32	0.01	0.41	0.47	0.99	1.26	62.1	297.0	300.0	0.30	0.46	180.0
2.	Hridaynagar	30.0	0.11	0.05	1.07	0.05	0.98	0.48	0.54	0.10	234.2	400.9	252.0	0.18	0.31	303.4
3.	Mohegaon	36.5	0.48	0.52	0.50	0.02	0.72	0.40	0.74	0.05	116.2	397.4	335.4	0.57	0.42	289.2
4.	Manot	41.2	0.95	0.99	0.50	0.02	0.10	0.40	0.99	0.99	286.9	450.4	480.0	0.90	0.86	426.5
5.	Amachi	21.1	0.48	0.48	0.65	0.01	0.16	0.60	0.69	0.20	80.0	441.8	394.9	0.20	0.53	220.6
6.	Anthrolli	47.5	0.49	0.54	0.50	0.03	0.73	0.40	0.30	0.94	118.6	213.2	325.8	0.78	0.45	327.3
7.	Attigundi	27.6	0.58	0.64	1.93	0.06	0.62	0.10	0.99	0.06	140.0	200.0	400.0	0.38	0.92	212.8
8.	Barchi	33.4	0.53	0.58	0.77	0.01	0.28	0.70	0.30	0.01	80.0	350.0	273.8	0.29	0.56	402.0
9.	Khanapur	15.0	0.21	0.27	0.50	0.05	0.99	0.30	0.71	0.10	112.2	300.0	299.7	0.45	0.70	250.0
10.	Hirehalla	15.1	0.47	0.51	0.50	0.03	0.18	0.10	0.10	0.01	194.5	251.8	350.0	0.13	0.23	323.9
11.	Sagar	41.6	0.10	0.09	0.50	0.02	0.99	0.59	0.99	0.10	92.5	236.8	347.3	0.16	0.34	374.1
12.	Sorab	45.3	0.53	0.68	0.52	0.01	0.86	0.31	0.99	0.10	93.5	391.7	398.0	0.40	0.63	485.6
13.	Dasanakatte	23.7	0.56	0.53	0.50	0.02	0.58	0.30	0.99	0.10	180.0	229.1	350.0	0.34	0.74	220.0
14.	Haladi	23.2	0.42	0.44	0.50	0.01	0.55	0.54	0.99	0.99	180.0	340.5	500.0	0.35	0.63	250.0
15.	Jadkal	29.1	0.47	0.59	0.50	0.01	0.99	0.30	0.99	0.99	179.6	338.6	400.0	0.38	0.67	325.5
16.	Kokkarne	20.1	0.10	0.13	0.50	0.01	0.10	0.48	0.99	1.99	100.0	400.0	400.0	0.35	0.90	200.0
17.	Halkal	21.6	0.33	0.37	0.50	0.01	0.77	0.42	0.99	0.99	180.0	399.8	400.0	0.38	0.66	200.0

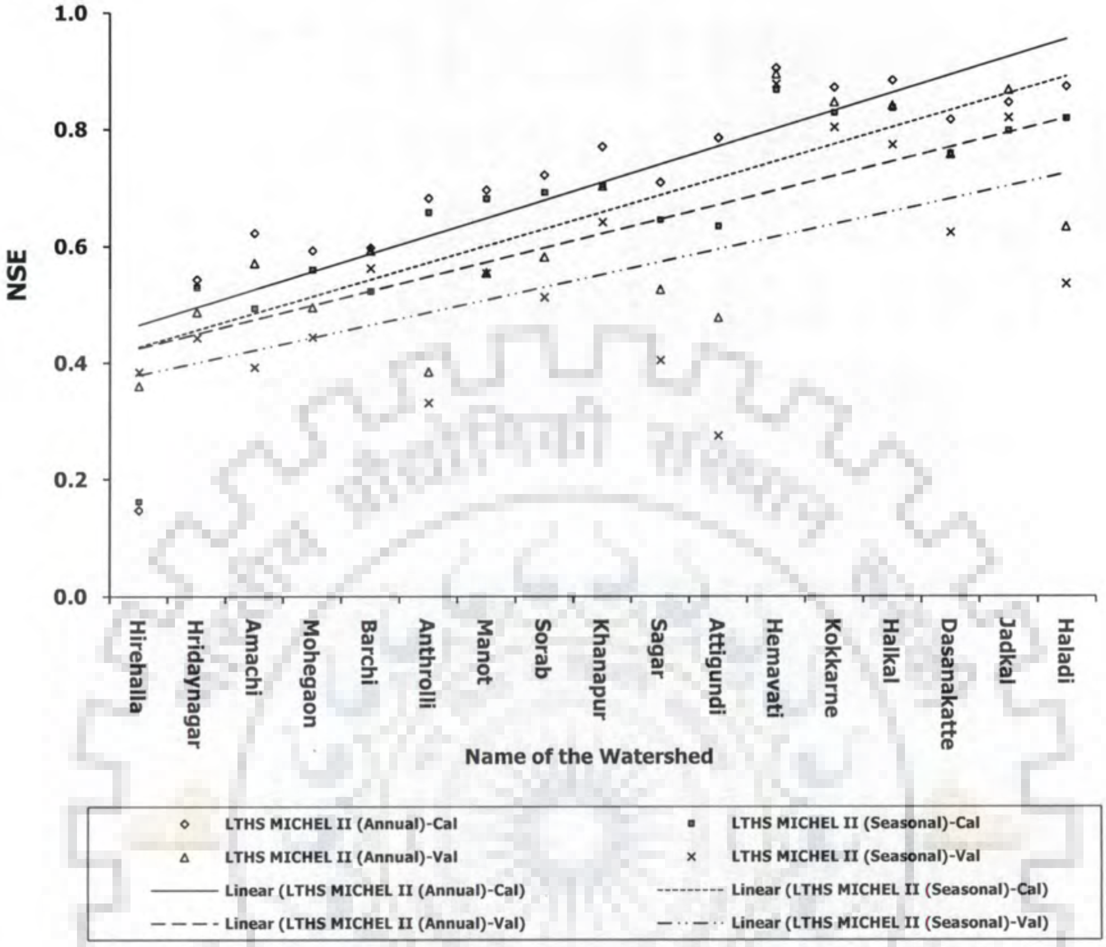


Fig. 5.14 **Comparative Performance of LTHS MICHEL II Model on Annual and Seasonal Data of Study Watersheds**

obtained as seen for the application of Model-II using annual data series. Obviously, the surface runoff is predominant as compared to lateral flow and base flow as seen for application of this Model-II to annual data. All other components excepts losses such as evapotranspiration and deep percolation are more significant in high runoff producing coastal watersheds than low runoff producing watersheds, whereas the losses shows reverse trends.

Table 5.14 Percent Estimates of Hydrological Components of LTHS MICHEL II Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotranspiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	49.4	23.4	29.7	13.8	15.9	15.0	0.2	78.2	80.9
2.	Hridaynagar	100	6.5	79.9	12.0	5.7	6.3	3.6	3.1	15.8	25.9
3.	Mohegaon	100	19.2	68.1	13.4	5.3	8.0	5.6	2.0	30.1	36.9
4.	Manot	100	24.1	55.1	21.2	8.5	12.7	12.1	0.1	44.6	47.0
5.	Amachi	100	5.7	66.3	28.4	17.0	11.4	6.9	3.2	29.6	30.7
6.	Anthrolli	100	21.0	57.5	21.1	8.4	12.6	3.8	8.9	33.2	40.6
7.	Attigundi	100	17.4	36.6	47.8	4.8	43.0	42.3	0.4	63.5	77.6
8.	Barchi	100	15.9	59.0	25.1	17.6	7.5	3.0	7.1	36.5	36.3
9.	Khanapur	100	16.3	41.4	43.0	12.9	30.1	21.1	8.8	50.3	61.6
10.	Hirehalla	100	9.0	95.8	10.5	1.1	9.4	0.9	7.7	11.0	13.1
11.	Sagar	100	28.6	42.8	29.3	17.3	11.9	12.0	0.1	58.0	66.5
12.	Sorab	100	37.3	43.2	18.4	5.7	12.7	13.8	0.1	56.8	63.4
13.	Dasanakatte	100	35.2	11.0	56.3	16.9	39.4	37.4	0.4	89.5	88.8
14.	Haladi	100	35.5	13.9	51.4	27.7	23.8	22.9	0.2	86.1	84.4
15.	Jadkal	100	54.9	7.5	38.7	11.6	27.1	26.7	0.3	93.1	93.0
16.	Kokkarne	100	44.4	18.1	38.3	18.3	19.9	19.2	0.2	81.9	80.3
17.	Halkal	100	43.0	11.3	46.4	19.6	26.8	26.1	0.3	88.7	89.6

5.5 MODIFIED SCS-CN CONCEPT BASED MODEL-III (LTHS ASMA I)

The LTHS ASMA I model (Model-III) is a further modification to LTHS MICHEL II model by incorporating an ASMA procedure to obviate the unrealistic sudden jump in the computation of surface runoff. As detailed in Chapter 3, an expression for initial soil moisture store level (V_0) is proposed based on advanced SMA procedure. The pre-antecedent moisture level (V_{00}) is considered to formulate the expression for initial soil moisture store level (V_0) and assumed that V_0 is the sum of V_{00} and a fraction (γ) of the part of rainfall not transformed into runoff owing to 5 days antecedent rainfall. The fraction γ is a coefficient of pre-antecedent soil moisture store level (V_{00}) and varies between 0 and 1. Thus, Model-III is developed using an appropriate mathematical expressions for an ASMA procedure to compute the surface runoff and consists of sixteen parameters as discribed in Chapter 3. Model-III is also tested for its performance on annual and seasonal data series of study watersheds as described in subsequent sections.

5.5.1 Application of Model-III on Annual Data

The estimated optimal set of parameters of Model-III obtained through calibration using annual data series of study watersheds marked for calibration is presented in Table 5.15. The performance of model in terms of NSE values obtained in calibration and validation is shown in Table 5.4. As seen from the Table 5.4, NSE varies from 0.76 to 0.90 in calibration for wet watersheds indicating very good model response (Fig. 5.1) to simulate the daily stream flow of these watersheds (Durbude et al., 2010). This model yields the maximum NSE of 0.90 both in calibration and validation for Hemavathi watershed, which is higher than the previous two models i.e. Models I and II. The minimum efficiency of 0.58 is found for Hridaynagar watershed in calibration and 0.43 for Amachi watershed in validation (excluding the most dry watershed Hirehalla watershed). Similar to Model-I and Model-II, Model-III also yields high efficiency for wet watersheds and low efficiency for dry watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry (Hirehalla) watershed (Fig. 5.1). It is also evident from the trend line drawn on Fig. 5.2 for NSE obtained for this model; NSE increases with watershed wetness in terms of average runoff coefficient (Durbude et al., 2010).

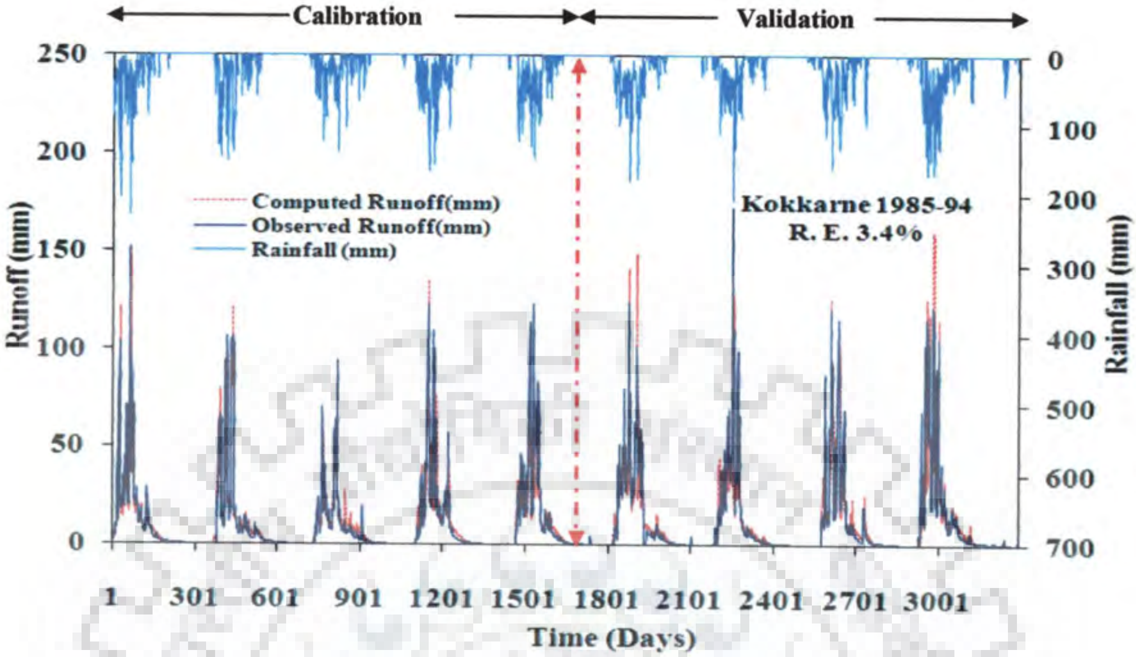
Table 5.15 Optimized Values of Parameters of LTHS ASMA I Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter															
		CN_0	δ	α	β	γ	K	P_1	P_2	P_3	P_4	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	33.3	1.22	0.12	0.10	0.18	1.47	0.05	0.28	0.10	0.99	65.2	136.9	320.5	0.30	1.33	200.2
2.	Hridaynagar	36.5	0.10	0.99	0.10	0.91	1.02	0.03	0.94	0.10	0.67	180.0	397.9	430.0	0.90	0.26	340.0
3.	Mohegaon	32.0	0.05	0.54	0.13	0.55	0.50	0.03	0.83	0.60	0.89	110.0	261.6	470.0	0.20	0.34	150.0
4.	Manot	35.6	0.10	0.36	0.50	0.34	0.50	0.01	0.22	0.40	0.60	200.0	382.5	320.0	0.51	0.66	350.0
5.	Amachi	30.9	0.80	0.24	0.10	0.10	0.50	0.01	0.10	0.58	0.40	62.3	288.7	204.6	0.22	0.65	530.3
6.	Anthrolli	30.3	0.99	0.43	0.59	0.48	0.50	0.01	0.94	0.17	0.22	200.0	373.2	330.4	0.78	0.42	290.0
7.	Attigundi	35.6	0.01	0.53	0.01	0.56	1.03	0.01	0.80	0.60	0.62	140.0	232.5	349.2	0.28	0.50	579.9
8.	Barchi	14.2	0.01	0.10	0.01	0.17	0.50	0.01	0.10	0.51	0.50	122.1	350.0	349.9	0.90	0.79	349.9
9.	Khanapur	10.4	0.10	0.10	0.03	0.16	0.50	0.02	0.99	0.31	0.53	60.0	400.0	400.0	0.45	0.72	160.0
10.	Hirehalla	15.0	0.01	0.45	0.27	0.48	0.50	0.02	0.35	0.26	0.99	127.0	322.9	398.5	0.25	0.17	350.1
11.	Sagar	42.1	0.10	0.87	0.21	0.92	0.50	0.01	0.43	0.49	0.85	99.1	330.8	309.7	0.21	0.49	299.9
12.	Sorab	58.7	0.10	0.43	0.01	0.54	0.54	0.01	0.32	0.47	0.69	110.4	340.0	289.8	0.40	0.67	521.6
13.	Dasanakatte	20.6	0.10	0.23	0.33	0.15	0.50	0.01	0.99	0.30	0.99	180.0	316.5	350.0	0.38	0.59	200.0
14.	Haladi	20.5	0.01	0.12	0.22	0.11	0.50	0.01	0.11	0.50	0.99	144.2	253.2	397.9	0.35	0.88	214.3
15.	Jadkal	25.3	0.10	0.17	0.40	0.16	0.50	0.01	0.99	0.30	0.99	179.8	263.7	209.7	0.34	0.61	230.3
16.	Kokkarne	20.3	0.01	0.10	0.34	0.07	0.50	0.01	0.10	0.47	0.99	120.0	400.0	400.0	0.35	0.89	230.0
17.	Halkal	19.0	0.01	0.17	0.39	0.15	0.50	0.01	0.92	0.37	0.99	120.0	400.0	400.0	0.38	0.61	180.0

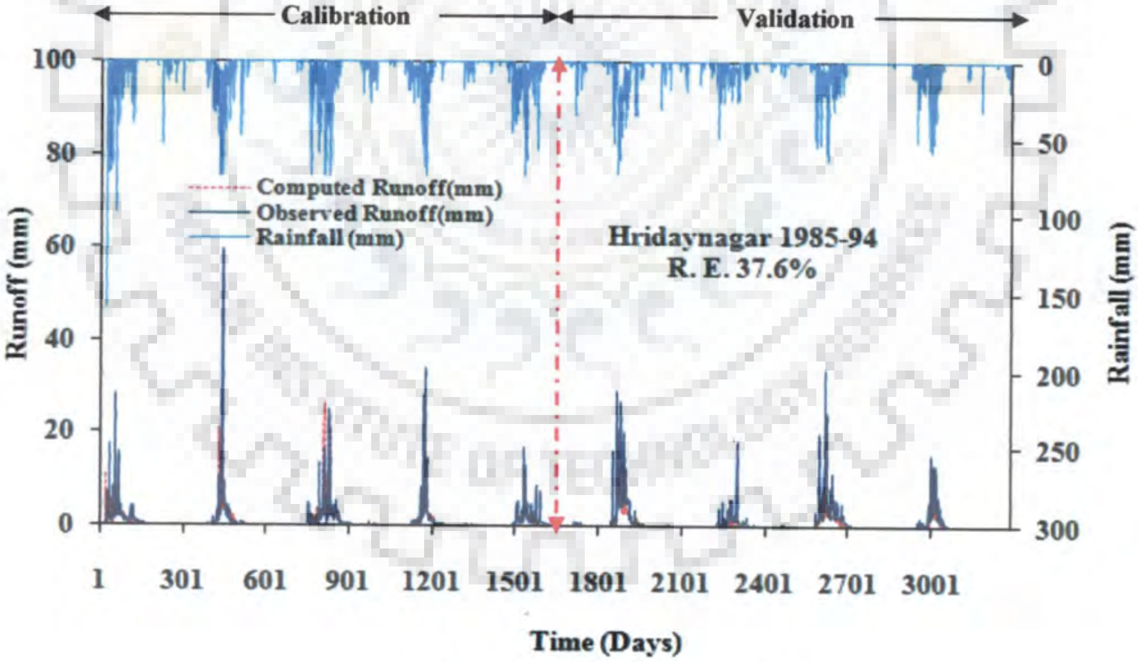
The improvement in NSE for Model III over Model I and Model II is mainly attributed to the advancement in SMA procedure.

Model-III is also evaluated based on absolute value of RE obtained in calibration and validation of model using annual data series of study watersheds as shown in Table 5.4. As seen from Table 5.4, the value of RE varies from 2.6 to 11.4% in calibration for all coastal high yielding watersheds, but it is more than 10% for all dry watersheds, except Amachi and Barchi watersheds showing better model performance for high yielding watershed than low yielding watershed (Donigian et al., 1983 and Harmel et al., 2006). The model performance is also very good for all watersheds under average condition except the Sorab watershed (13%). The trend analysis presented in Fig. 5.3 for annual average of absolute values of RE (Table 5.5 and Appendix A) indicates a reverse trend of RE with watershed wetness in terms of average runoff coefficient. It can also be seen from Fig. 5.3 that LTHS ASMA I model performs better than LTHS MICHEL I and LTHS MICHEL II models (Durbude et al., 2010).

The performance of this model is further analyzed on the basis of subjective assessment through visual comparison between observed and computed runoff for all years for all study watersheds as shown in Appendices (B and C) for calibration and validation, respectively, for this model. Figs. 5.15 (a, b) depict the daily variations of computed and observed runoff along with RE (%) for selected watersheds under various categories of watersheds in term of wetness in calibration and validation, respectively, at a larger scale for better visualization. As seen from these figures, the model fit in simulation of daily stream flows for wet watersheds (e.g. Kokkarne and Hemavathi watersheds, etc.) is better than dry watershed (for example, Hridaynagar watershed) in calibration and validation, respectively. The sample calibration and validation results showing very good and worst (poor) performance of this model is also shown at larger scale in Figs. 6.16 (a, b).

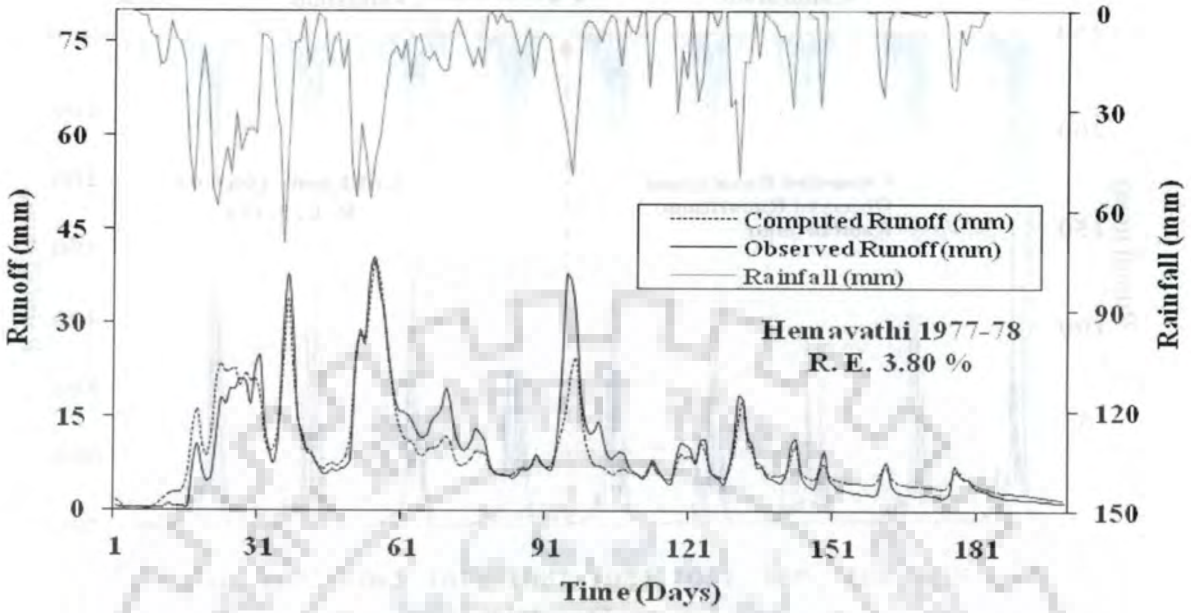


(a) Kokkarne Watershed

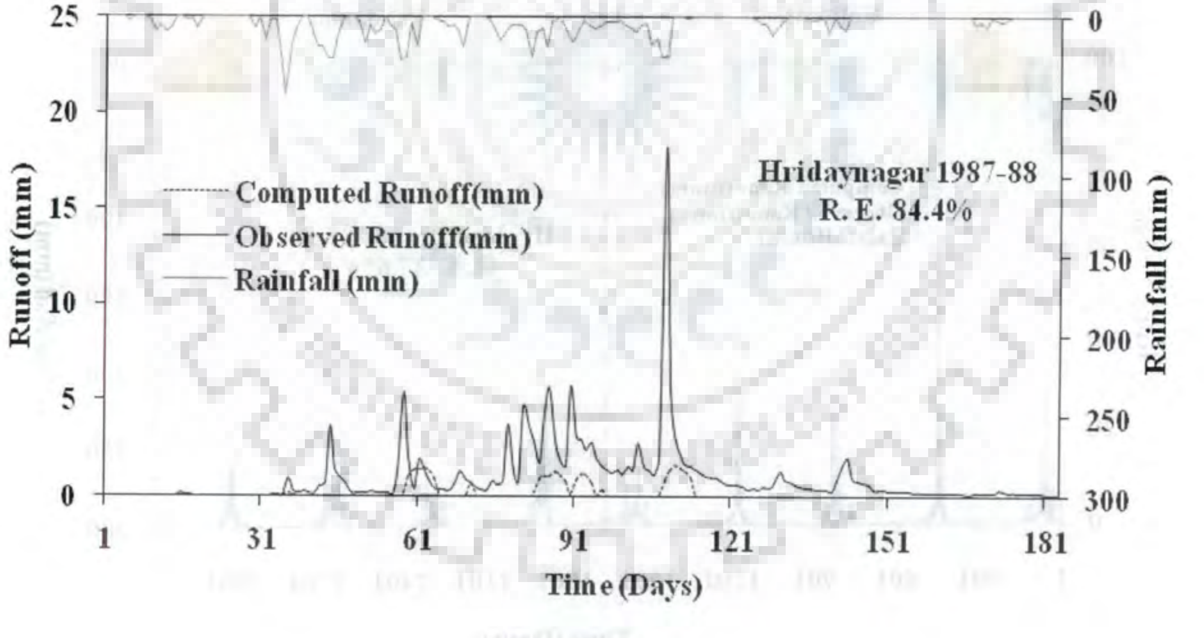


(b) Hridaynagar Watershed

Fig. 5.15 (a, b) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) of (a) Kokkarne (Wet) and (b) Hridaynagar (Dry) Watersheds in Calibration and Validation of LTHS ASMA I Model (Day 1 represnets June 1)



(a) Calibration



(b) Validation

Fig. 5.16 (a, b) Performance of LTHS ASMA I Model: (a) Best Performance on Hemavathi (Wet) Watershed in Calibration and (b) Wrost Performance on Hridaynagar (Dry) Watershed in Validation of LTHS ASMA I Model (Day 1 represents June 1)

The annual average values in terms of percentage of rainfall of various runoff generating components are also estimated and presented in Table 5.16. Similar to earlier LTHS models, this model also distinguishes the dormant and dominant components/processes of hydrologic cycle. The dormancy/dominancy of these components is obtained by plotting annual average runoff coefficient of various watersheds and annual average values in percentage of these components. A separate trend line fitted for each component of stream flow generation process is shown in Fig. 5.17, exhibiting trends similar to earlier models.

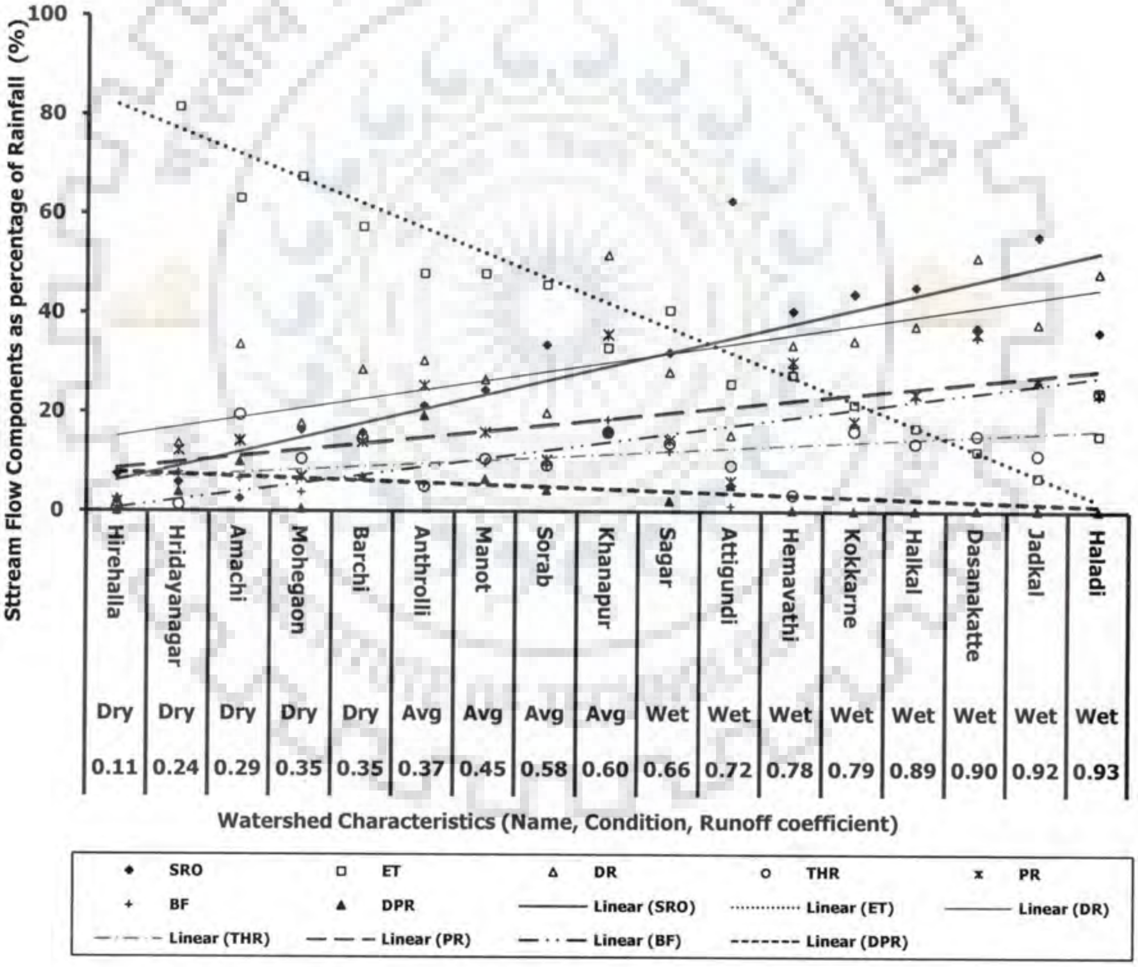


Fig. 5.17 Trend Analysis of Average Annual Variation in Various Stream Flow Generating Components of LTHS ASMA I Model

Table 5.16 Percent Estimates of Hydrological Components of LTHS ASMA I Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotran-spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	40.5	27.6	33.7	3.4	30.3	29.2	0.3	73.0	77.9
2.	Hridaynagar	100	5.9	81.6	13.7	1.4	12.3	7.8	3.9	15.0	24.3
3.	Mohegaon	100	16.4	67.4	17.7	10.6	7.1	3.9	0.5	30.8	34.7
4.	Manot	100	24.5	47.9	26.5	10.6	15.9	9.7	6.5	44.8	44.2
5.	Amachi	100	2.5	63.0	33.6	19.4	14.2	6.6	9.9	28.5	28.7
6.	Anthrolli	100	21.3	47.9	30.4	5.1	25.3	5.5	19.3	31.8	36.6
7.	Attigundi	100	12.2	22.8	65.1	39.0	26.0	17.0	10.3	68.2	71.6
8.	Barchi	100	15.9	57.4	28.5	14.6	13.9	7.0	6.9	37.5	35.1
9.	Khanapur	100	16.0	33.0	51.7	16.0	35.7	18.5	16.5	50.4	59.4
10.	Hirehalla	100	7.5	103.5	2.5	0.7	1.9	0.7	0.0	8.9	11.2
11.	Sagar	100	32.1	40.7	28.1	13.8	14.4	12.2	2.1	58.1	65.5
12.	Sorab	100	33.6	45.7	19.8	9.3	10.5	9.4	4.3	52.3	58.4
13.	Dasanakatte	100	37.2	12.2	51.4	15.4	35.9	35.2	0.4	87.9	90.0
14.	Haladi	100	36.3	15.5	48.2	24.2	24.0	23.3	0.2	83.8	93.0
15.	Jadkal	100	55.6	7.0	38.0	11.4	26.6	26.3	0.3	93.3	92.5
16.	Kokkarne	100	43.9	21.6	34.5	16.2	18.3	17.7	0.2	77.8	79.2
17.	Halkal	100	45.3	17.0	37.5	13.8	23.7	23.0	0.2	82.1	88.3

5.5.2 Application of Model-III on Seasonal Data

The performance of Model-III (LTHS ASMA I) is also tested on seasonal data series of study watersheds. The estimated optimal set of model parameters obtained through calibration on seasonal data series is shown in Table 5.17. The performance of this model in terms of NSE values in calibration and validation is presented in Table 5.8. The model yields the maximum NSE of 0.87 in calibration and 0.88 in validation (Fig. 5.7) for Hemavathi watershed (Table 5.8), while the minimum efficiency of 0.52 in calibration is seen for Barchi watershed and 0.26 in validation for Attigundi watershed (excluding Hirehalla watershed). The plot of runoff coefficient (seasonal average) of different watersheds in ascending order and NSE values (Fig. 5.8) reveals results similar to earlier models, i.e. NSE increases with watershed wetness in terms of average runoff coefficient. Likewise, the plot of runoff coefficient for annual and seasonal data series (Fig. 5.18) also reveals that the model efficiency is better in both calibration and validation of Model-III using annual data series than seasonal data series for all the study watersheds.

Similarly, Model-III is also evaluated based on absolute RE obtained in calibration and validation (Table 5.8). From Table 5.8, RE goes up to 4.0% in calibration for all high yielding watersheds resulting into a very good model response to simulate the total stream flow, while RE for dry watersheds varies from 2.0 to 15.0%, yielding a very good to good response as recommended by Donigian et al., (1983) and Harmel et al., (2006). The results are also very encouraging in validation of model using seasonal data (Table 5.8). The model performance is satisfactory when tested with the seasonal data of all watersheds under average condition. The annual observed, computed runoff, and RE for each year are also analyzed as given in Appendix D and the annual average values of absolute RE are shown in Table 5.9. The trend analysis presented in Fig. 5.10 for annual average of absolute values of RE (Table 5.9) indicates the reverse trend of RE with watershed wetness in terms of seasonal average runoff coefficient.

The annual average values in terms of percentage of rainfall of various runoff generating components are also estimated for this model when applied to seasonal data of

Table 5.17 Optimized Values of Parameters of LTHS ASMA I Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter															
		CN_0	δ	α	β	γ	K	P_1	P_2	P_3	P_4	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Hemavathi	35.0	0.53	0.44	0.10	0.53	1.23	0.01	0.83	0.10	0.99	68.1	397.3	317.6	0.31	0.55	322.3
2.	Hridaynagar	33.7	0.10	0.99	0.10	0.92	0.98	0.03	0.10	0.30	0.41	293.7	450.0	419.1	0.24	0.80	308.1
3.	Mohegaon	31.1	1.97	0.63	0.14	0.65	0.50	0.02	0.99	0.50	0.31	100.0	294.5	470.0	0.61	0.27	161.4
4.	Manot	45.4	0.10	0.56	0.38	0.54	0.50	0.02	0.97	0.40	0.60	130.0	330.7	310.2	0.36	0.41	377.7
5.	Amachi	30.1	0.80	0.47	0.10	0.31	0.50	0.01	0.11	0.58	0.40	50.0	286.0	278.3	0.20	0.63	473.4
6.	Anthrolli	31.5	0.01	0.50	0.68	0.56	0.50	0.02	0.31	0.20	0.42	200.0	314.8	245.4	0.58	0.53	200.0
7.	Attigundi	30.0	0.01	0.60	0.01	0.60	1.34	0.02	0.73	0.50	0.99	140.0	180.0	323.2	0.56	0.45	199.2
8.	Barchi	31.0	0.01	0.49	0.01	0.55	0.81	0.02	0.96	0.48	0.64	73.3	297.9	349.9	0.29	0.34	348.8
9.	Khanapur	15.0	0.01	0.58	0.23	0.65	0.63	0.02	0.52	0.40	0.99	80.0	350.0	450.0	0.52	0.52	150.0
10.	Hirehalla	15.0	0.01	0.48	0.10	0.52	0.50	0.04	0.25	0.60	0.99	121.2	245.7	388.5	0.80	0.10	360.7
11.	Sagar	42.9	0.10	0.85	0.17	0.90	0.50	0.01	0.53	0.58	0.88	60.0	300.0	235.5	0.12	0.45	226.4
12.	Sorab	38.9	0.10	0.41	0.01	0.55	0.56	0.01	0.91	0.27	0.99	123.4	365.3	400.0	0.90	0.28	374.2
13.	Dasanakatte	20.5	0.10	0.30	0.31	0.21	0.50	0.01	0.99	0.30	0.99	180.0	343.1	350.0	0.38	0.60	200.0
14.	Haladi	20.9	0.01	0.12	0.21	0.10	0.50	0.01	0.10	0.59	0.99	180.0	200.0	374.0	0.35	0.87	200.0
15.	Jadkal	31.3	0.10	0.78	0.36	0.81	0.50	0.01	0.99	0.30	0.99	180.0	336.1	400.0	0.38	0.63	308.5
16.	Kokkarne	21.8	0.10	0.14	0.35	0.10	0.50	0.01	0.10	0.48	0.99	157.5	400.0	400.0	0.35	0.83	401.0
17.	Halkal	22.8	0.01	0.58	0.40	0.54	0.50	0.01	0.82	0.35	0.99	180.0	400.0	400.0	0.38	0.59	180.0

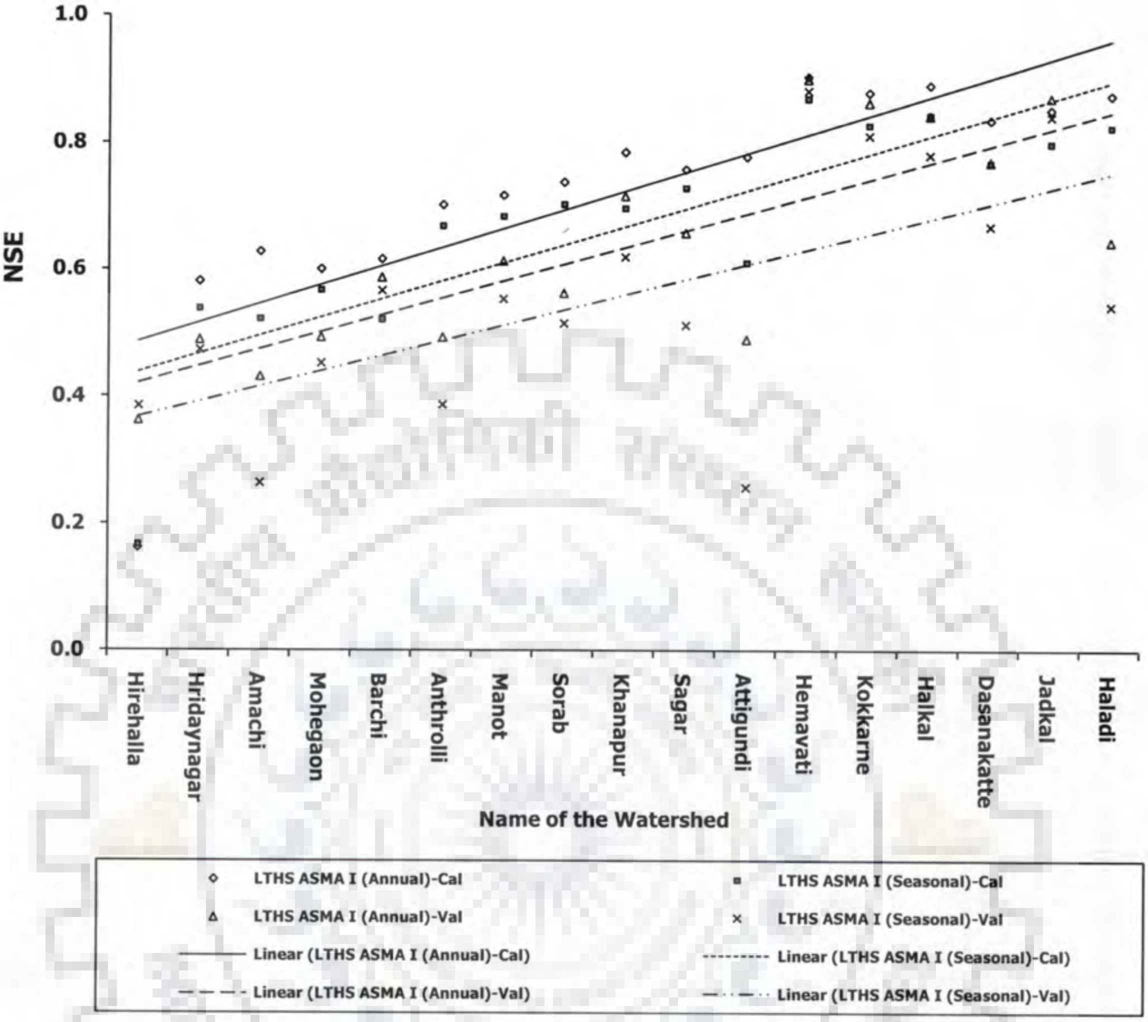


Fig. 5.18 Comparative Performance of LTHS ASMA I Model on Annual and Seasonal Data of Study Watersheds

study watersheds and presented in Table 5.18. Similar results are obtained as seen for the model when tested with annual data. Obviously, the surface runoff is predominant compared to lateral flow and base flow, while other components excepts evapotranspiration and deep percolation are more significant/dominant in high runoff producing coastal watersheds than low runoff producing watersheds, whereas the losses show reverse trends.

Table 5.18 Percent Estimates of Hydrological Components of LTHS ASMA I Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotran-spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	46.3	24.4	30.8	3.1	27.8	27.5	0.3	76.8	80.9
2.	Hridaynagar	100	6.1	72.7	22.3	6.6	15.6	6.0	8.7	18.8	25.9
3.	Mohegaon	100	18.4	58.8	24.9	12.5	12.5	2.9	6.4	33.7	36.9
4.	Manot	100	24.7	50.7	24.4	9.8	14.6	9.2	6.1	43.6	47.0
5.	Amachi	100	2.1	59.5	37.7	21.8	15.9	7.0	10.4	30.8	30.7
6.	Anthrolli	100	23.3	54.6	22.3	4.5	17.8	7.2	9.9	35.0	40.6
7.	Attigundi	100	17.0	25.9	58.2	29.1	29.1	28.1	0.3	74.1	77.6
8.	Barchi	100	16.7	61.0	24.0	11.6	12.4	8.0	4.4	36.3	36.3
9.	Khanapur	100	23.7	50.5	27.8	11.1	16.7	15.7	0.2	50.5	61.6
10.	Hirehalla	100	9.2	108.7	1.4	0.8	0.6	0.0	0.0	10.0	13.1
11.	Sagar	100	33.1	34.6	32.9	19.1	13.8	12.0	1.6	64.2	66.5
12.	Sorab	100	36.8	41.7	20.8	5.5	15.2	14.7	0.2	57.1	63.4
13.	Dasanakatte	100	36.4	10.8	53.5	16.1	37.5	36.5	0.4	89.1	88.8
14.	Haladi	100	35.9	12.2	52.3	31.0	21.3	20.6	0.2	87.5	84.4
15.	Jadkal	100	54.7	7.8	38.0	11.4	26.6	26.1	0.3	92.2	93.0
16.	Kokkarne	100	44.6	18.8	36.4	17.4	19.0	18.7	0.2	80.7	80.3
17.	Halkal	100	46.5	12.2	41.7	14.6	27.1	26.3	0.3	87.4	89.6

5.6 MODIFIED SCS-CN CONCEPT-BASED MODEL-IV (LTHS ASMA II)

Model-IV is further modification to LTHS ASMA I model for the computation of sub-surface drainage flow based on the conceptual frame-work of Yaun et al. (2005). This 15-parameter model uses ASMA procedure of Model-III for surface flow and modified concept of Yuan et al. for sub-surface drainage flow computation to simulate daily stream flow. The new parameters introduced in the formulation of this model are CNd_0 and λ_d. As explained earlier (Chapter 3), CNd_0 represents the curve numbers for sub-surface flow on the first day of simulation, similar to curve number (CN_0) for surface flow. Model-IV is also tested for its performance on annual and seasonal data of study watersheds and described in subsequent sections.

5.6.1 Application of Model-IV on Annual Data

The estimated optimal set of model parameters using annual data series of study watersheds is presented in Table 5.19. The performance of this model in terms of NSE values in calibration and validation periods is given in Table 5.4. As seen from Table 5.4, NSE in calibration varies from 0.79 to 0.92 for high yielding wet watersheds indicating very good model response (Fig. 5.1) (Motovilov et al., 1999). The model yields maximum NSE of 0.92 in calibration for Kokkarne watershed and 0.90 in validation for Hemavathi watershed, while the minimum efficiency of 0.59 in calibration is visible for Hridaynagar watershed (excluding most dry Hirehalla watershed) and 0.39 in validation for Anthrolli watershed. Similar to previous models, Model IV also yields high efficiency for wet watersheds and lesser efficiency for dry watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry (Hirehalla) watershed. Fig. 5.2 shows the plot of runoff coefficient of different watersheds in ascending order and NSE values. It is evident from trend line drawn on Fig. 5.2 both for calibration and validation, NSE increases with watershed wetness in terms of average runoff coefficient.

Similarly, the performance of this model is evaluated based on absolute values of RE obtained in calibration and validation periods as presented in Table 5.4. From Table 5.4, the

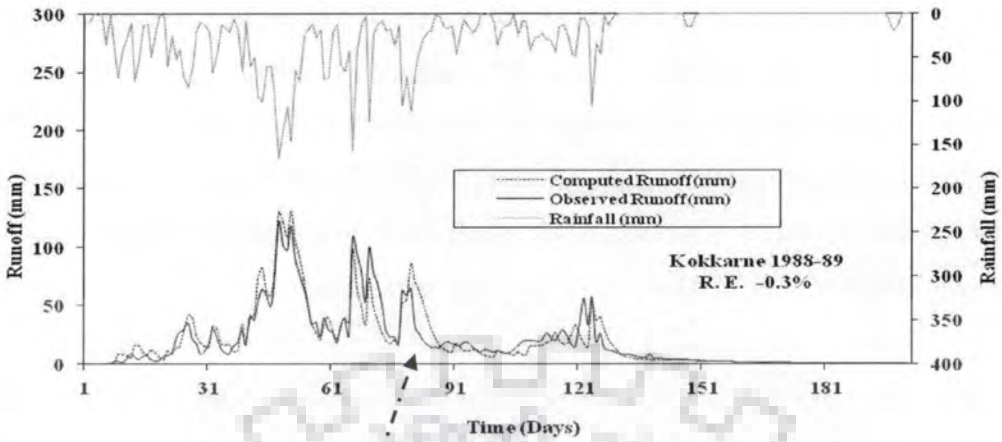
Table 5.19 Optimized Values of Parameters of LTHS ASMA II Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	δ	α	β	γ	K	P_1	P_3	P_4	θ_w	ψ_f	E_s	ψ_0	CNd_0	λ_d
1.	Hemavathi	30.5	2.33	0.41	0.14	0.44	1.52	0.01	0.11	0.99	40.3	300.0	0.32	300.3	64.7	0.01
2.	Hridaynagar	27.5	0.01	0.54	0.01	0.52	1.23	0.04	0.00	0.59	299.7	496.2	0.26	253.6	60.7	0.01
3.	Mohegaon	37.0	0.05	0.46	0.01	0.50	5.00	0.03	0.60	0.16	119.7	395.3	0.32	469.4	58.3	0.07
4.	Manot	35.3	6.63	0.85	0.00	0.95	3.02	0.02	0.60	0.48	298.9	413.8	0.36	377.1	56.6	0.57
5.	Amachi	17.4	0.10	0.40	0.02	0.42	2.00	0.01	0.20	0.44	80.0	310.0	0.34	242.9	32.3	0.02
6.	Anthrolli	28.6	4.92	0.43	0.01	0.46	1.69	0.01	0.39	0.10	220.0	259.8	0.54	358.8	78.2	0.13
7.	Attigundi	20.0	0.02	0.45	0.001	0.58	5.98	0.05	0.24	0.98	162.5	373.9	0.38	199.4	44.8	0.26
8.	Barchi	38.1	0.01	0.53	0.01	0.54	2.00	0.01	0.35	0.50	148.9	279.2	0.38	551.5	55.4	0.09
9.	Khanapur	11.3	0.14	0.46	0.02	0.57	3.18	0.01	0.60	0.99	179.9	405.0	0.50	198.3	18.3	0.15
10.	Hirehalla	14.6	0.06	0.48	0.10	0.50	2.07	0.09	0.80	0.06	130.3	300.0	0.49	350.0	35.8	0.03
11.	Sagar	21.4	0.21	0.50	0.01	0.54	0.64	0.01	0.59	0.54	45.5	400.0	0.90	191.0	50.8	0.09
12.	Sorab	52.8	0.13	0.53	0.01	0.61	1.63	0.01	0.50	0.84	105.0	302.3	0.40	397.0	51.9	0.05
13.	Dasanakatte	15.6	0.11	0.59	0.24	0.61	0.76	0.00	0.40	0.99	123.6	399.9	0.38	394.4	20.4	0.02
14.	Haladi	25.6	0.02	0.56	0.23	0.60	1.66	0.01	0.47	0.99	103.8	400.0	0.35	389.1	37.1	0.05
15.	Jadkal	30.8	0.98	0.47	0.34	0.53	0.53	0.05	0.48	0.99	160.0	400.0	0.39	405.7	42.2	0.06
16.	Kokkarne	15.8	4.99	0.57	0.18	0.56	2.06	0.00	0.55	0.99	127.4	407.9	0.30	220.2	25.9	0.01
17.	Halkal	26.5	0.01	0.65	0.30	0.66	1.34	0.01	0.47	0.99	240.0	262.9	0.38	303.4	33.5	0.01

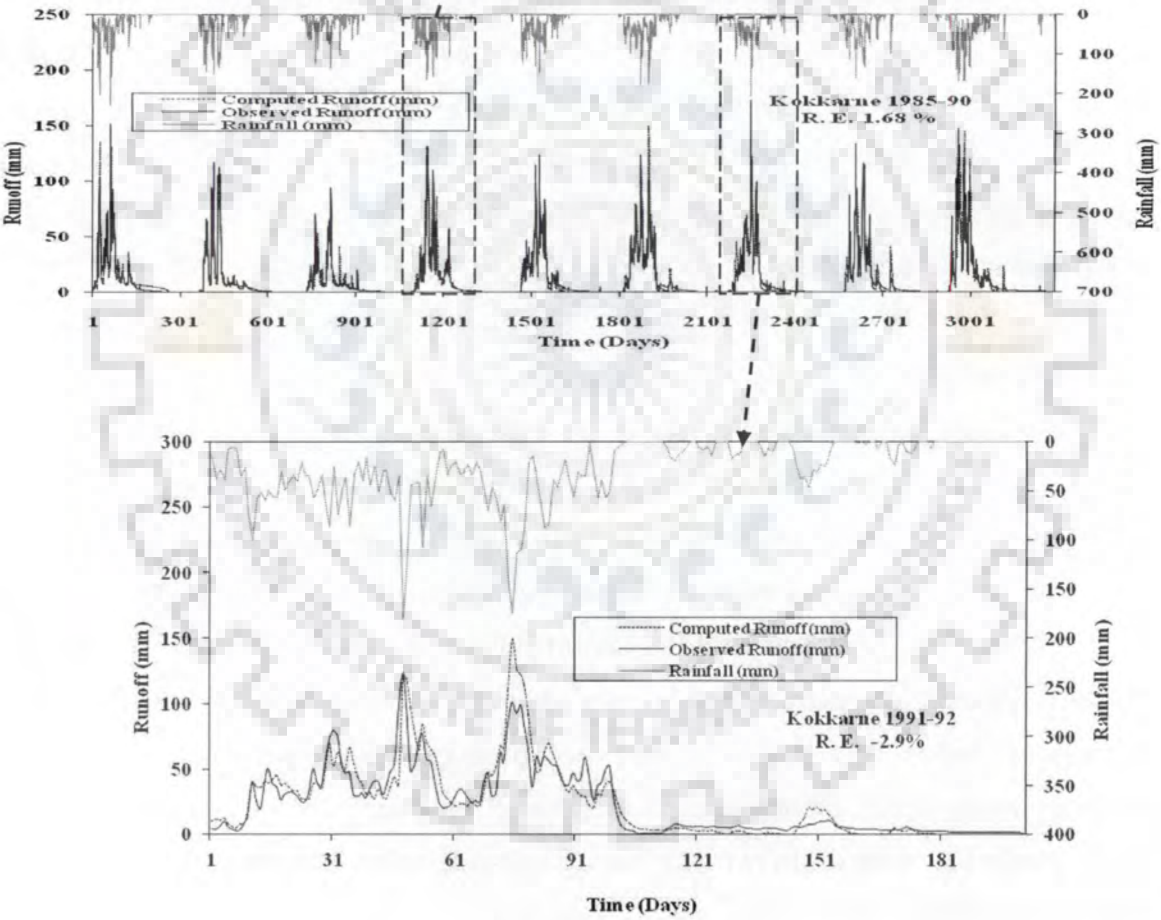
value of RE is seen to go up to 5% in calibration for all coastal high yielding watersheds, but it is more in case of dry watershed (up to 10%) indicating better model performance for high yielding wet watershed than low yielding dry watershed. It is evident from the trend analysis (Fig. 5.3) for average annual values of absolute RE (Table 5.5 and Appendix A) that RE exhibits a reverse trend with average runoff coefficient. The model performance in calibration is also very good for all watersheds under average condition.

The performance of Model IV is further analyzed visually as earlier. The plot of observed and computed runoff for all watersheds along with RE (%) is shown in Appendices (B and C), for calibration and validation, respectively, which depicts daily variations of computed and observed runoff. For better visualization of model results in calibration and validation, some plots (Appendices B and C) are reproduced at larger scale (Figs. 5.19 (a, b) and 5.20 (a, b)). The model fit for high yielding watersheds (e.g. Kokkarne watershed) is better showing very good performance than that for dry watershed (Hridaynagar watersheds) in calibration and validation.

The annual average values of different process/components (in terms of percentage of rainfall) are also estimated and presented in Table 5.20. Similar to previous models, this model also distinguishes the dormant and dominant components/processes of hydrologic cycle involved in the present model. To analyse the dormancy/dominancy of these components, annual average values of these components are plotted against annual average runoff coefficient and separate trend line are fitted for each component as shown in Fig. 5.21. The surface runoff is seen to be predominant compared to lateral flow and base flow, similar to previous models. All other components except evapotranspiration and deep percolation losses are more significant/dominant in high runoff producing coastal watersheds than low runoff producing watersheds, whereas the evapotranspiration and deep percolation losses show reverse trends.

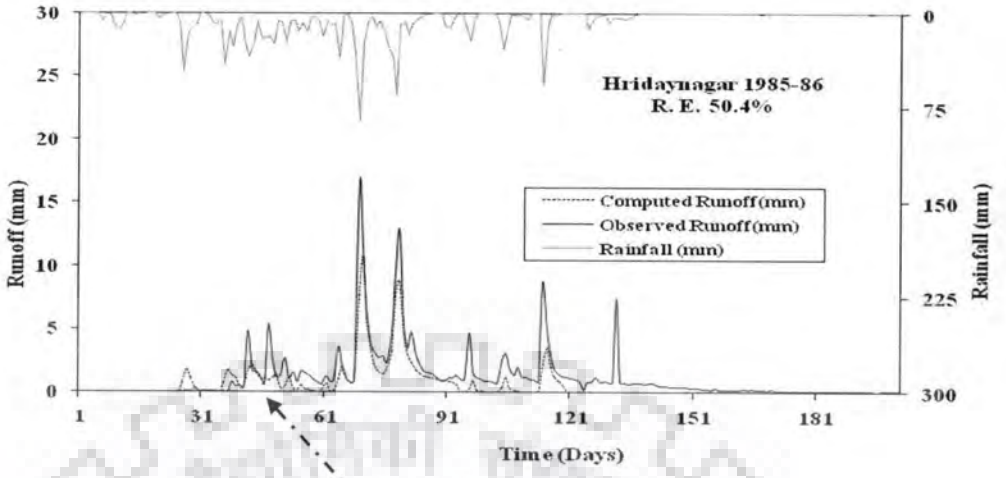


(a) Calibration

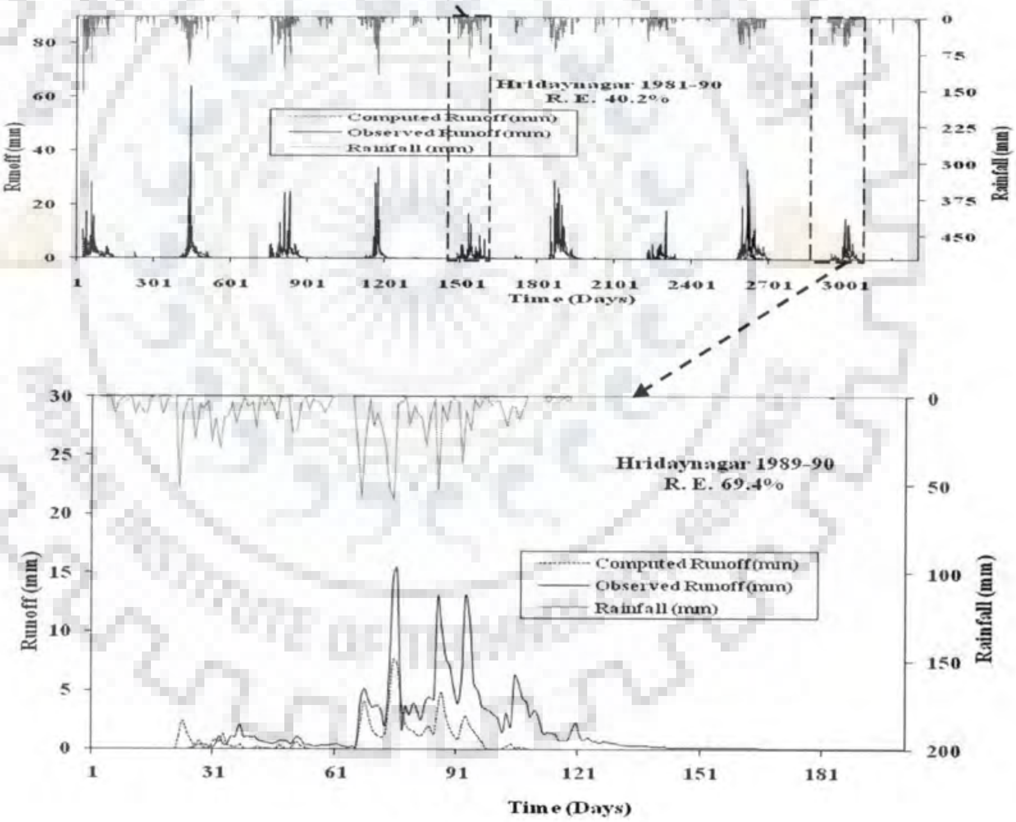


(b) Validation

Fig. 5.19 (a, b) Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) Showing Very Good Performance in (a) Calibration and (b) Validation of LTHS ASMA II Model on Kokkarne (Wet) Watershed (Day 1 represents June 1)



(a) Calibration



(b) Validation

Fig. 5.20 (a, b) **Daily Variation of Rainfall, Observed Runoff, Computed Runoff, and RE (%) Showing Poor Performance in (a) Calibration and (b) Validation of LTHS ASMA II Model on Hridaynagar (Dry) Watershed (Day 1 represents June 1)**

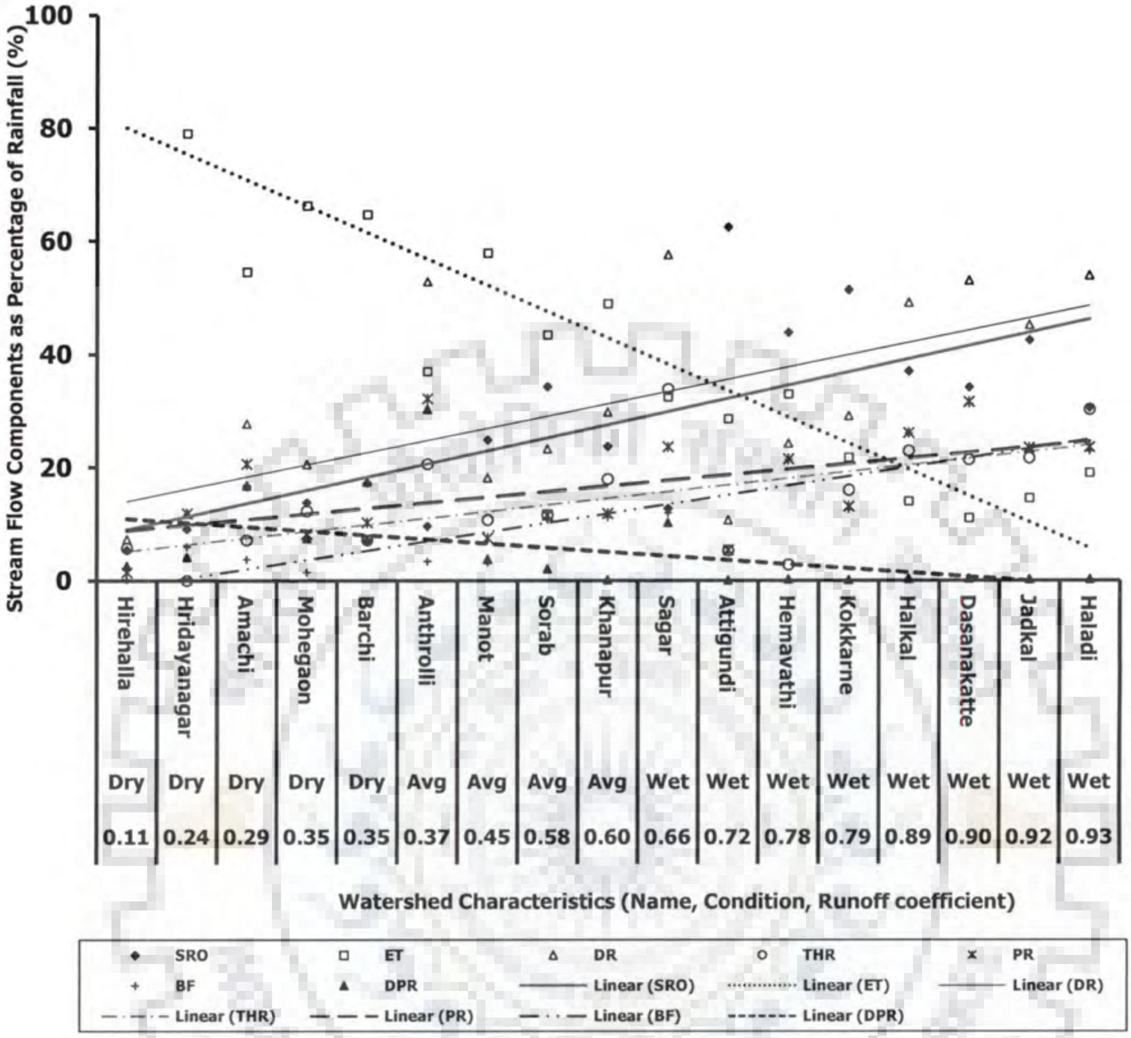


Fig. 5.21 Trend Analysis of Average Annual Variation in Various Stream Flow Generating Components of LTHS ASMA II Model

Table 5.20 Percent Estimates of Hydrological Components of LTHS ASMA II Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)								
		Rainfall (%)	Surface Runoff	Evapotran-spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	43.8	33.0	24.3	2.7	21.5	21.3	0.2	67.8	77.9
2.	Hridaynagar	100	9.0	79.0	11.9	0.0	11.9	6.0	4.2	15.1	24.3
3.	Mohegaon	100	13.8	66.2	20.5	12.3	8.2	1.4	7.5	27.5	34.7
4.	Manot	100	24.9	57.9	18.2	10.7	7.5	3.3	3.8	38.8	44.2
5.	Amachi	100	7.2	61.5	32.7	6.5	26.2	11.3	14.5	25.0	28.7
6.	Anthrolli	100	9.6	37.0	52.8	20.6	32.2	3.4	30.3	33.6	36.6
7.	Attigundi	100	27.2	27.5	47.7	11.3	36.4	34.6	0.7	73.2	71.6
8.	Barchi	100	11.7	71.6	15.8	5.5	10.3	6.7	6.7	24.0	35.1
9.	Khanapur	100	23.7	48.9	29.8	17.9	11.9	11.2	0.1	52.9	59.4
10.	Hirehalla	100	5.4	102.7	7.3	5.8	1.5	0.2	2.6	11.3	11.2
11.	Sagar	100	12.7	32.5	57.6	33.9	23.7	11.9	10.3	58.5	65.5
12.	Sorab	100	34.3	43.4	23.2	11.6	11.6	10.8	2.1	56.7	58.4
13.	Dasanakatte	100	34.2	11.1	53.0	21.4	31.6	31.2	0.3	86.8	90.0
14.	Haladi	100	30.6	19.0	53.9	30.3	23.6	22.9	0.2	83.7	93.0
15.	Jadkal	100	42.4	14.6	45.2	21.6	23.5	23.3	0.2	87.3	92.5
16.	Kokkarne	100	51.3	21.8	29.1	16.0	13.2	12.6	0.1	79.9	79.2
17.	Halkal	100	37.0	14.1	49.1	22.9	26.2	26.0	0.3	85.9	88.3

5.6.2 Application of Model-IV on Seasonal Data

Model-IV is also tested on monsoon period data (June to November) of study watersheds. The model is calibrated and validated using the daily rainfall and flow data for monsoon periods as for earlier LTHS models (Table 4.1). As already mentioned, the initial conditions of the soil retention capacity are computed on the assumption that the curve number on the first day of each year (1st June) is equal to the optimized value of CN_0; a different set of optimal values of parameters is obtained as given in Table 5.21. The performance of model using seasonal data series is presented in terms of NSE and absolute RE (percent) values in calibration and validation are given in Table 5.8. From Table 5.8, the model yields the maximum NSE of 0.87 and 0.88, respectively, in calibration and validation for Hemavathi watershed, while the minimum efficiency of 0.54 in calibration is found for Amachi watershed (excluding Hirehalla watershed) and 0.33 in validation for Anthrolli watershed. Fig. 5.8 shows plot of runoff coefficient (seasonal) of different watersheds in ascending order of NSE values. The results obtained using seasonal data shows similar trend as for annual data; NSE increases with watershed wetness. But the model efficiency is better for annual data series than for seasonal data series (Fig. 5.22) as in earlier models.

Similarly, this model is also evaluated for errors based on absolute RE values obtained in calibration and validation using seasonal data as in Table 5.8. The value of RE is seen to go up to 4.6 % in calibration for all high yielding watersheds which can be termed as very good model response to simulate the total stream flow, while the value of RE in case of dry watersheds varies from 0.4 to 11.6% yielding a very good to good response as recommended by Donigian et al., (1983) and Harmel et al., (2006). The results are also encouraging for validation using seasonal data (Table 5.8). The model performance is satisfactory when tested with the seasonal data of all watersheds under average condition. The annual simulated runoff and computed values of RE for each year is also analyzed and presented in Table 5.9 and Appendix D. The trend analysis presented in Fig. 5.10 for seasonal average values of absolute RE indicates the reverse trend of RE with watershed wetness, as earlier. The annual average values of the process components in terms of percentage of rainfall of various runoff generating components are also estimated and presented in Table 5.22. Similar results are obtained as for the model application to annual data series.

Table 5.21 Optimized Values of Parameters of LTHS ASMA II Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	δ	α	β	γ	K	P_1	P_3	P_4	θ_w	ψ_f	E_s	ψ_0	CNd_0	λ_d
1.	Hemavathi	30.4	0.45	0.36	0.18	0.43	1.35	0.01	0.09	0.99	40.0	341.3	0.31	300.1	34.2	0.02
2.	Hridaynagar	28.0	0.01	0.51	0.01	0.48	1.29	0.05	0.00	0.65	298.0	492.6	0.23	261.2	49.9	0.01
3.	Mohegaon	30.5	1.99	0.48	0.01	0.51	2.00	0.01	0.60	0.34	119.7	398.7	0.24	441.8	47.9	0.05
4.	Manot	30.1	3.80	0.37	0.01	0.48	3.80	0.02	0.60	0.38	250.5	368.7	0.36	375.8	47.3	0.47
5.	Amachi	11.3	6.19	0.41	0.01	0.42	2.16	0.01	0.21	0.48	101.9	318.4	0.35	162.3	36.1	0.01
6.	Anthrolli	33.6	0.12	0.54	0.15	0.57	0.68	0.02	0.46	0.28	179.5	364.3	0.45	364.5	58.8	0.04
7.	Attigundi	30.0	0.01	0.77	0.13	0.86	2.50	0.05	0.10	0.99	100.7	400.0	0.42	234.5	49.23	0.08
8.	Barchi	30.8	0.50	0.51	0.01	0.53	2.00	0.01	0.26	0.43	140.0	280.0	0.29	430.2	50.9	0.06
9.	Khanapur	12.9	0.10	0.48	0.08	0.55	1.97	0.09	0.43	0.99	180.0	405.0	0.45	198.0	31.2	0.09
10.	Hirehalla	24.8	0.01	0.53	0.05	0.56	3.36	0.09	0.75	0.10	133.4	300.0	0.37	434.6	42.2	0.04
11.	Sagar	49.8	0.10	0.46	0.01	0.57	1.58	0.04	0.57	0.69	145.1	260.6	0.10	417.2	57.5	0.08
12.	Sorab	54.4	0.10	0.51	0.01	0.60	1.27	0.02	0.54	0.99	104.2	360.6	0.30	448.9	58.3	0.06
13.	Dasanakatte	16.1	0.10	0.49	0.17	0.52	0.97	0.01	0.47	0.99	122.8	299.9	0.30	200.1	24.5	0.07
14.	Haladi	20.9	0.01	0.46	0.03	0.52	3.87	0.02	0.57	0.99	160.0	350.0	0.35	200.0	40.3	0.08
15.	Jadkal	35.6	0.10	0.48	0.28	0.51	1.16	0.09	0.56	0.99	160.0	354.9	0.36	340.9	45.7	0.01
16.	Kokkarne	21.0	0.01	0.52	0.16	0.54	2.07	0.01	0.54	0.90	180.0	407.8	0.35	228.0	31.7	0.02
17.	Halkal	19.6	0.99	0.53	0.10	0.62	2.54	0.01	0.56	0.99	180.0	300.0	0.33	200.0	30.9	0.23

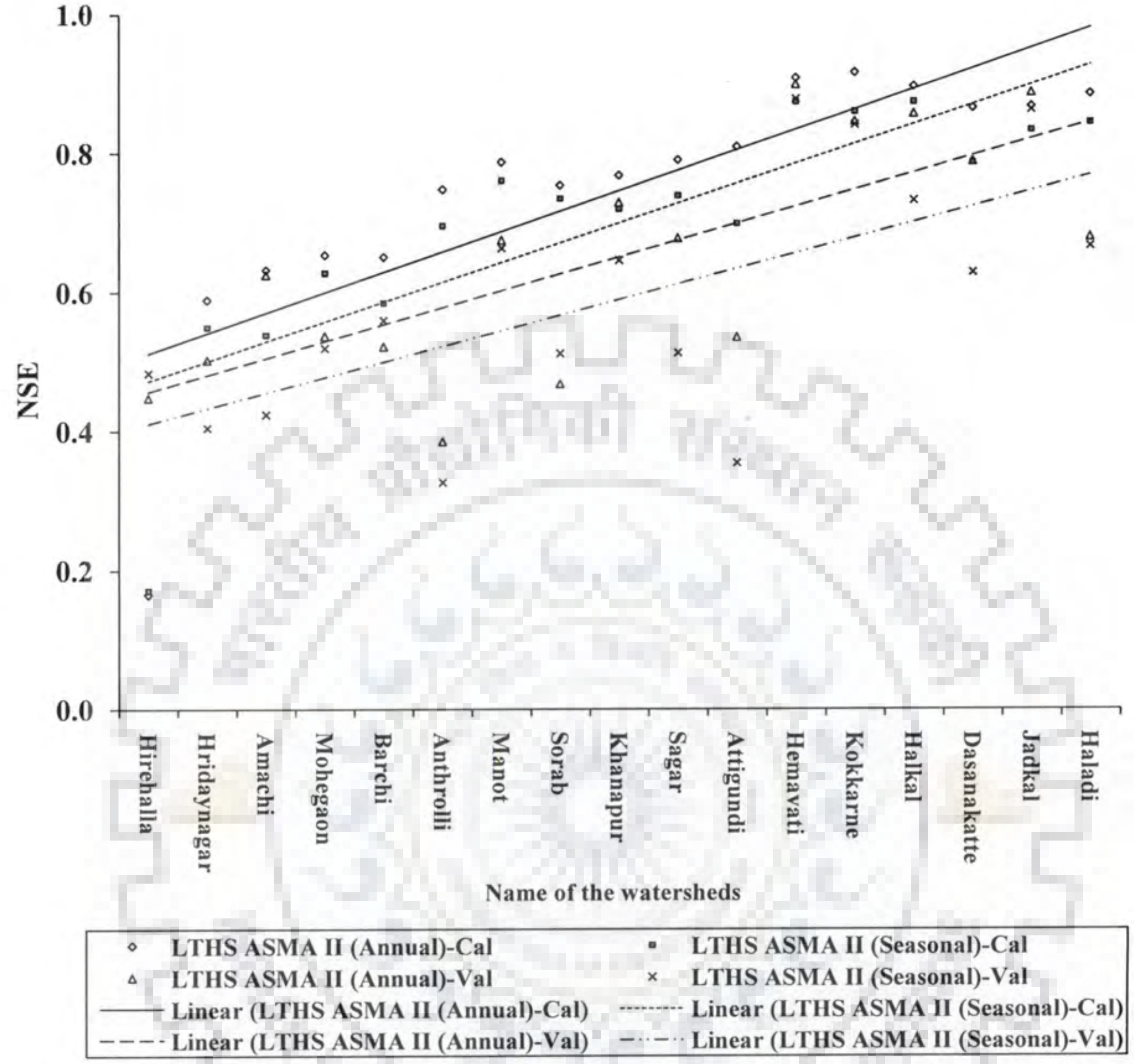


Fig. 5.22 Comparative Performance of LTHS ASMA II Model on Annual and Seasonal Data of Study Watersheds

Table 5.22 Percent Estimates of Hydrological Components of LTHS ASMA II Model using Seasonal Data of Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotran -spiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	49.3	24.7	26.9	2.4	24.5	24.0	0.2	75.8	80.9
2.	Hridaynagar	100	9.6	78.7	11.8	0.0	11.8	6.5	3.4	16.1	25.9
3.	Mohegaon	100	12.7	62.8	24.9	14.9	10.0	3.6	6.8	31.1	36.9
4.	Manot	100	25.8	50.9	22.9	13.7	9.1	3.5	5.7	43.0	47.0
5.	Amachi	100	4.5	53.9	42.8	9.1	33.7	15.7	16.9	29.2	30.7
6.	Anthrolli	100	11.8	51.0	37.6	17.2	20.4	5.8	14.6	34.8	40.6
7.	Attigundi	100	22.4	28.0	52.3	5.3	47.1	45.5	0.5	73.1	77.6
8.	Barchi	100	12.3	52.7	31.4	8.2	23.2	10.9	14.6	31.5	36.3
9.	Khanapur	100	18.7	49.7	33.4	16.3	17.1	16.3	0.2	51.3	61.6
10.	Hirehalla	100	8.2	95.0	6.3	4.7	1.6	0.6	5.5	13.5	13.1
11.	Sagar	100	32.0	38.1	29.9	16.9	13.0	9.9	4.4	58.8	66.5
12.	Sorab	100	31.0	42.4	26.1	14.0	12.1	13.2	0.1	58.2	63.4
13.	Dasanakatte	100	27.6	19.5	54.0	25.3	28.7	28.7	0.3	81.6	88.8
14.	Haladi	100	22.4	20.2	59.4	33.7	25.7	25.5	0.3	81.5	84.4
15.	Jadkal	100	43.2	13.0	45.4	25.3	20.2	20.0	0.2	88.4	93.0
16.	Kokkarne	100	31.0	21.5	46.9	25.4	21.4	18.9	2.1	75.4	80.3
17.	Halkal	100	36.9	17.1	47.0	26.2	20.8	20.6	0.2	83.7	89.6

5.7 INTER-COMPARISON OF THE PROPOSED MODELS

The results of all proposed (four) LTHS models detailed in the previous sections are compared for their relative performance based on various performance indicators in terms of NSE and RE. Table 5.4 and Table 5.9 show the values of NSE and RE for all the proposed LTHS models both for calibration and validation using annual and seasonal data series of study watersheds. The comparative evaluation of the proposed models is also carried out based on statistics of RMSE and SE. Since SE is a better goodness-of-fit measure compared to RMSE as stated earlier hence SE is considered only in the present analysis of inter-comparison of the proposed LTHS models. The SE values obtained for all the proposed LTHS models using annual and seasonal data series of study watersheds is presented in Table 5.23.

A close scrutiny of values of NSE listed in Table 5.4 reveals that Model-IV (LTHS ASMA II) yields highest range of NSE (0.79, 0.92) in calibration for all high yielding watersheds indicating very good response to simulate stream flow followed by Model-III (NSE varies from 0.76 to 0.90 for LTHS ASMA I) as in Fig. 5.1. The NSE values for other models vary from 0.71 to 0.90 and 0.70 to 0.88 in calibration of Model-II and Model-I, respectively, indicating satisfactory to very good performance of the models. The maximum NSE of 0.92 in calibration is observed for Model-IV using annual data of Kokkarne watershed (coastal wet watershed) followed by Model-III and Model-II (NSE of 0.90 for Hemavathi watershed). The maximum NSE of 0.90 in validation is observed for the Model-IV using annual data of Hemavathi watershed (wet watershed) followed by 0.89 for the Model-II. The minimum NSE of 0.52 in calibration and 0.34 in validation is observed for Model-I using annual data of Hridaynagar (dry watershed) and Anthrolli (average watershed) watershed, respectively, excluding the most dry watershed, Hirehalla for which the NSE value is very low (NSE = -0.001).

It is evident from the scatter plot of NSE (Fig. 5.23) derived for calibration and validation of proposed LTHS models using annual data series of study watersheds and further trend analysis as shown in Figs. (5.2, 5.8), the proposed Model-IV performed better than other models. The best fit of line drawn for LTHS ASMA II model (Figs. (5.2 and 5.8)), is found on the higher side of the ordinate of NSE followed by LTHS ASMA I and LTHS MICHEL II

Table 5.23 SE Values Obtained in Calibration and Validation of the Proposed LTHS Models on Study Watersheds

Sr. No.	Name of Watershed	SE Value															
		Annual Data								Seasonal Data							
		Calibration				Validation				Calibration				Validation			
		M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV	M-I	M-II	M-III	M-IV
1.	Haladi	6.44	6.18	6.07	5.81	9.63	9.99	9.81	9.33	8.83	8.68	8.42	8.01	13.12	13.45	13.32	11.40
2.	Jadkal	9.53	9.17	8.94	8.48	8.63	9.29	9.13	8.53	12.97	12.92	12.75	11.72	12.02	12.80	11.94	11.12
3.	Dasanakatte	7.89	7.84	7.39	6.72	10.63	11.01	10.69	10.25	11.07	10.87	10.50	10.21	14.73	16.42	15.37	16.31
4.	Halkal	7.15	6.99	6.70	6.55	11.99	11.29	11.15	10.63	9.95	9.99	9.64	8.72	16.70	16.27	15.92	17.61
5.	Kokkarne	7.10	7.00	6.76	5.63	8.51	8.95	8.42	8.94	10.00	9.94	9.83	8.94	11.89	12.26	11.99	10.99
6.	Hemavathi	3.55	3.10	3.08	3.02	11.05	5.93	5.73	5.75	4.54	3.43	4.34	4.33	16.56	7.93	7.70	7.78
7.	Attigundi	2.41	2.19	2.21	2.14	5.12	5.01	5.02	5.02	3.33	3.27	2.95	2.85	7.02	7.01	6.96	6.87
8.	Sagar	3.62	3.58	3.26	3.04	4.31	4.48	3.80	3.68	5.23	5.19	4.50	4.45	6.10	5.80	5.25	5.24
9.	Khanapur	5.99	5.56	5.37	5.57	9.88	9.90	9.67	9.44	8.11	8.05	8.07	7.82	13.82	13.62	14.02	13.53
10.	Sorab	3.22	2.83	2.74	2.66	3.53	3.57	3.65	4.03	4.53	4.02	3.92	3.73	4.86	4.78	4.77	4.78
11.	Manot	2.66	2.48	2.39	2.08	4.09	4.02	3.75	3.43	3.53	3.43	3.39	2.97	5.55	5.52	5.52	4.78
12.	Anthrolli	1.31	1.17	1.13	1.04	2.36	2.28	2.07	2.28	1.68	1.62	1.58	1.53	3.08	2.96	2.83	2.97
13.	Mohegaon	3.08	2.91	2.88	2.68	2.81	2.71	2.71	2.59	4.18	4.15	4.08	3.82	3.90	3.87	3.84	3.59
14.	Barchi	2.38	2.28	2.22	2.14	2.27	2.35	2.37	2.55	2.64	3.25	3.21	2.95	3.71	3.24	3.22	3.43
15.	Amachi	1.64	1.50	1.49	1.48	2.66	2.22	2.56	2.08	2.42	2.19	2.11	2.09	3.55	3.33	3.67	3.24
16.	Hridaynagar	1.88	1.91	1.83	1.81	2.40	2.24	2.24	2.20	2.76	2.63	2.59	2.58	3.30	3.11	3.03	3.21
17.	Hirehalla	0.83	0.80	0.79	0.79	1.55	1.24	1.23	1.15	1.12	1.05	1.04	1.05	2.18	1.70	1.70	1.56

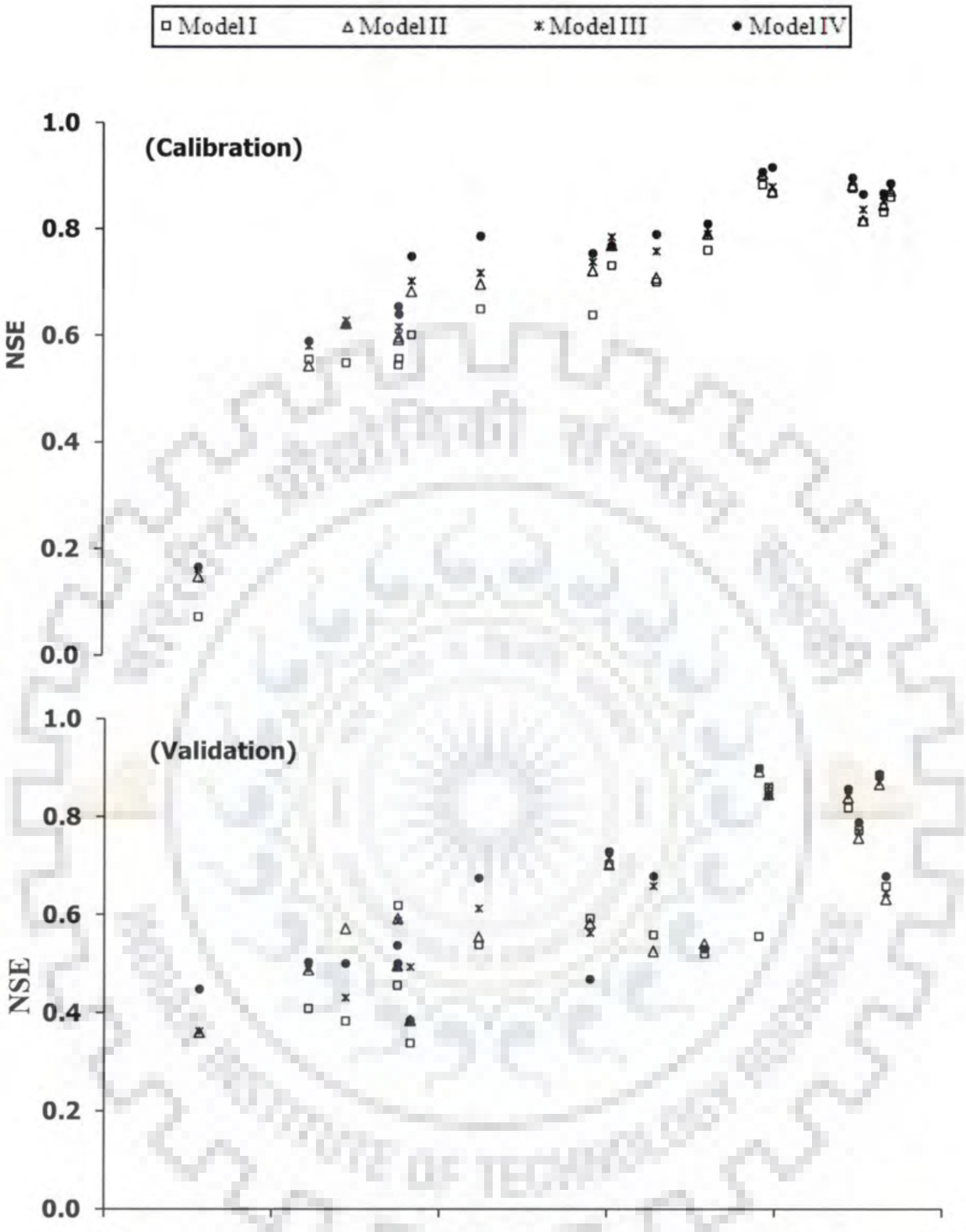


Fig. 5. 23 Scatter Plots of NSE Obtained for the Proposed LTHS Models

indicating the better efficiency and in turn, the better performance of LTHS ASMA II model followed by LTHS ASMA I, LTHS MICHEL II and LTHS MICHEL I. It is also evident from the range of NSE values obtained for the proposed models (Table 5.24) that the performance of Model-IV is better than other proposed models. Similar inferences are also drawn from the application of models using seasonal data series.

Table 5.24 Comparison of the Proposed LTHS Models

Sr. No.	Proposed LTHS Model	Performance Indicator						Rank
		NS Efficiency		SE (mm)		Absolute RE (%)		
		Cal	Val	Cal	Val	Cal	Val	
1.	LTHS MICHEL I	0.07-0.88	(-0.001)-0.88	0.83-9.53	1.55-12.06	0.2-68.8	1.6-57.1	4
2.	LTHS MICHEL II	0.15-0.90	0.36-0.89	0.80-9.17	1.24-11.20	0.1-16.2	0.8-54.3	3
3.	LTHS ASMA I	0.16-0.90	0.36-0.90	0.79-8.94	1.23-11.15	0.2-13.7	0.0-56.5	2
4.	LTHS ASMA II	0.17-0.92	0.39-0.90	0.79-8.48	1.15-10.63	0.1.13.4	0.4-55.8	1

Thus, in general, the proposed LTHS models in the present study yield high efficiency for wet (high yielding) watersheds and lower for dry (low yielding) watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry watershed (based on average runoff coefficient) of Hirehalla. However, the results obtained using LTHS ASMA II model are better than LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models for study watersheds in both calibration and validation, and therefore, LTHS ASMA II (Model-IV) is evaluated best model among the proposed LTHS models. Better performance of Model-IV may be attributed to the improvement/advancement in the SMA procedure and the proposed modification in the formulation of the sub-surface flow components.

Similar to NSE, the comparative evaluation of proposed models based on SE values obtained for annual and seasonal data series of study watersheds is also performed and shown in Figs. 5.24 (a, b). As seen from Figs. 5.24 (a, b), SE decreases from LTHS MICHEL I to

LTHS MICHEL II, and to LTHS ASMA I, and further to LTHS ASMA II in calibration indicating performance as: Model-I < Model-II < Model-III < Model-IV. This can also be seen from the Table 5.24 showing the range of SE for proposed LTHS models obtained in calibration and validation of annual data series. The values of SE range (0.83, 9.53), (0.80, 9.17), (0.79, 8.94), and (0.79, 8.48) in calibration and (1.55, 12.06), (1.24, 11.20), (1.23, 11.15), and (1.15, 10.63) in validation of LTHS MICHEL I, LTHS MICHEL II, LTHS ASMA I and LTHS ASMA II models, respectively. The scatter plots of SE and runoff coefficient for calibration and validation of the proposed LTHS models (Fig. 5.25) shows that the values of SE for LTHS ASMA II model are on the lower side of ordinate of SE for most study watersheds followed by LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models. It indicates that the LTHS ASMA II model gives a better fit between the observed and computed runoff than LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models. The plot of mean values of SE for these models in calibration and validation using annual and seasonal data series are shown in Fig. 5.26 which also gives lower values of SE and shows the performance order as: LTHS ASMA II> LTHS ASMA I> LTHS MICHEL II> LTHS MICHEL I models.

The inter-comparison of proposed models is further evaluated using the percent relative error criteria (Table 5.4). As seen from Table 5.4, the LTHS ASMA II model yields absolute RE values in the range (0.3, 4.9) % for all coastal high yielding watersheds in calibration which indicates a very good model performance (Donigian et al., 1983; Harmel et al., 2006). The range of absolute RE for model LTHS ASMA I (2.6, 11.4) % and LTHS MICHEL II (0.1, 13.22) % in calibration of wet watersheds shows the performance of these models as good to very good (absolute RE<15%). The range of absolute RE (0.6, 18.5) % in case of LTHS MICHEL I model indicates its performance as very good to fair (absolute RE<25%). Similarly, for dry watersheds, RE ranges (5.4 to 13.4)% and (2.0 to 13.7)%, for LTHS ASMA II and LTHS ASMA I, respectively, indicating good to very good performance on dry watersheds. But the performance based on absolute RE is very good to fair (Donigian et al., 1983; Harmel et al., 2006) in case of LTHS MICHEL II (RE range (6.0 to 15.3) %) and LTHS MICHEL I (absolute RE range (0.2, 21.8) %, excluding Hirehalla watershed) models. The performance of LTHS MICHEL I model for most dry Hirehalla watershed is unsatisfactory (absolute RE>25%). Overall range of absolute RE values in calibration and

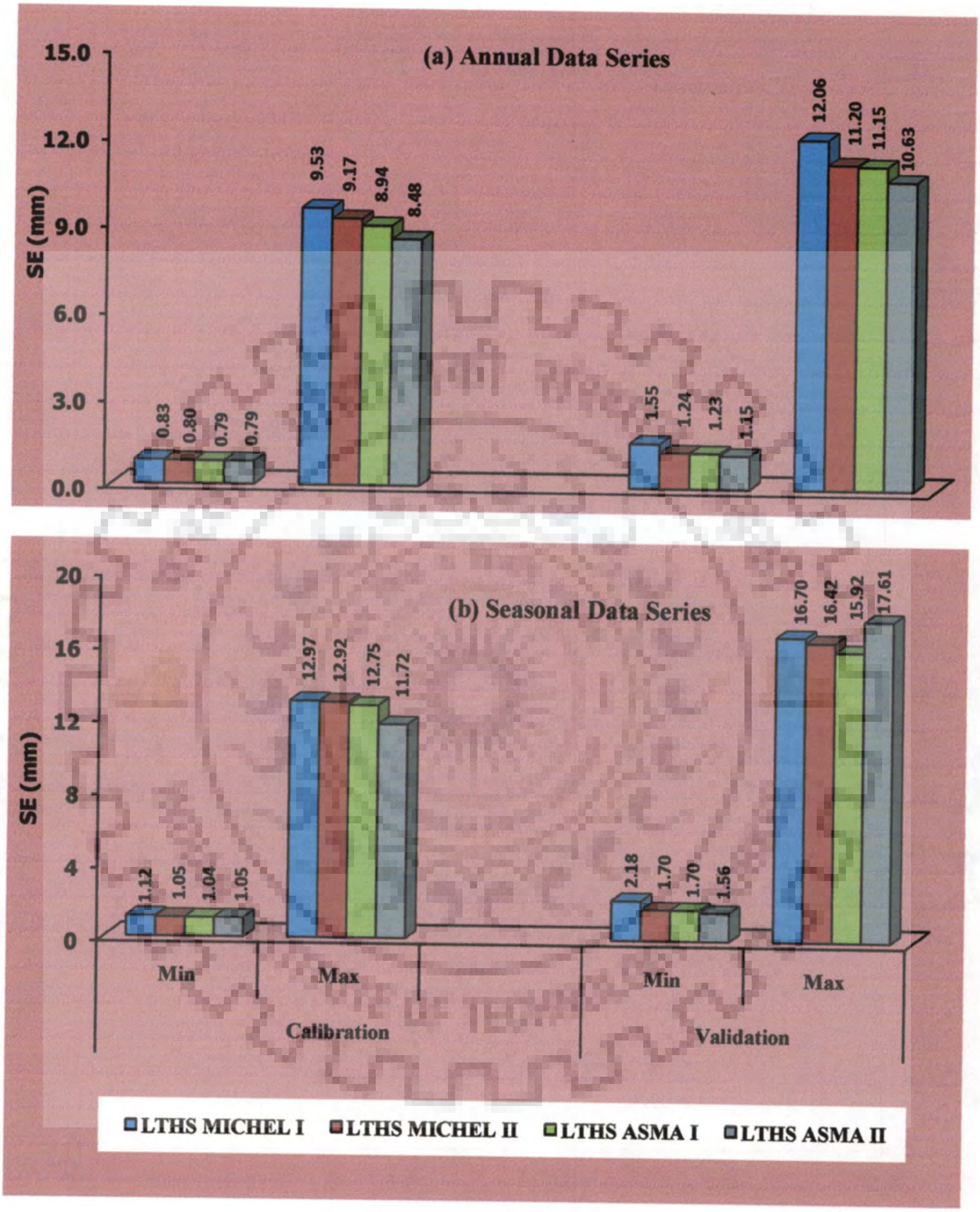


Figure 5.24 Range of SE Obtained in Calibration and Validation of the Proposed LTHS Models on (a) Annual Data and (b) Seasonal Data of Study Watersheds

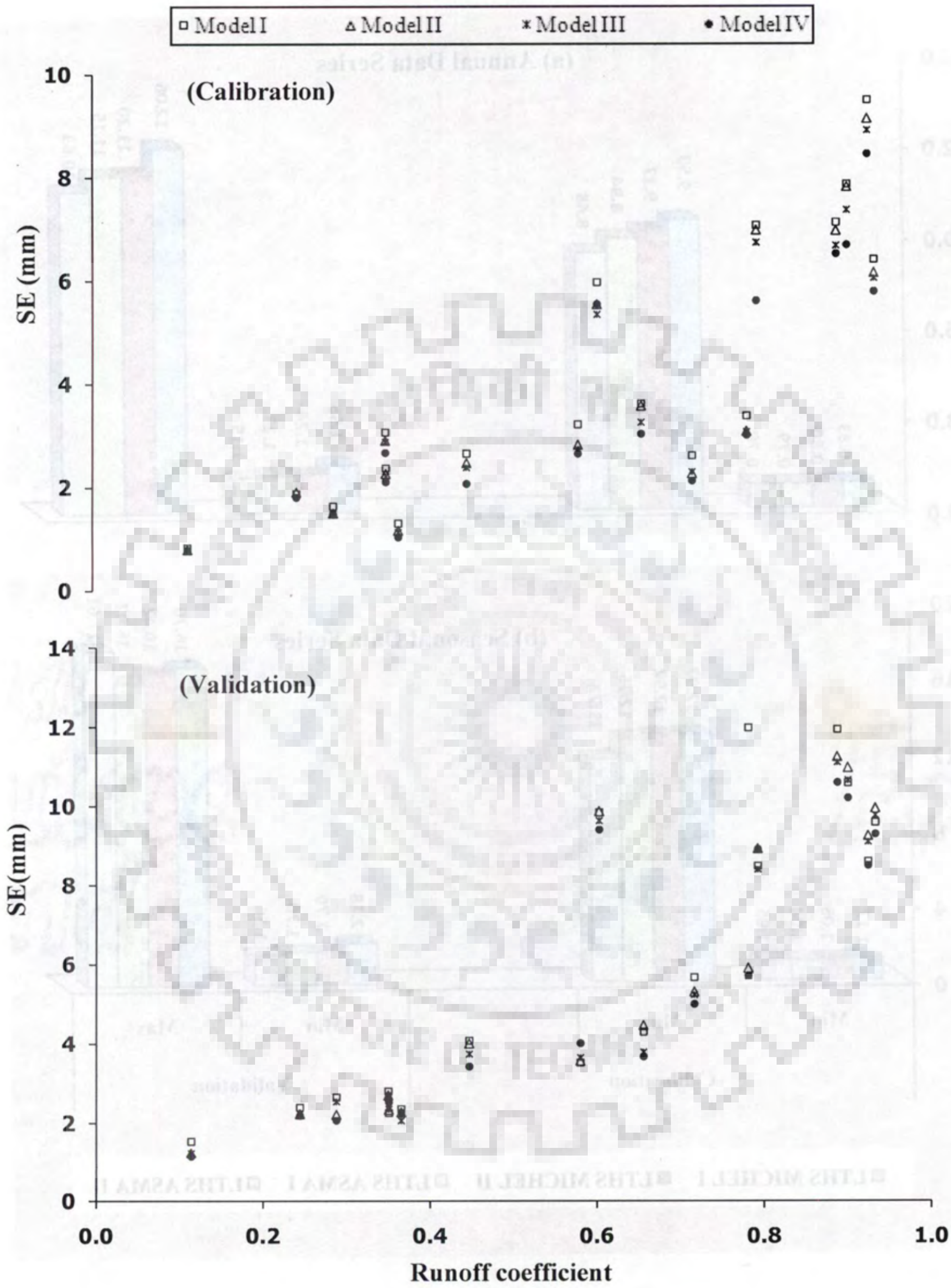


Fig. 5.25 Scatter Plots of SE Obtained for the Proposed LTHS Models

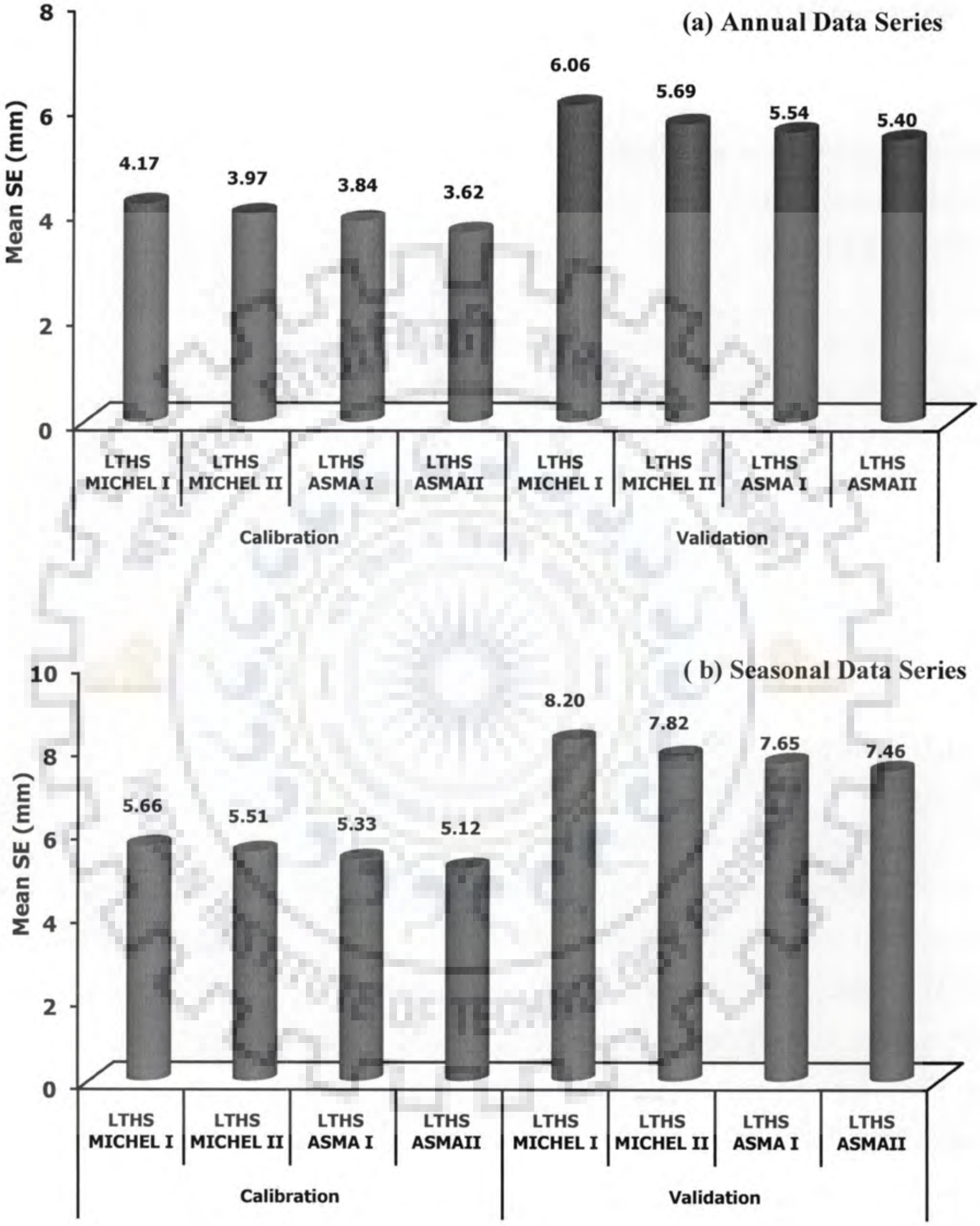


Fig. 5.26 Mean Values of SE in Calibration and Validation of the Proposed LTHS Models on (a) Annual Data and (b) Seasonal Data

validation of the proposed models using annual data series of study watersheds is presented in Table 5.24 and the rank is assigned to the proposed LTHS models based on their comparative performance in terms of various performance indicators, viz., NSE, SE, and absolute RE (%). As seen from Table 5.24, the performance of LTHS ASMA II model is better than other models on the basis of performance indicators in terms of NS efficiency, SE and RE, and therefore, ranked first in performance followed by LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I.

In brief, it can be observed from the relative performance of the proposed models based on various performance indicators that the LTHS ASMA II model, which is formulated based on the advancement in SMA procedure in Michel et al. (2005) concept for underlying SMA procedure in the SCS-CN method and SCS-CN concept based sub-surface drainage flow computation produces better results than the other proposed LTHS models ranked as, LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models.

5.8 COMPARISONS OF PROPOSED MODELS WITH EXISTING SCS-CN BASED LTHS MODELS

The performance of the proposed best model (LTHS ASMA II) is further compared with the existing LTHS model having similar model structure. Accordingly, the recently developed SCS-CN based continuous models such as generalized continuous Michel et al. (2005) sub-model and Geetha et al. (2008) lumped conceptual rainfall-runoff (LCRR) model were selected for comparison among the existing ones. The formulations for these models to compute various stream flow generating surface and sub-surface flow components (Putty and Prasad, 2000) have already been discussed in Chapter 2 (Sections 2.6.7, 2.6.8, and 2.7.1). Using those formulations, the existing models via generalized continuous Michel et al. (2005) model linked with SAHYADRI model (Putty and Prasad, 2000) for sub-surface flow components (hereafter referred as MICHEL model) and Geetha et al. (2008) model (hereafter referred as LCRR model) are also tested on annual data series of study watersheds to compare their performance with the proposed models.

The existing MICHEL model consists of 14 parameters namely, CN_0, α, β, K, P_1, P_2, P_3, P_4, θ_w, θ_f, ψ_f, E_s, E_g, and ψ_0, while LCRR model consist of 15 parameters namely, CN_0, λ_1, α, β, K, C_1, C_2, C_3, B_{COEF}, θ_w, θ_f, ψ_f, E, and ψ_0. The parameters of LCRR such as C_1, C_2, C_3, B_{COEF} are similar to parameters P_1, P_2, P_3, P_4, respectively of the proposed model. The detailed description of these parameters is given in Chapter 2 (Section 2.6.8). The estimated optimal set of parameters of MICHEL and LCRR models obtained using similar calibration scheme as for the proposed model for study watersheds are presented in Table 5.25 and Table 5.26. The performance of the existing models in terms of model efficiency (NSE) and the resulting errors in calibration and validation are presented in Table 5.27 for MICHEL model and Table 5.28 for LCRR model. The NSE values obtained in calibration and validation of the existing models and the best model (LTHS ASMA II) using annual data series are compared in Fig. 5.27 and Table 5.29. As seen from Fig. 5.27, the performance of the proposed 15- parameter LTHS ASMA II model is better than the existing 14-parameter MICHEL and 15- parameter LCRR models in calibration and validation. This indicates that the proposed model (LTHS ASMA II) exhibits an improvement over the existing SCS-CN based long term simulation models.

Table 5.25 Optimized Values of Parameters of MICHEL (Michel et al., 2005) Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter													
		CN_0	α	β	K	P_1	P_2	P_3	P_4	θ_w	θ_f	ψ_f	E_s	E_g	ψ_0
1.	Haladi	20.5	0.40	0.10	0.50	0.01	0.10	0.60	0.99	145.5	200.9	200.0	0.20	0.73	344.6
2.	Jadkal	20.5	0.30	0.17	0.50	0.01	0.10	0.60	0.99	231.2	371.8	226.9	0.14	0.52	467.3
3.	Dasanakatte	22.8	0.17	0.01	0.50	0.07	0.35	0.52	0.99	300.0	120.0	350.0	0.38	0.67	280.0
4.	Halkal	23.2	0.10	0.10	0.50	0.07	0.48	0.42	0.99	150.0	156.7	368.0	0.38	0.73	257.1
5.	Kokkarne	24.2	0.66	0.02	0.50	0.01	0.31	0.60	0.99	146.7	376.5	222.7	0.35	0.53	488.3
6.	Hemavathi	21.3	0.19	0.11	1.38	0.01	0.60	0.60	0.85	99.9	190.0	399.8	0.23	0.14	999.0
7.	Attigundi	15.0	0.13	0.01	0.50	0.03	0.98	0.30	0.80	180.0	220.0	200.1	0.39	0.58	313.7
8.	Sagar	24.7	0.10	0.02	0.50	0.05	0.86	0.23	0.99	134.1	207.4	294.8	0.40	0.36	298.9
9.	Khanapur	30.0	0.44	0.10	2.54	0.05	0.99	0.10	0.69	100.0	345.7	460.0	0.41	1.18	260.0
10.	Sorab	34.7	0.26	0.69	0.50	0.04	0.60	0.60	0.99	149.4	200.7	199.8	0.36	0.10	250.2
11.	Manot	23.6	0.25	0.10	0.50	0.02	0.10	0.10	0.81	150.0	381.7	350.7	0.90	0.87	350.0
12.	Anthrolli	26.8	0.23	0.20	0.50	0.02	0.43	0.15	0.29	109.2	244.0	280.7	0.10	0.72	265.3
13.	Barchi	19.0	0.30	0.50	0.50	0.02	0.16	0.60	0.40	159.8	187.1	250.0	0.28	0.42	350.0
14.	Mohegaon	30.7	0.49	0.10	0.50	0.02	0.10	0.10	0.32	150.0	261.0	395.8	0.31	0.78	322.6
15.	Amachi	20.0	0.55	0.43	0.50	0.01	0.53	0.60	0.53	63.7	239.0	379.2	0.20	0.31	180.2
16.	Hridaynagar	30.0	0.72	0.10	0.97	0.05	0.74	0.41	0.40	234.5	301.1	300.8	0.15	0.11	483.0
17.	Hirehalla	24.4	0.36	0.27	1.71	0.05	0.41	0.60	0.10	191.7	250.1	361.4	0.37	0.10	368.0

Table 5.26 Optimized Values of Parameters of LCRR (Geetha et al. 2008) Model using Annual Data of Study Watersheds

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	λ_1	α	β	K	C_1	C_2	C_3	BCOEF	S_{abs}	θ_w	θ_f	E	Ψ_f	ψ_0
1.	Haladi	25.5	0.551	3.50	0.10	0.93	0.05	0.99	0.12	0.99	890.9	150.0	150.0	0.35	250.0	150.0
2.	Jadkal	33.1	0.551	3.99	0.10	0.50	0.05	0.99	0.31	0.99	764.0	180.0	180.0	0.30	320.0	250.0
3.	Dasanakatte	24.3	0.551	3.50	0.01	0.50	0.05	0.99	0.20	0.99	969.6	220.0	219.2	0.37	319.8	180.0
4.	Halkal	30.0	0.551	5.50	0.10	0.75	0.05	0.99	0.30	0.99	842.6	150.0	180.0	0.36	400.0	250.0
5.	Kokkarne	26.3	0.551	5.99	0.10	0.50	0.05	0.99	0.30	0.99	962.4	180.0	228.9	0.35	493.3	250.0
6.	Hemavathi	45.0	0.001	5.00	3.19	0.93	0.03	0.04	0.09	0.93	835.8	60.0	319.4	0.49	347.8	140.0
7.	Attigundi	20.4	0.551	2.50	0.20	0.50	0.05	0.60	0.17	0.99	1142.5	120.0	180.0	0.40	312.7	150.0
8.	Sagar	52.8	0.551	3.40	0.50	0.50	0.05	0.57	0.23	0.99	442.0	100.0	166.7	0.27	135.0	150.0
9.	Khanapur	16.0	0.551	1.80	0.86	0.50	0.05	0.90	0.43	0.99	1483.5	80.0	270.6	0.40	466.5	150.0
10.	Sorab	80.0	0.151	6.99	0.40	0.50	0.05	0.99	0.16	0.99	693.9	120.0	188.7	0.22	300.0	350.0
11.	Manot	32.0	0.002	6.00	2.21	0.09	0.04	0.61	0.17	0.50	650.0	60.0	374.0	0.79	220.0	140.0
12.	Anthrolli	34.5	0.551	3.40	0.99	0.50	0.05	0.48	0.60	0.99	582.1	100.0	206.4	0.77	419.8	150.0
13.	Barchi	27.1	0.551	1.84	0.99	0.50	0.05	0.49	0.60	0.99	784.2	120.0	170.5	0.90	284.1	100.0
14.	Mohegaon	30.0	0.001	5.00	1.14	0.05	0.04	0.03	0.31	0.30	556.4	60.0	114.5	0.61	321.1	140.0
15.	Amachi	30.0	0.551	1.35	0.99	0.64	0.05	0.99	0.01	0.82	692.7	100.0	200.0	0.26	194.4	100.0
16.	Hridaynagar	30.0	0.001	6.00	2.28	1.32	0.04	0.03	0.11	0.35	877.6	60.0	461.3	0.26	173.2	140.0
17.	Hirehalla	40.8	0.651	1.50	0.01	0.50	0.05	0.99	0.54	0.50	544.0	125.0	242.6	0.50	250.0	150.0

Table 5.27 NS Efficiency and Error Statistics in Calibration and validation of MICHEL Model

Sr. No.	Watershed Characteristics			Calibration				Validation			
	Name	Area (Sq. Km.)	Runoff Coefficient	NSE	RMSE (mm)	SE (mm)	Absolute RE (%)	NSE	RMSE (mm)	SE (mm)	Absolute RE (%)
1.	Haladi	505.0	0.93	0.86	6.44	6.46	14.29	0.72	8.70	8.74	13.12
2.	Jadkal	90.0	0.92	0.84	9.35	9.38	17.81	0.89	8.55	8.59	10.37
3.	Dasanakatte	135.0	0.90	0.78	8.46	8.49	1.60	0.81	9.77	9.81	4.50
4.	Halkal	108.0	0.89	0.83	8.40	8.43	9.40	0.80	12.45	12.51	12.97
5.	Kokkarne	343.0	0.79	0.88	6.83	6.85	6.27	0.88	7.83	7.87	3.89
6.	Hemavathi	600.0	0.78	0.86	3.69	3.72	5.22	0.83	7.36	7.42	16.31
7.	Attigundi	4.51	0.72	0.79	2.23	2.24	9.42	0.56	4.83	4.85	8.44
8.	Sagar	75.0	0.66	0.73	3.46	3.47	12.58	0.61	4.05	4.07	22.18
9.	Khanapur	320.0	0.60	0.73	6.03	6.06	0.89	0.67	10.42	10.47	27.65
10.	Sorab	96.0	0.58	0.70	2.95	2.96	11.06	0.63	3.33	3.35	8.05
11.	Manot	4661.0	0.45	0.72	2.39	2.40	5.85	0.58	3.86	3.88	21.50
12.	Anthrolli	503.0	0.37	0.71	1.11	1.11	2.96	0.56	1.92	1.93	18.79
13.	Barchi	14.5	0.35	0.57	2.35	2.36	7.55	0.64	2.20	2.22	12.52
14.	Mohegaon	5032.0	0.35	0.55	3.05	3.07	6.81	0.50	2.67	2.68	14.12
15.	Amachi	87.0	0.29	0.60	1.55	1.55	2.74	0.50	2.39	2.40	22.74
16.	Hridayanagar	3370.0	0.24	0.53	1.92	1.93	6.67	0.47	2.27	2.28	51.21
17.	Hirehalla	1296.0	0.11	0.04	0.85	0.85	59.50	0.03	1.52	1.53	53.43

Table 5.28 NS Efficiency and Error Statistics in Calibration and Validation of LCRR Model

Sr. No.	Watershed Characteristics			Calibration				Validation			
	Name	Area (Sq. Km.)	Runoff Coefficient	NSE	RMSE (mm)	SE (mm)	Absolute RE (%)	NSE	RMSE (mm)	SE (mm)	Absolute RE (%)
1.	Haladi	505.0	0.93	0.87	6.13	6.15	4.23	0.67	9.38	9.43	3.80
2.	Jadkal	90.0	0.92	0.85	8.92	8.95	4.54	0.87	9.12	9.16	1.35
3.	Dasanakatte	135.0	0.90	0.84	7.43	7.37	1.14	0.79	10.27	10.32	5.76
4.	Halkal	108.0	0.89	0.88	6.99	7.01	3.13	0.84	11.25	11.30	5.63
5.	Kokkarne	343.0	0.79	0.87	6.97	7.00	0.17	0.88	8.00	8.04	2.04
6.	Hemavathi	600.0	0.78	0.88	4.08	4.10	1.73	0.89	6.25	6.30	7.09
7.	Attigundi	4.51	0.72	0.78	2.27	2.28	18.35	0.53	5.00	5.02	13.49
8.	Sagar	75.0	0.66	0.76	3.25	3.26	4.13	0.64	3.88	3.90	32.64
9.	Khanapur	320.0	0.60	0.77	5.52	5.55	1.36	0.71	9.69	9.74	29.74
10.	Sorab	96.0	0.58	0.68	3.01	3.03	8.32	0.55	3.68	3.70	0.84
11.	Manot	4661.0	0.45	0.74	2.93	2.93	6.58	0.64	3.84	3.86	15.37
12.	Anthrolli	503.0	0.37	0.70	1.12	1.12	24.90	0.21	2.57	2.58	20.22
13.	Barchi	14.5	0.35	0.57	2.33	2.35	6.05	0.59	2.34	2.36	0.42
14.	Mohegaon	5032.0	0.35	0.69	2.56	2.57	20.19	0.53	2.71	2.72	12.66
15.	Amachi	87.0	0.29	0.61	1.53	1.53	2.86	0.53	2.32	2.33	1.08
16.	Hridayanagar	3370.0	0.24	0.60	1.96	1.96	20.60	0.52	2.06	2.07	47.06
17.	Hirehalla	1296.0	0.11	0.12	0.81	0.81	55.21	0.35	1.24	1.24	48.20

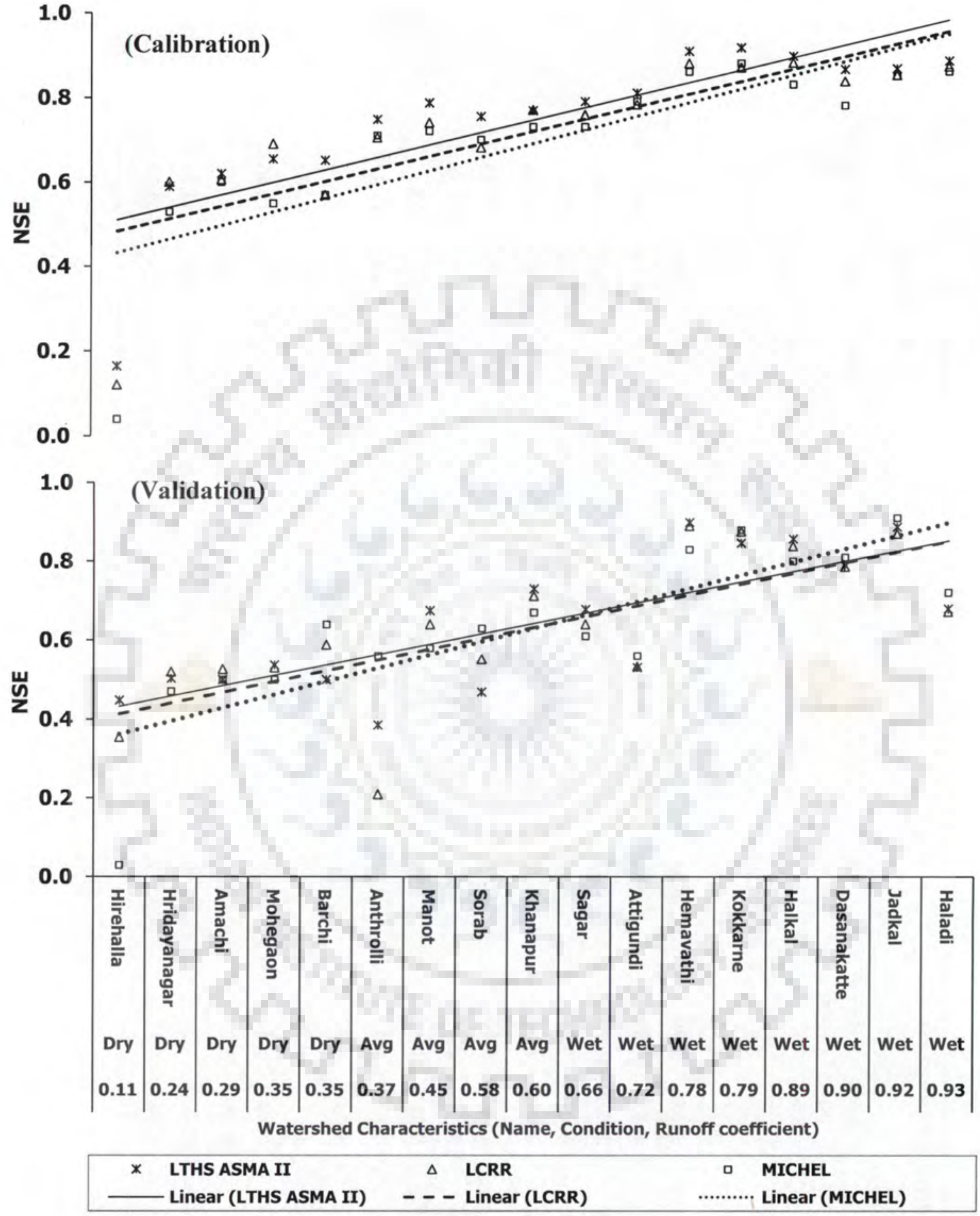


Fig. 5.27 Comparative Performance in terms of NSE between Existing and Proposed LTHS ASMA II Model on Annual Data of Study Watersheds

Table 5.29 Comparisons between Existing and Proposed SCS-CN-Based LTHS Models

Watershed Characteristics			Data Length (Annual data) (Years)		NS Efficiency					
Name	Area (Sq. Km.)	Runoff Coefficient			Calibration			Validation		
			Cal	Val	MICHEL	LCRR	LTHS ASMA II	MICHEL	LCRR	LTHS ASMA II
Haladi	505.00	0.93	5	4	0.86	0.87	0.89	0.72	0.67	0.68
Jadkal	90.00	0.92	5	4	0.84	0.85	0.87	0.89	0.87	0.89
Dasanakatte	135.00	0.90	5	4	0.78	0.84	0.86	0.81	0.79	0.79
Halkal	108.00	0.89	5	4	0.83	0.88	0.90	0.80	0.84	0.86
Kokkarne	343.00	0.79	5	4	0.88	0.87	0.92	0.88	0.88	0.85
Hemavathi	600.00	0.78	3	2	0.86	0.88	0.91	0.83	0.89	0.90
Attigundi	4.51	0.72	5	4	0.79	0.78	0.81	0.56	0.53	0.53
Sagar	75.00	0.66	5	4	0.73	0.76	0.79	0.61	0.64	0.68
Khanapur	320.00	0.60	5	4	0.73	0.77	0.77	0.67	0.71	0.73
Sorab	96.00	0.58	5	4	0.70	0.68	0.75	0.63	0.55	0.47
Manot	4661.00	0.45	5	4	0.72	0.74	0.79	0.58	0.64	0.67
Anthrolli	503.00	0.37	5	4	0.71	0.70	0.75	0.56	0.21	0.38
Barchi	14.50	0.35	3	2	0.57	0.57	0.65	0.64	0.59	0.61
Mohegaon	5032.00	0.35	5	4	0.55	0.69	0.65	0.50	0.53	0.54
Amachi	87.00	0.29	5	4	0.60	0.61	0.62	0.50	0.53	0.50
Hridayanagar	3370.00	0.24	5	4	0.53	0.60	0.59	0.47	0.52	0.50
Hirehalla	1296.00	0.11	5	4	0.04	0.12	0.17	0.03	0.35	0.45

5.9 REMARKS

This chapter discussed the results obtained for four different conceptual long term hydrologic simulation models when applied to the daily rainfall and stream flow data of selected watersheds from different agro-climatic zones of India. The proposed models in the present study are developed based on the SCS-CN concept incorporating various sets of SMA procedure and applied with two different sets of daily hydrologic data sets, annual data and seasonal (monsoon) data. The performance of these models has been evaluated in terms of watershed response and stream flow generation based on NS efficiency and relative error criteria. It is observed from the results that the performance of the developed LTHS models is very good on wet watersheds and good to satisfactory on dry watersheds and poor on most dry (Hirehalla) watershed. The rank assigned to the developed models based on their comparative performance in terms of various performance indicators, viz., NSE, SE, and absolute RE (%) shows that the LTHS ASMA II is better than the LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models. The best LTHS ASMA II model among the proposed models also performs better than the existing best lumped continuous SCS-CN-based models indicating the improvement over the existing models.

Apart from the above, the proposed models were used to estimate the various stream flow generating components to identify the dormant and dominant components of the hydrologic cycle of the studied watersheds. The surface runoff is prominant in most study watersheds and more significant in wet watersheds than lateral flow and base flow. The base flow is more significant in high runoff producing wet watersheds than low runoff producing dry watersheds. All other components, except losses, show linearly increasing trends with runoff coefficient while losses show reverse trends.

CHAPTER 6

SENSITIVITY ANALYSIS AND MODEL SIMPLIFICATION

6.1 GENERAL

The proposed LTHS models based on different SMA procedures for long term simulation of stream flow described in earlier chapters have certain number of parameters. These parameters were estimated by using non-linear Marquardt (1963) algorithm coupled with trial and error, utilizing the objective function of minimizing errors between the computed and observed stream flow as described in the previous chapters. But it is difficult to find the interaction between the parameters of the model and various processes being considered. According to Dawdy (1969), a large amount of information about model parameters can be derived using sensitivity analysis, besides model simplification (Breierova and Choudhari, 1996). It is well accepted that if a model requires determination of many parameters, its applicability is limited for field applications. Hence, there is a need to have the model containing fewer parameters, require minimum data input, and are able to describe fairly accurately the component processes involved, such as transpiration, drainage, percolation including deep percolation, through flow, and moisture in unsaturated and saturated soil zones besides others. The details of the sensitivity analysis and its utility for model simplification are described in the following sections.

6.2 SENSITIVITY ANALYSIS

Sensitivity analysis is the study of how the variation (uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of a model (Saltelli et al., 2008). It can be used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how certain change in the value of parameter causes change in the dynamic behavior of the system simulated by the model. Sensitivity analysis is a useful tool in model building as well as in model evaluation. It can also be used to investigate the robustness of the model predictions and to perform what-if analysis to explore the impact of varying inputs, assumptions and scenarios (Breierova and Choudhari, 1996).

It can help build confidence in the model by studying the uncertainties that are often associated with parameters in the model. Many parameters in a model represent quantities that are very difficult, or even impossible to measure to the desired level of accuracy in the real world. Also, some parameter values change in the real world. Therefore, while building a model, the modeler is usually somewhat uncertain about the parameter values he chooses and mostly rely on estimates. Sensitivity analysis allows determining what level of accuracy is necessary for a parameter to make the model sufficiently useful and valid. If the tests reveal that the model is insensitive to certain parameters, then it may be possible to use an estimate rather than a value with greater precision. Sensitivity analysis can also indicate which parameter values are reasonable to use in the model. If the model behaves as expected from real world observations, it gives some indication that the parameter values reflect, at least in part, the "real world".

Thus, sensitivity analysis is conducted to develop a comprehensive understanding of response of the model due to change in calibration parameter values. The results of the sensitivity analysis represent quantitative indices and hydrological responses for the variation of calibration parameters. Sensitivity analysis can also be used to check the range of parameter values and assist in selection of parameters for model calibration, operations and improvement of model capabilities. Keeping this in view, in the subsequent sections, an effort has been made to investigate the sensitivity of the parameters of the proposed models. This is further used to simplify the model. The mathematical frame-work of the concept of sensitivity analysis is also outlined.

6.2.1 Methods for Sensitivity Analysis

There are several procedures or methods to perform sensitivity analysis (SA), which are described below:

1. Local sensitivity analysis methods, such as the simple derivative of the output with respect to an input factor, where the derivative is taken at some fixed point in the space of the input (hence the 'local' in the name of the class). Adjoint modeling (Cacuci, 2005; Cacuci et al., 2005) and Automated Differentiation (Grievank, 2000) are methods in this type of sensitivity analysis.
2. A sampling based sensitivity is one in which the model is executed repeatedly for combinations of values sampled from the distribution (assumed known) of the input factors. Once the sample is generated, several strategies (including simple input-output scatter plots) can be used to derive sensitivity measures for the factors (Helton et al., 2006).
3. Screening methods is a particular instance of sampling based sensitivity methods. The objective in such case is to estimate a few active factors in models with many factors (Morris, 1991; Campolongo et al., 2007).
4. The variance based methods, in which the unconditional variance of output is decomposed into terms due to individual factors plus terms due to interaction among factors. Full variance decompositions are only meaningful when the input factors are independent from one another (Sobol', 1990, Homma and Saltelli, 1996; Saltelli et al., 2000).
5. High Dimensional Model Representations (HDMR) is a particular case of the variance based methods (Rabitz, 1989). In HDMR, the output is expressed as a linear combination of terms of increasing dimensionality (Li et al., 2002; Li et al., 2006).
6. Sensitivity methods based on Monte Carlo filtering are sampling-based sensitivity and the objective is to identify regions in the space of the input factors corresponding to particular values (e.g. high or low) of the output (Hornberger and Spear, 1981; Saltelli et al. 2004).

In the present study, the local sensitivity analysis is performed to determine the parameter sensitivity so that it can be further used for model simplification.

6.2.2 Mathematical Principles of Sensitivity Analysis

Sensitivity is a measure or the effect of change in one factor on another factor (McCuen, 1973; McCuen and Synder, 1986). The sensitivity analysis, which is a modeling tool, provides the model designer a better understanding of the correspondence between the model parameters and the physical processes being modeled (McCuen, 1973; McCuen, 2003). Mathematically, the sensitivity can be expressed by considering a Taylor series of the explicit function as,

$$F_0 = f\,(F_1, F_2, \ldots\ldots\ldots, F_n) \tag{6.1}$$

The change in factor F_0 resulting from change in factor F_i is given by

$$f(F_i + \Delta F_i, F_j / j \neq i) = F_0 + \frac{\partial F_0}{\partial F_i}\Delta F_i + \frac{1}{2}\frac{\partial^2 F_0}{\partial F_i^2} + \ldots\ldots\ldots\ldots\ldots\ldots (6.2)$$

If the non-linear terms are small in comparison with the linear terms, Eq. (6.2) reduces to

$$f(F_i + \Delta F_i, F_j / j \neq i) = F_0 + \frac{\partial F_0}{\partial F_i}\Delta F_i \tag{6.3}$$

Thus,

$$\Delta F_0 = f(F_i + \Delta F_i, F_j / j \neq i) - F_0 = \frac{\partial F_0}{\partial F_i}\Delta F_i \tag{6.4}$$

Eq. (6.4) is referred to as linearized sensitivity equation, which measures the changes in factor F_0 that results from changes in factor F_i. The general definition of sensitivity is derived from Eq. (6.1) and (6.4) as follows:

$$S = \frac{\partial F_0}{\partial F_i} = \frac{\lfloor f(F_i + \Delta F_i, F_j / j \neq i) - x(F_1, F_2, \ldots\ldots, F_n) \rfloor}{\partial F_i} \tag{6.5}$$

This mathematical form of general definition of sensitivity (Eq. 6.5) suggests two methods of computation (McCuen, 1973; McCuen and Synder, 1986). One method (the left hand side of Eq. (6.5)) suggests that the sensitivity of factor F_0 to changes in factor F_i can be estimated by differentiating the explicit relationship of Eq. 6.1 with respect to factor F_i as,

$$S = \frac{\partial F_0}{\partial F_i} \tag{6.6}$$

Analytical differentiation is not used extensively for evaluating the sensitivity of hydrologic models due to the analytical differentiation produced by complexity of most hydrologic models (McCuen, 2003). Instead, the method of factor perturbation is the more commonly used method in hydrologic analysis (McCuen, 1973, 2003). The second method (the right hand side of Eq. (6.5)) suggests that the sensitivity of F_0 to change in F_i can be derived by incrementing F_i and computing the resulting changes in the solution of F_0:

$$S = \frac{\Delta F_0}{\Delta F_i} = \frac{\lfloor f(F_i + \Delta F_i, F_j / j \neq i) - x(F_1, F_2, \ldots\ldots, F_n) \rfloor}{\Delta F_i} \tag{6.7}$$

The sensitivity analysis also provides the information pertaining to the relative importance of variables in terms of their effect on various quantities and processes, which can be univariate or multi-variate (Zerihun et al., 1996). The analysis presented in this study is confined to univariate case, which deals with single variable at a time.

6.2.3 Relative Sensitivity

There are various forms of sensitivity such as absolute, relative, deviation, etc. Sensitivity values computed using Eq. (6.5) are in absolute form. Such values cannot be used for comparison of parametric sensitivities because the computed values are not invariant to the dimensions of either factor F_0 or F_i. Dividing the numerator by F_0 and the denominator by F_i provides an estimate of the relative change in F_0 with respect to a relative change in F_i:

$$RS = \frac{\partial F_0 / F_0}{\partial F_i / F_i} = \left(\frac{\partial F_0}{\partial F_i} \right) \times \frac{F_i}{F_0} \tag{6.8}$$

Relative sensitivity (RS) values are invariant to the dimensions of F_0 and F_i and thus provide a valid means for comparing factor sensitivity. Deviation sensitivity, which is a third form of sensitivity, can be computed as the change in the output (ΔF_0):

$$\Delta F_0 = \left(\frac{\partial F_0}{\partial F_i} \right) \Delta F_i \tag{6.9}$$

In the present study, the relative sensitivity is calculated by using Eq. (6.8) and plotted graphically against changes in parameter values as described in the subsequent sections.

6.2.4 Sensitivity of Model Parameters

The sensitivity of model parameter indicates the significance of each parameter in the developed model due to which a qualitative categorization is possible to determine the role of each parameter in the model. In the present study, it is found that the LTHS ASMA II model performs better than other three LTHS SCS-CN concept-based SMA models, viz., LTHS MICHEL I, LTHS MICHEL II, and LTHS ASMA I models as stated earlier. Therefore, the sensitivity analysis of LTHS ASMA II model is carried out in the subsequent sections for all study watersheds. This quantitative analysis is prepared using the entire data length as used in simulation. The results of the sensitivity analyses of each watershed are presented in the subsequent sections.

The relative sensitivity (RS) of dependent parameters is estimated due to variations of independent parameters involved in the model, and thus, the significance of the independent parameters can be determined. The simulated stream flow is considered as dependent parameter and corresponding variations in stream flow are plotted. Based on thess non-dimensional RS values, suitable range and symbol are decided and presented in Table 6.1 to quantify the sensitivity of parameters. This will help determine the degree/role of sensitivity of each parameter in hydrologic simulation. The RS of parameters with respect to stream flow is classified as insensitive denoted by N, less sensitive (L), moderately sensitive (M), highly sensitive (H), very highly sensitive (VH), and most sensitive (MS) as given in Table 6.1. The LTHS ASMA II model contains 15 parameter s, viz., CN_0, δ, α, β, γ, K, P_1, P_2, P_3, θ_w, ψ_f, E_g, ψ_0, CNd_0, λ_d as explained in Chapter 3. In this analysis, the RS of the simulated stream flow due to variations of these 15 independent parameters are estimated. The percent variations (in upper and lower boundary) of 0, 10, 25, 50, 75, and 100% in the optimized values of these model parameters is considered to compute the range of RS values of each parameters and, accordingly, the respective RS plots for each watershed are prepared. The independent variables are varied within a range (Table 5.2) depending on the physical significance of each of them. For example, the value of curve number at the starting day of simulation lies between 0 and 100 and hence can be varied in this limit. Similarly, the coefficients for through flow, base flow cannot exceed 1 and thus these varied within range 0-1.

Table 6.1 Range of Sensitivity Classes and its Symbol

Descriptions	**Not sensitive**	**Less sensitive**	**Moderately sensitive**	**Highly sensitive**	**Very highly sensitive**	**Most sensitive**
Range of RS	≤ 0.01	0.01-0.20	0.20-0.40	0.40-0.80	0.8-1.00	>1.0
Symbol	N	L	M	H	VH	MS

Thus, depending on the optimized values of parameters, the upper and lower boundaries for the variation in optimized values of independent variables within range (Table 5.2) are selected as shown in Table (6.2) and (6.3) for Hemavathi and Hridaynagar watersheds, respectively, and Appendix E for the remaining watersheds. Since the results of all other watersheds were similar, only those of the first two watersheds are discusses here. As seen from Table 6.2, all the parameters except P_4, θ_w, ψ_f, ψ_0, and CNd_0 are increased up to100% above the optimized value and decreased up to 75% below the optimized value. The model parameter P_4 varies in the range of 0-1 and its optimized value is 0.99. Therefore, it cannot be increased further, while it can be decreased up to 75%. Thus, P_4 is decreased only

Table 6.2 Range of Variation for Independent Variables and Corresponding RS Values for Hemavathi Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	30.506	75	100	0.504	H
2	δ	2.332	75	100	0.015	L
3	α	0.415	75	100	No change	N
4	β	0.137	75	100	0.103	L
5	γ	0.441	75	100	2.486	MS
6	K	1.516	75	100	0.003	N
7	P_1	0.005	75	100	No change	N
8	P_3	0.114	75	100	0.050	L
9	P_4	0.990	75	0	0.273	M
10	θ_w	40.247	25	100	0.031	L
11	ψ_f	300.017	50	75	0.141	L
12	E_g	0.323	75	100	0.092	L
13	ψ_0	300.256	50	100	No change	N
14	CNd_0	64.719	75	50	0.082	L
15	λ_d	0.012	75	100	No change	N

Table 6.3 Range of Variation for Independent Variables and Corresponding RS Values for Hridaynagar Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	27.484	75	100	4.626	MS
2	δ	0.010	75	100	No change	N
3	α	0.544	75	75	No change	N
4	β	0.010	75	100	0.251	M
5	γ	0.520	75	75	4.503	MS
6	K	1.225	75	100	0.033	L
7	P_1	0.043	75	100	No change	N
8	P_3	0.001	75	100	0.005	N
9	P_4	0.589	75	50	0.488	H
10	θ_w	299.727	75	50	1.025	MS
11	ψ_f	496.224	75	50	1.342	MS
12	E_g	0.260	75	100	No change	N
13	ψ_0	253.637	50	100	No change	N
14	CNd_0	60.736	75	50	0.747	H
15	λ_d	0.011	75	100	0.128	L

up to 75%. Similarly, the parameter θ_w is given an increment of 100% but decreased by 25% only. The other parameters such as ψ_f and CNd_0 are also varied between 0 and 100%. By varying the values of parameters within the range selected for each parameter, the corresponding RS values are computed and RS plots are drawn as presented in Figs. 6.1(a, b, c) and 6.2 (a, b, c) for Hemavathi and Hridaynagar watersheds, respectively, and Appendix F for other watersheds. The qualitative categorization of these parameters into different sensitivity classes for Hemavathi and Hridaynagar watersheds are also presented in Tables (6.2) and (6.3), respectively, and Appendix E for other watersheds and summarized in Table 6.4. As seen from Table 6.4 and Figs. (6.2) and (6.3) and figures shown in Appendix F, RS plot for simulated stream flow is very sharp for all study watersheds if the independent variable, γ (coefficient of pre-antecedent soil moisture store level (V_{00})) is changed. It is the most sensitive (MS) parameter among all parameters of the model. The underestimation or overestimation of this parameter will bring large errors in the simulated stream flow. Therefore, a greater attention is required while estimating this parameter. For majority of watersheds, the curve numbers at the starting day of simulation for surface flow (CN_0), and subsurface drainage flow (CNd_0) are very highly (VH) to most sensitive (MS) parameters and contribute significantly in the error, and hence, necessary precaution should be taken while estimating these parameters. Similarly, the parameters related with soil characteristics, e.g. wilting point (θ_w) and field capacity (ψ_f), are moderately (M) to highly (H) sensitive, and hence, over- or under-estimation of these parameters may result in considerable variation in simulated stream flow. It is apparent from Table 6.4 that the variation in the parameters P_3, P_4, E_g, δ, and K does not contribute significant error in the estimation of stream flow in almost all watersheds, and hence, the degree of sensitivity is low (L). The remaining parameters such as α, β, P_1, ψ_0, λ_d are not sensitive (N) parameters as they do not contribute errors in the estimation of stream flow, these parameters can therefore be fixed to make model simpler to reduce number of optimizing parameters.

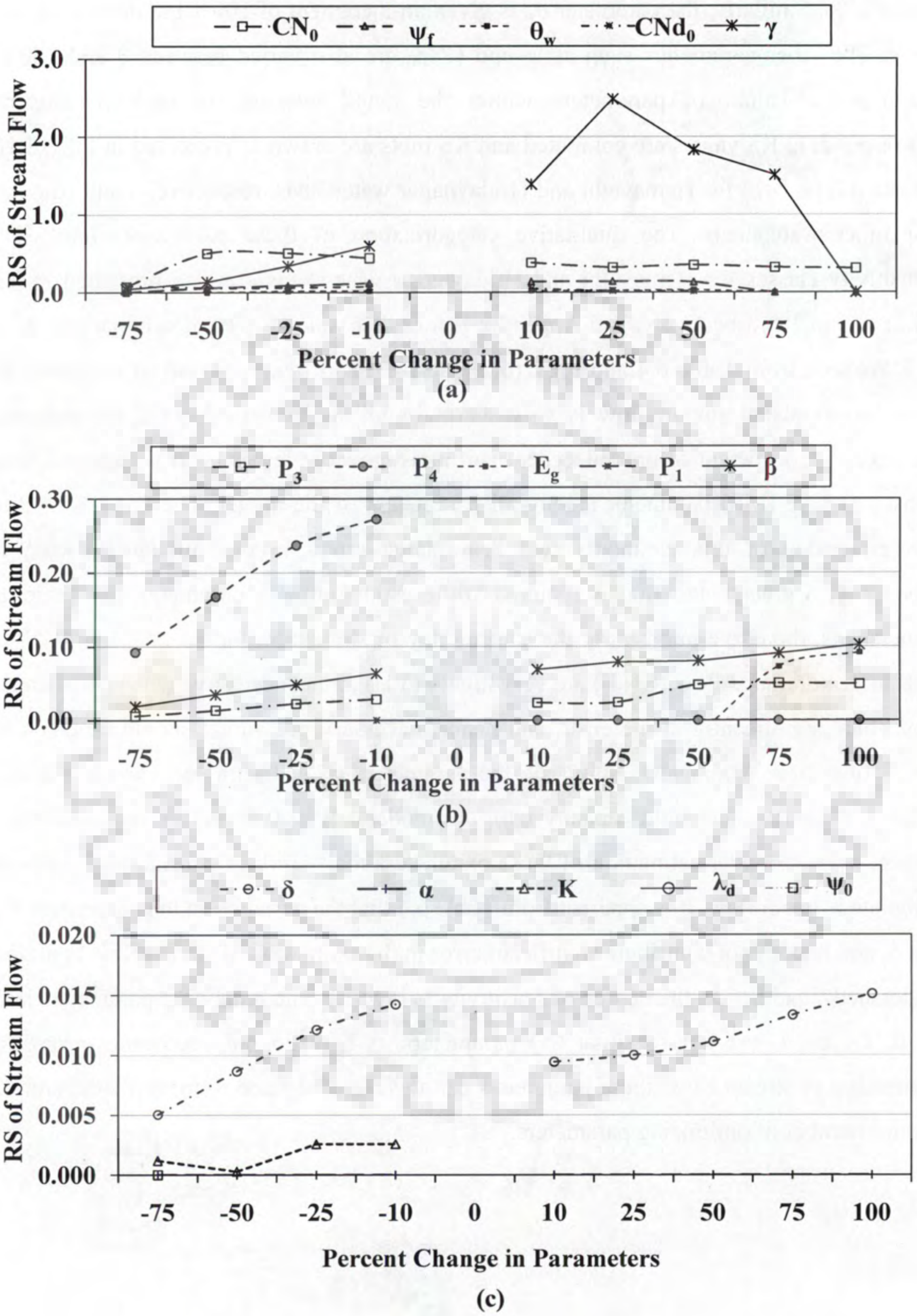
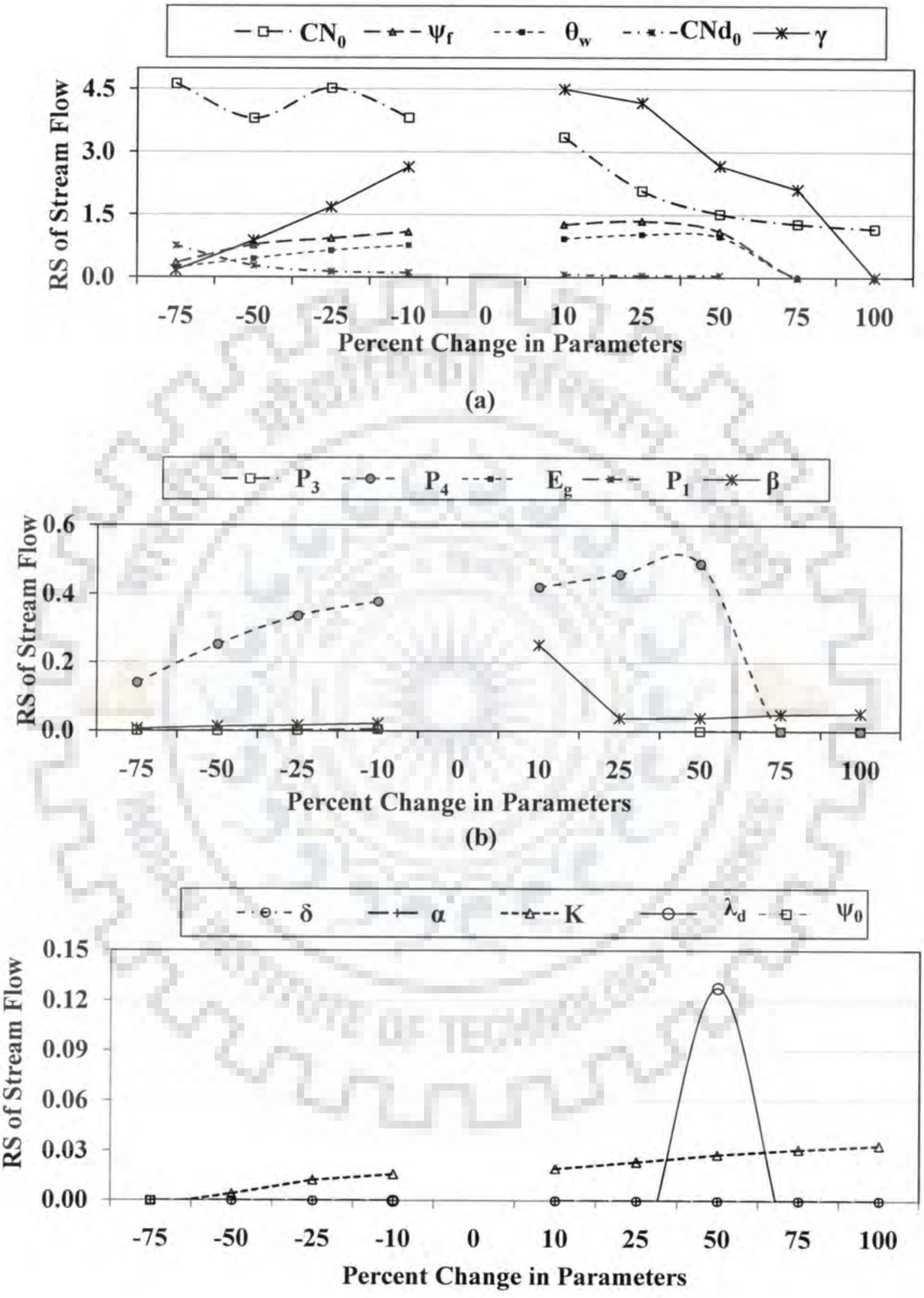


Fig. 6.1 RS Plots of Stream Flow for Hemavathi Watershed



(a)

(b)

(c)

Fig. 6.2 RS Plots of Stream Flow for Hridaynagar Watershed

Table 6.4 Summary of Sensitivity Classes of Model Parameters

Sr. No.	Name of Watershed	Model Parameter														
		CN_0	δ	α	β	γ	K	P_1	P_3	P_4	θ_w	ψ_f	E_g	ψ_0	CNd_0	λ_d
1.	Hemavati	H	L	N	L	MS	N	N	L	M	L	L	L	N	L	N
2.	Hridaynagar	MS	N	N	M	MS	L	N	N	H	MS	MS	N	N	H	L
3.	Mohegaon	VH	N	N	L	MS	L	N	H	L	H	MS	N	N	MS	N
4.	Manot	MS	N	N	N	MS	L	N	M	L	H	VH	N	N	MS	N
5.	Amachi	MS	L	N	L	MS	L	N	M	L	L	M	N	N	MS	N
6.	Anthroli	VH	N	N	L	MS	N	N	VH	L	MS	H	L	N	VH	N
7.	Attigundi	N	N	N	L	MS	L	N	N	L	L	L	N	N	MS	N
8.	Barchi	MS	N	N	L	MS	L	N	L	M	M	H	N	N	H	N
9.	Khanapur	N	N	N	L	MS	L	N	N	L	L	M	N	N	MS	N
10.	Hirehalla	N	N	N	M	MS	N	N	H	N	M	H	N	N	MS	N
11.	Sagar	H	N	N	L	MS	N	N	M	M	L	H	N	N	MS	N
12.	Sorab	M	N	N	N	MS	L	N	L	L	L	M	N	N	MS	N
13.	Dasanakatte	L	N	N	M	MS	N	N	L	M	L	L	L	N	M	N
14.	Haladi	H	N	N	M	MS	L	N	H	MS	L	L	H	L	H	N
15.	Kokkarne	H	L	N	M	MS	N	N	L	L	L	L	N	N	L	N
16.	Halkal	M	N	N	H	MS	N	N	N	M	H	L	L	N	H	N
17.	Jadkal	VH	L	N	H	MS	L	N	VH	M	M	M	MS	L	VH	N

6.3 MODEL SIMPLIFICATION

The sensitivity analysis presented above reveals that the parameters of the proposed model exhibit different levels of relative sensitivity (RS). Some of the parameters of the model are highly sensitive while some are very less or not sensitive at all. The results obtained here are in general in agreement with other studies reported in literature. In case of the modified 13-parameters SFB model, Mein and Brown (1978) showed that a drastic reduction in the number of optimized parameters only caused a slight reduction of the model performance. Chiew and McMahon (1994), in case of the MODHYDROLOG model, indicated that all 19 parameters are not necessary and that, in most cases, the calibration of only nine of them is sufficient to give adequate estimates of stream flow. Zhao and Liu (1995) noted that the output of the Xinanjiang model is generally sensitive to only seven of the 15 parameters in the model. Similarly, in the case of the SMAR model family, Tan and O'Connor (1996) showed that the eight-parameter SMARY version is more versatile than the nine-parameter SMARG version. Abdulla et al. (1999), in case of the four base flow parameters of the ARNO model, observed that one or more of the parameters may not be useful and that a reparameterised model involving fewer parameters might perform equally well. Uhlenbrook et al. (1999) also reported that good simulations could be achieved with the HBV model over a wide range of parameter values even for sensitive parameters and that the increase in simulation quality was quite small when more complex versions of the model were used.

Thus, there are clear advantages of simplifying the models. The data requirements are reduced; it is much easier to get an understanding of the underlying causes of system behaviour; and in some cases, certain useful mathematical analysis becomes possible. Nash and Sutcliffe (1970) presented some principles for building models with optimized parameters. They expressed the need for both simplicity and lack of duplication in model structures. They also added the requirement of versatility, where adding parts to the model is only acceptable if they substantially increase model accuracy and robustness.

6.3.1 Simplification Approach

A model is considered simpler than another (the detailed one) with the same set of input and output variables if i) the number of its variables are less than that of the detailed one and/or ii) the algebraic form of its model equations is simpler, together with the number of the model parameters being less than that of the corresponding model elements in the detailed model. Model simplification can be performed by applying model simplification assumptions (Hangos and Cameron, 2001). A model simplification assumption is formally described by a triplet of a model element (e.g. a model parameter), an operation (say ‘‘¼’’) and a constant or another model element. There are several methods proposed in the literature for performing model simplification and reduction in number of parameters in different ways to obtain a model with suitable size and complexity.

Before attempting to simplify a model, one has to consider the hierarchy of the model elements (Lakner et al., 1999). A model can be seen as a hierarchically structured set of model elements, such as balance volumes over which conservation balances are constructed (the highest level), balance equations, terms in balance equations corresponding to mechanisms, constitutive equations, and variables and parameters (the lowest level). If one makes a simplifying assumption to any of the model elements that will influence all the other elements on the lower level(s) that are related to this model element. For example, leaving out a balance volume from a model implies to leave out all the balance equations, their terms, constitutive equations, variables and parameters that belong to that particular balance volume. Two simplifying assumptions are not related if they are hierarchically independent, i.e. they have no common elements in their sub-hierarchy. Naturally, one tries to perform model simplification by applying assumptions or influencing parameters in their descending order of hierarchy levels, i.e. to apply the lowest influential parameters first.

Among the several approaches/methods available in literature, sensitivity analysis is one of the useful and necessary preparatory steps of model simplification (Hangos and Cameron, 2001). Rose and Harmsen (1978) demonstrated that sensitivity analysis could be used for model simplification. Hearne (1985, 1987) showed a way to handle the parameter combination sensitivity problem even if systems have large number of parameters. Martin (1980) developed a technique for functional sensitivity of a model. This can be used to identify how important (sensitive) the choice of parameter in a model is.

In the present study, the model simplification is carried out based on the sensitivity analysis of the model parameters. The insensitive and less sensitive non-measurable parameters were considered first to omit or fix according to the response of model after incorporation of values of these parameters. The step-by-step systematic approach is followed by repeating it for all study watersheds. Finally, the simplification step is selected on engineering judgment based on statistical criteria to get a simplified model. The output response is generated with the simplified model and compared with the response of the original (detailed) model. Based on some decision criterion, the acceptance of the simplification step is decided. Once the simplification step is accepted then the output response is compared with the original (detailed) model. Accordingly, a systematic approach to minimize the model parameters based on statistical analysis of the optimized parameters involved in the LTHS ASMA II (detailed) model is carried out. The necessary preparatory steps are performed by preparing the hierarchy for model parameters according to parameter sensitivity analysis to preselect model elements from the hierarchy to be omitted.

6.3.2 Statistical Analysis

In the present study, the simplification of LTHS ASMA II model which performs comparatively better than other three LTHS models as mentioned in Chapter 5 is carried out. The set of optimized model parameters of LTHS ASMA II for annual data series of study watersheds (Table 5.19) is considered for simplification. The sensitivity analysis performed in earlier indicates that some parameters like δ, β, γ , α, λ_d, P_1, P_3, P_4, K, E_g (Table 6.5) are not sensitive (insensitive) or less sensitive and are non-measurable. These parameters are considered first for model simplification purpose. The range of values is assigned to these parameters based on statistical analysis. The step-by-step procedure was followed to fix up the values of these parameters according to the input-output behavior of model, using model efficiency NSE, for the range of values assigned to these parameters.

The statistical analysis is performed with the set of optimized model parameters of LTHS ASMA II (Table 6.5) to determine the mean, weighted mean, median, standard deviation, and confidence interval at various levels of significance of the parameters as given in Table 6.5. Based on this statistic, different values ranging between the minimum and maximum were assigned to these parameters. The model was run by using annual data series of study watersheds for these assigned values to individual parameter as well as the parameters in combinations, and accordingly, the values of parameters were fixed. Repeated model runs with different assigned values of non-measurable parameters reveals that there is negligible change or no change in the model efficiency (NSE) due to the variation in values of non-measurable parameters like δ, β, γ, α, λ_d, P_1, P_3. These values were fixed, and accordingly, the model formulation was refined. The refinement also made for various combinations of model parameters. The refined model was tested on annual data series of study watersheds and model response in terms of NSE was obtained. The results of selected run of model in terms of NSE for all study watersheds are presented in Table 6.6.

Various simplification steps were followed to reduce/fix the values of model parameters. The performance of simplified model at various levels is compared with the performance of LTHS ASMA II (original) model based on statistical criteria like correlation coefficient (r) and statistical t-test of significance (Table 6.6). Thus, the gradual minimization of the model parameters through fixing the values for non-measurable insensitive or less sensitive parameters is followed. According to conclusion drawn by Franchini and Michele (1991) based on a comparative analysis of seven different lumped conceptual models that the model should not be made too simple, because it will then cause a loss of the link with the physics of the problem. Hence, the simplification of model by reducing or fixing the values of parameters of LTHS ASMA II model is step down up to the permissible level only so that the simplification should not cause a loss of the link with the physical realization of the problem (Naef, 1981; Wilcox et al., 1990; Franchini and Michele, 1991). Based on p-value of t-test of significance (Table 6.6), it is seen that there is no significant difference in model efficiency (NSE values) of original (LTHS ASMA II) model and various simplified models at 95% confidence interval. The various simplification steps are selected for significant value of t-statistics and correlation coefficient (r) between the sets of NSE obtained for LTHS ASMA II model and simplified models. Finally, the simplification is step down up to the permissible level based on the significant r value. It is seen that there is no significant difference in value of r up to 9-parameter simplified model. Hence, the simplification step at fixation of six parameters, viz., δ, β, γ, α, λ_d, P_1 is selected. Thus, the 15-parameter LTHS ASMA II model is simplified into 9-parameter LTHS ASMA SIMP model.

Table 6.5 Statistical Analysis of LTHS ASMA II Model Parameters

Statistical Parameter	Model Parameter														
	Non-measurable Parameter										Measurable Parameter				
	P_1	P_3	P_4	δ	β	γ	α	λ_d	K	E_g	CN_0	Ψ_0	θ_w	Ψ_f	CNd_0
Minimum	0.00	0.00	0.06	0.01	0.00	0.42	0.40	0.01	0.53	0.26	11.30	191.00	40.30	259.80	18.30
Maximum	0.09	0.80	0.99	6.63	0.34	0.95	0.85	0.57	5.98	0.90	52.80	551.50	299.70	496.20	78.20
Mean	0.02	0.43	0.68	1.22	0.10	0.56	0.52	0.10	2.14	0.41	26.40	329.54	152.09	359.19	45.11
Wt. mean	0.03	0.46	0.44	2.34	0.03	0.64	0.60	0.20	1.85	0.35	30.93	364.57	209.42	403.97	54.59
Median	0.01	0.47	0.84	0.11	0.02	0.54	0.50	0.05	1.69	0.38	26.50	350.00	130.30	395.30	44.80
S. D.	0.02	0.20	0.35	2.16	0.12	0.12	0.11	0.14	1.46	0.15	10.64	103.26	76.32	67.37	16.52
95% CI															
Upper	0.03	0.54	0.86	2.33	0.16	0.63	0.58	0.17	2.89	0.49	31.87	382.63	191.33	393.83	53.61
Lower	0.01	0.33	0.51	0.11	0.04	0.50	0.47	0.03	1.39	0.34	20.93	276.45	112.85	324.55	36.62
S. E.	0.00	0.00	0.06	0.01	0.00	0.42	0.40	0.01	0.53	0.26	11.30	191.00	40.30	259.80	18.30

Table 6.6 Performance of LTHS ASMA II Model for Assigned Values to Various Combinations of Model Parameters

Sr. No.	Name of Watershed	Model Efficiency (NSE)							
		Original	$\delta = 0.0$	$\delta = 0.0$ $\lambda_d = 0.06$	$\delta = 0.0$ $\lambda_d = 0.06$ $P_1 = 0.01$	$\delta = 0.0$ $\lambda_d = 0.06$ $P_1 = 0.01$ $\beta = 0.11$	$\delta = 0.0$ $\lambda_d = 0.06$ $P_1 = 0.01$ $\beta = 0.11$ $\gamma = 0.54$	$\delta = 0.0$ $\lambda_d = 0.06$ $P_1 = 0.01$ $\beta = 0.11$ $\gamma = 0.54$ $\alpha = 0.50$	$\delta = 0.0$ $\lambda_d = 0.06$ $P_1 = 0.01$ $\beta = 0.11$ $\gamma = 0.54$ $\alpha = 0.50$ $P_3 = 0.48$
1	Hemavati	0.908	0.889	0.875	0.833	0.854	0.886	0.854	0.848
2	Hridaynagar	0.589	0.571	0.582	0.596	0.560	0.539	0.520	0.556
3	Mohegaon	0.654	0.669	0.646	0.655	0.638	0.640	0.637	0.624
4	Manot	0.787	0.794	0.774	0.767	0.773	0.773	0.767	0.758
5	Amachi	0.632	0.632	0.638	0.606	0.635	0.509	0.531	0.393
6	Anthroli	0.748	0.720	0.701	0.700	0.759	0.740	0.725	0.718
7	Attigundi	0.809	0.770	0.796	0.793	0.728	0.711	0.731	0.665
8	Barchi	0.651	0.652	0.647	0.648	0.654	0.658	0.594	0.617
9	Khanapur	0.768	0.745	0.747	0.763	0.749	0.677	0.732	0.615
10	Hirehalla	0.165	0.152	0.149	0.148	0.125	0.116	0.126	0.099
11	Sagar	0.790	0.794	0.793	0.778	0.767	0.734	0.773	0.744
12	Sorab	0.754	0.748	0.754	0.752	0.739	0.760	0.765	0.758
13	Dasanakatte	0.865	0.869	0.867	0.865	0.835	0.803	0.839	0.835
14	Haladi	0.885	0.886	0.884	0.868	0.891	0.838	0.894	0.836
15	Kokkarne	0.916	0.901	0.915	0.916	0.892	0.902	0.896	0.882
16	Halkal	0.896	0.894	0.908	0.907	0.904	0.890	0.878	0.873
17	Jadkal	0.867	0.861	0.854	0.853	0.855	0.856	0.869	0.845
	Paired sample t test at 95% confidence interval for degree of freedom (df)=16								
	t-statistic		2.391	2.432	2.539	3.357	4.246	4.522	4.062
	p-value(S=significant)		0.029(S)	0.027(S)	0.022(S)	0.004(S)	0.001(S)	0.000(S)	0.001(S)
	Corr. Coeffi. (r)-->		0.9970	0.9968	0.9933	0.9917	0.9801	0.9885	0.9530
	Simplifi. Steps-->			Step 1		Step 2		Step 3	

6.4 LTHS ASMA SIMP MODEL

Based on the statistical analysis as above, the model LTHS ASMA II is simplified as LTHS ASMA SIMP model. The LTHS ASMA SIMP model contains 9 parameters only, viz., CN_0, P_3, P_4, θ_w, ψ_f, E_g, ψ_0, CNd_0. In this model, the values of parameters are fixed as stated in Table 6.6 and, accordingly, the model is formulated by incorporating the appropriate changes in LTHS ASMA II model. The simplified model (LTHS ASMA SIMP) is also tested for its performance to compare with detailed model (LTHS ASMA II) on annual data of study watersheds and described in subsequent sections.

6.4.1 Application of LTHS ASMA SIMP Model

The optimal set of model parameters is presented in Table 6.7. The range and initial values of the parameters for this model is similar as LTHS ASMA II model (Table 5.2) and similar calibration scheme is also followed to calibrate the parameters of this model. The model evaluation is carried out using the model efficiency in terms of NSE in calibration and validation as shown in Table 6.8. As seen from Table 6.8, NSE in calibration and validation vary from 0.84 to 0.90 and 0.81 to 0.89, respectively, for all high yielding coastal watersheds indicating very good model response (Motovilov et al., 1999). The model yields the maximum NSE of 0.90 and 0.89 in calibration and validation, respectively, for Kokkarne watershed, while the minimum efficiency of 0.52 in calibration is seen for Hridaynagar watershed, and 0.42 in validation for Attigundi watershed (excluding most dry Hirehalla watershed for which efficiency is very poor (NSE=0.12)). Fig. 6.3 compares the performance of LTHS ASMA II with simplified LTHS ASMA SIMP model and both are comparable.

Similar to LTHS ASMA II model, this model also yields high efficiency for wet (high yielding) watersheds and lesser efficiency for dry (low yielding) watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry Hirehalla watershed. It is evident from trend line drawn on the plot of runoff coefficient of different watersheds in ascending order and NSE values (Fig. 6.4) for calibration and validation, NSE increases with catchment wetness in terms of average runoff coefficient. Fig. 6.4 shows a comparable performance of both

Table 6.7 Optimized Values of Parameters of LTHS ASMA SIMP Model for Study Watersheds

Sr. No.	Name of Watershed	Model Parameter								
		CN_0	P_3	P_4	Ψ_f	E_s	Ψ_0	θ_w	K	CNd_0
1.	Hemavati	34.00	0.35	0.99	204.05	0.38	303.58	92.44	1.00	47.87
2.	Hridaynagar	22.40	0.12	0.49	339.58	0.36	261.56	224.19	1.43	26.65
3.	Mohegaon	44.86	0.60	0.12	399.63	0.63	769.27	125.00	5.00	72.91
4.	Manot	35.63	0.54	0.21	343.46	0.90	350.00	300.00	5.00	41.39
5.	Amachi	15.62	0.10	0.52	449.96	0.31	363.19	100.00	1.26	34.38
6.	Anthrolli	43.72	0.33	0.10	209.54	0.54	337.15	184.76	2.00	72.35
7.	Attigundi	16.10	0.21	0.99	312.52	0.41	281.62	180.00	1.43	44.98
8.	Barchi	30.99	0.37	0.30	449.18	0.37	650.55	190.00	2.50	47.70
9.	Khanapur	12.48	0.33	0.56	420.00	0.43	160.00	75.37	3.18	23.84
10.	Hirehalla	17.67	0.80	0.10	298.04	0.54	397.15	124.74	3.21	28.33
11.	Sagar	33.97	0.43	0.99	251.86	0.24	226.07	80.15	0.62	42.68
12.	Sorab	72.97	0.50	0.75	396.78	0.20	743.24	100.03	1.27	77.87
13.	Dasanakatte	18.55	0.54	0.99	450.00	0.35	160.00	179.90	2.02	33.91
14.	Haladi	19.05	0.59	0.99	520.00	0.32	350.00	154.45	6.03	38.02
15.	Jadkal	24.20	0.60	0.99	299.93	0.34	200.00	139.94	2.09	42.24
16.	Kokkarne	22.86	0.60	0.99	300.00	0.35	200.00	150.00	2.64	35.75
17.	Halkal	23.49	0.42	0.99	480.00	0.38	200.00	240.00	1.35	41.44

Table 6.8 NS Efficiency and Error Statistics for LTHS ASMA SIMP Model

Sr. No.	Name of Watershed	Calibration			Validation		
		NSE	Absolute RE (%)	SE (mm)	NSE	Absolute RE (%)	SE (mm)
1.	Hemavati	0.85	16.26	3.82	0.87	28.30	6.59
2.	Hridaynagar	0.52	5.18	1.96	0.53	40.23	2.14
3.	Mohegaon	0.64	0.12	2.74	0.57	14.53	2.50
4.	Manot	0.77	0.88	2.16	0.70	9.94	3.31
5.	Amachi	0.53	11.15	1.67	0.54	0.75	2.29
6.	Anthrolli	0.72	12.42	1.09	0.44	3.39	2.17
7.	Attigundi	0.73	1.49	2.54	0.47	9.79	5.32
8.	Barchi	0.59	4.62	2.29	0.64	16.70	2.19
9.	Khanapur	0.73	4.84	6.03	0.62	38.19	11.15
10.	Hirehalla	0.13	19.63	0.81	0.43	3.55	1.17
11.	Sagar	0.77	1.32	3.15	0.66	19.70	3.80
12.	Sorab	0.76	15.08	2.60	0.48	0.74	3.98
13.	Dasanakatte	0.84	5.34	7.20	0.81	3.13	9.57
14.	Haladi	0.89	3.29	5.58	0.70	2.06	9.03
15.	Jadkal	0.87	4.62	8.44	0.88	8.84	8.91
16.	Kokkarne	0.90	4.37	6.18	0.89	8.20	7.70
17.	Halkal	0.88	11.87	6.97	0.82	18.71	11.92

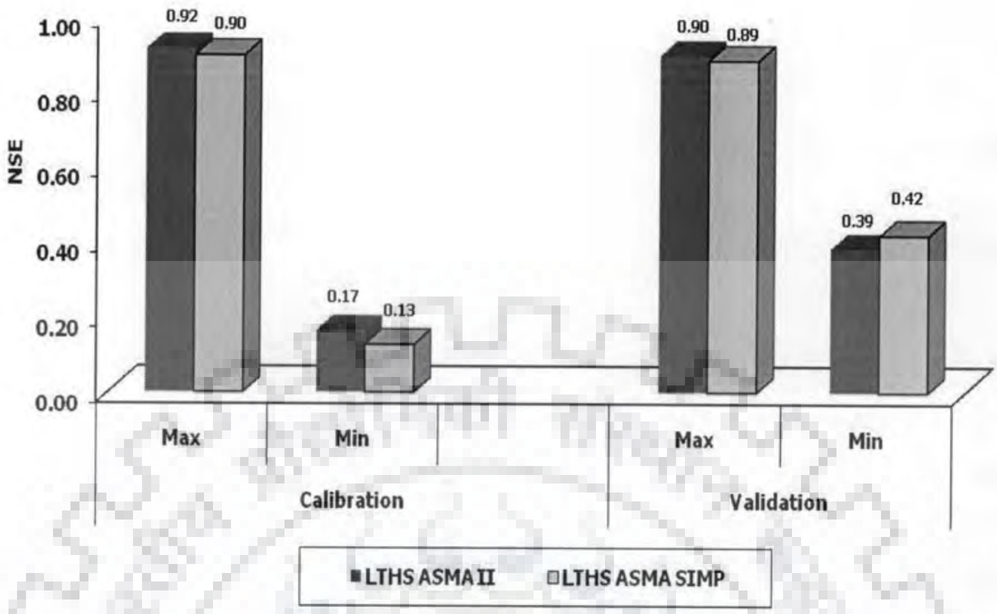


Figure 6.3 Range of NSE Obtained for LTHS ASMA II (Detailed) and LTHS ASMA SIMP (Simplified) Models

15-parameter and 9-parameter models with only a slight reduction of NSE.

The LTHS ASMA SIMP model is further evaluated based on the absolute value of RE obtained during calibration and validation periods is also presented in Table 6.8. As seen from Table 6.8, RE varies from 3.29 to 11.87% in calibration for all coastal high yielding wet watersheds, but it is more than 15% for most dry watershed, Hirehalla, showing better performance for high yielding watersheds than low yielding watersheds (Donigian et al., 1983; Harmel et al., 2006). The model performance is also very good for all watersheds under average condition except for the Khanapur watershed. The annual simulated runoff and computed values of RE for each year is also analyzed and presented in Appendix G. The annual average values of absolute RE is presented in Table 6.9. The trend analysis performed on the plot of annual average values of absolute RE (Table 6.9) as shown in Fig. 6.5 shows the reverse trend of RE with watershed wetness in terms of average runoff coefficient. If the individual year is analyzed (Appendix G), the model performs very good to fair in some years. As mentioned earlier, this may be attributed to the high rainfall to which the model did not respond well, resulting in underestimation of runoff. The computed runoff as percentage

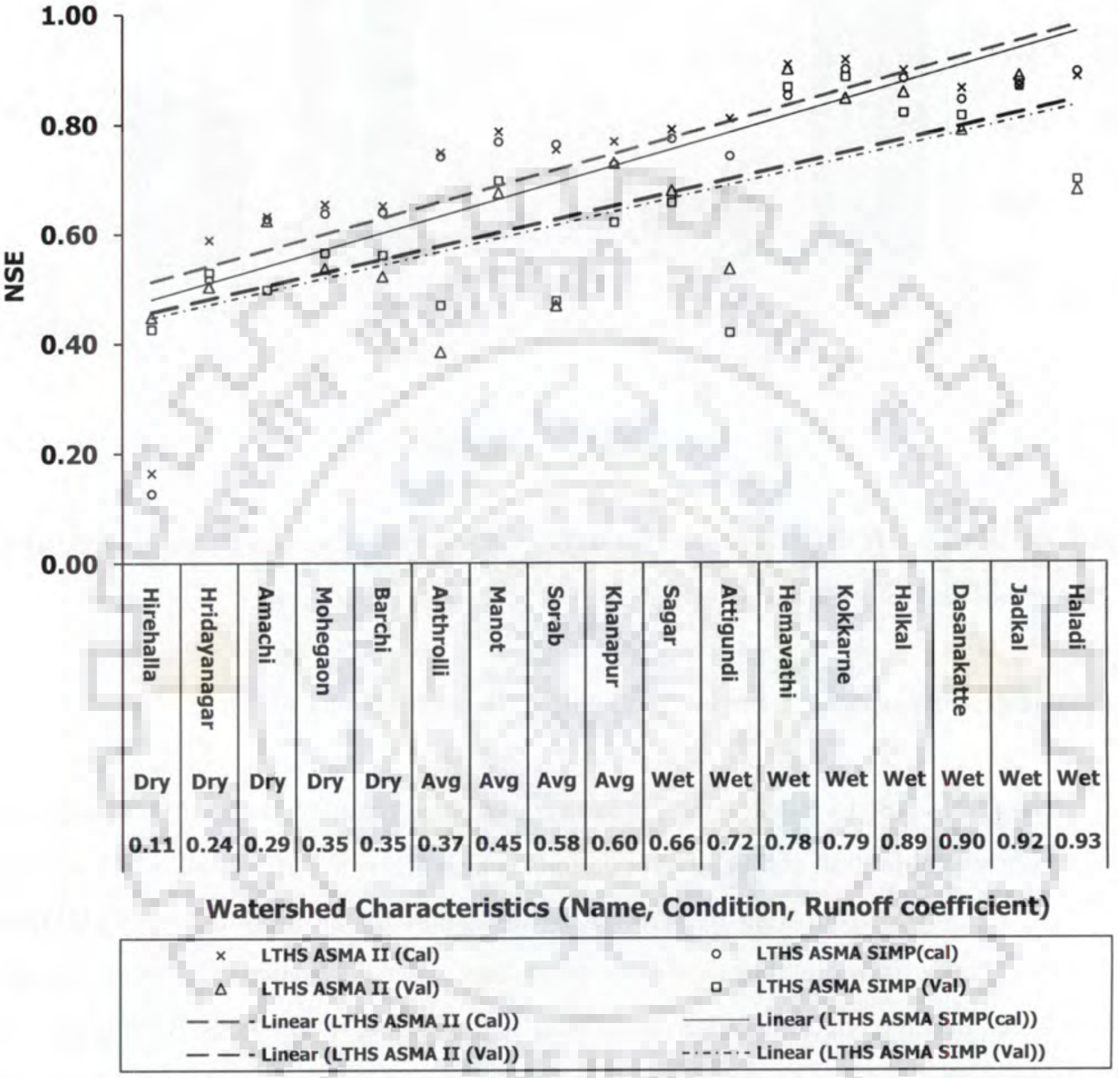


Figure 6.4 Comparative Performance in terms of NSE between LTHS ASMA SIMP (9-parameter) Model and LTHS ASMA II (15-parameter) Model

of rainfall for both simplified and detailed models for all study watersheds are also plotted to compare their performance (Fig. 6.6). The trend line fit on this plot shows that the simplified models (LTHS SIMP) giving comparable results with the detailed/original model (LTHS ASMA II).

Table 6.9 Annual Rainfall, Observed Runoff, Simulated Runoff, and Absolute RE (%) for LTHS ASMA SIMP Model

Sr. No.	Name of Watersheds	Rainfall	Observed Runoff	Simulated Runoff	Absolute RE
		(mm)	(mm)	(mm)	(%)
1	Hemavathi	2858.7	2232.7	1753.6	20.6
2	Hridaynagar	1441.8	351.8	288.4	25.0
3	Mohegaon	1231.5	431.1	404.5	13.3
4	Manot	1263.6	564.8	535.6	19.5
5	Amachi	1707.3	491.7	515.5	15.9
6	Anthrolli	998.9	365.2	375.3	16.0
7	Attigundi	1960.6	1404.2	1323.3	13.3
8	Barchi	1419.4	497.7	450.6	21.7
9	Khanapur	3980.3	2398.8	1822.4	28.2
10	Hirehalla	594.5	67.8	72.4	27.2
11	Sagar	1864.4	1222.0	1015.1	17.1
12	Sorab	1321.2	766.4	740.4	25.0
13	Dasanakatte	4628.7	4166.5	3989.7	10.3
14	Haladi	4718.2	4400.6	3873.7	18.3
15	Jadkal	5209.3	4815.1	4492.1	10.5
16	Kokkarne	5061.6	4010.6	3758.8	7.9
17	Halkal	5239.9	4650.2	3930.9	15.8

As stated earlier, if the number of parameters involved in the model is comparatively less than the number of time steps (data points), then only one error criterion, i.e. SE, is sufficient to evaluate the model performance. Since the number of parameters involved in simplified LTHS ASMA SIMP model is less than the detailed LTHS ASMA II model, the SE criterion can be useful to compare the performance of these models. Hence, the calculated values of SE only are computed here using daily outputs for all the study watersheds and presented in Table 6.8. As seen from Table 6.8, the values of SE obtained for LTHS ASMA SIMP model vary from 0.81 to 8.44 and 1.17 to 11.92 in calibration and validation, respectively (Fig. 6.7). It is seen from Fig. 6.7 that there is no much significant difference in the values of SE in calibration and validation of LTHS ASMA SIMP and LTHS ASMA II models, indicating comparable performance of both the models.

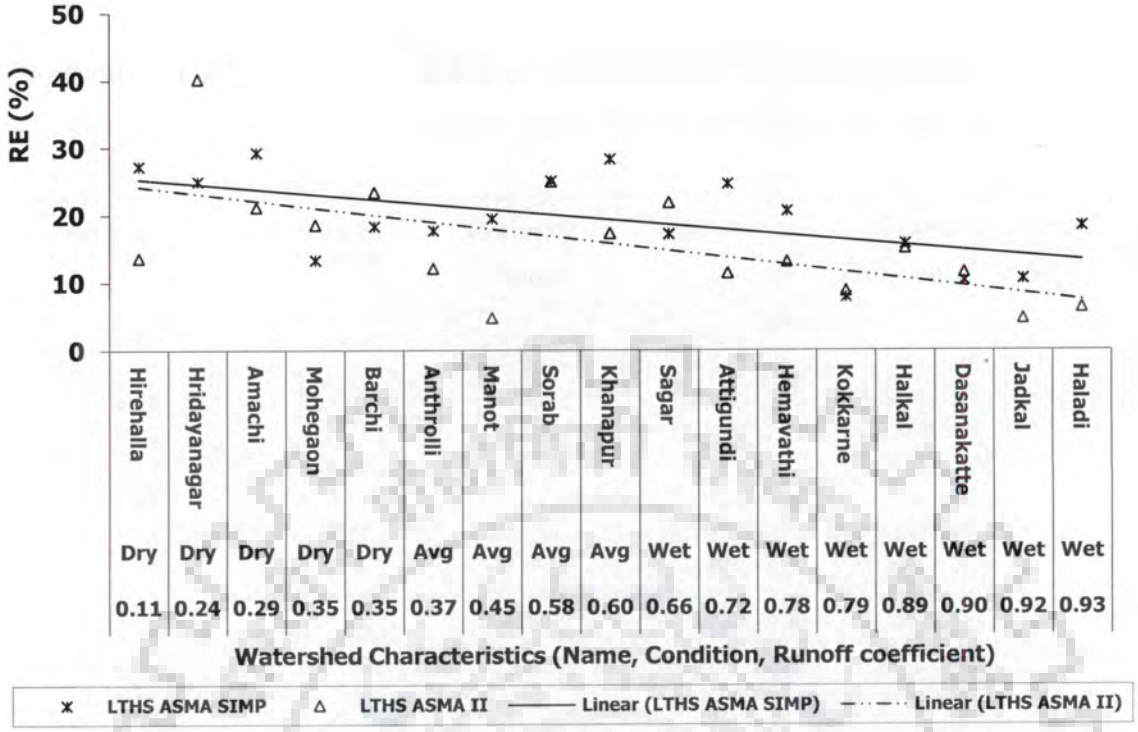


Figure 6.5 Comparisons between Absolute Average RE for LTHS ASMA SIMP and LTHS ASMA II Models

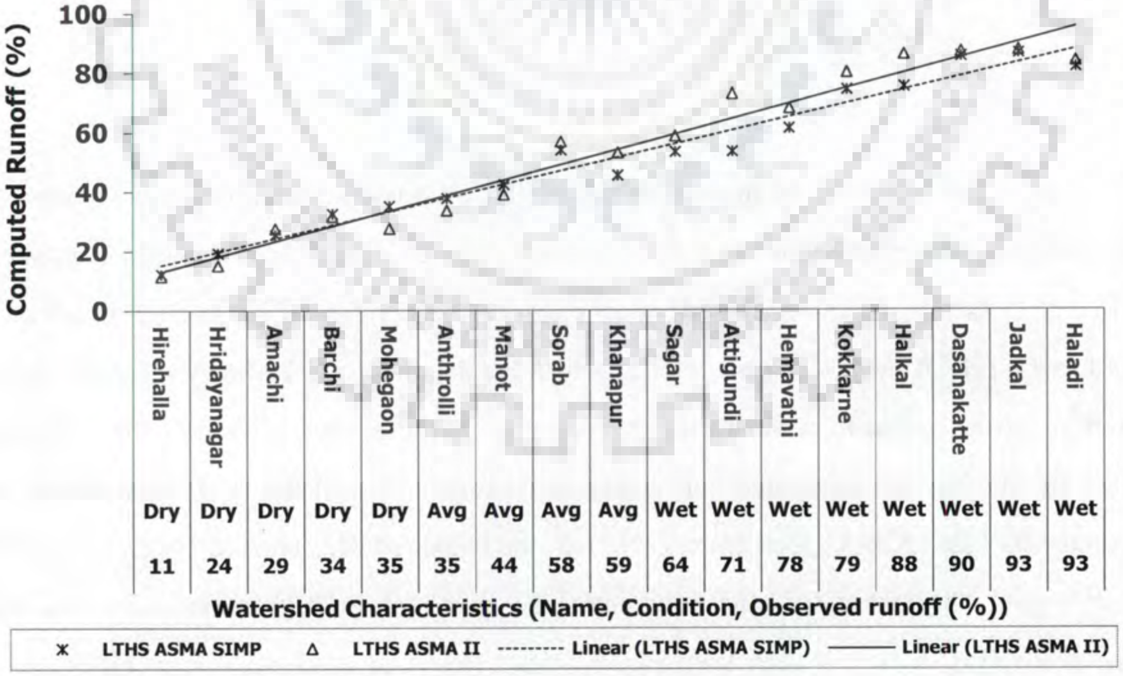


Figure 6.6 Comparisons between Computed Runoff (as percentage of rainfall) Obtained for LTHS ASMA SIMP and LTHS ASMA II Models

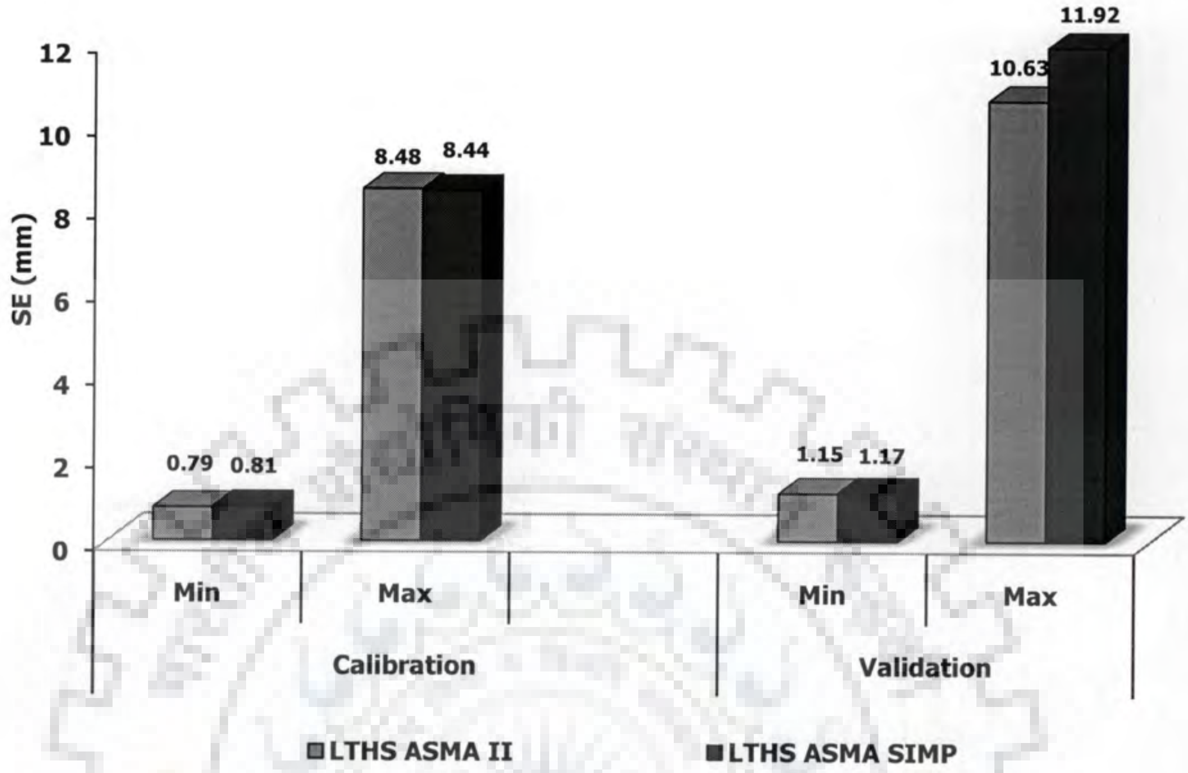


Figure 6.7 Range of SE Obtained for LTHS ASMA II (Detailed) and LTHS ASMA SIMP (Simplified) Models

The annual average values in terms of percentage of rainfall of various runoff generating components are also estimated to analyse the dominancy/dormancy of various processes/componenets of hydrologic cycle involved in the model and presented in Table 6.10. The process yielding less than 10% runoff contribution is termed as the dormant, it is dominant, otherwise as stated earlier in Chapter 5. The annual average values of these components were plotted against annual average runoff coefficient and a separate trend line was fitted for each component as shown in Fig. 6.8. Obviously, similar results as obtained for LTHS ASMA II model (Chapter 5) are also obtained for this model. For example, surface runoff is more prominant than lateral flow and base flow and all the components excepts evapotranspiration and deep percolation are more significant/dominant in high runoff producing coastal watersheds than low runoff producing watersheds, whereas the losses shows reverse trends.

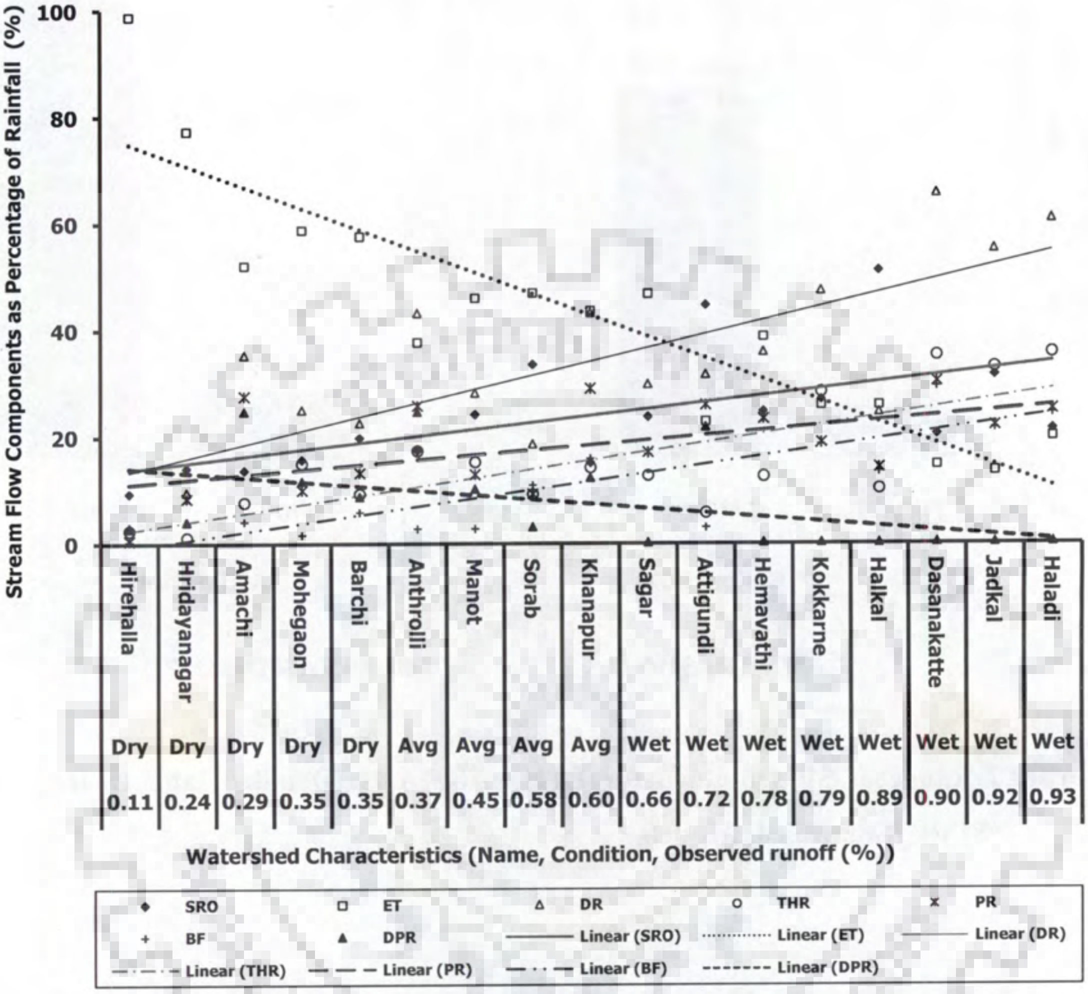


Figure 6.8 Trend Analysis of Average Annual Variation in Various Stream Flow Generating Components of LTHS ASMA SIMP Model

Table 6.10 Percent Estimates of Hydrological Components of LTHS ASMA SIMP Model for Study Watersheds

Sr. No.	Name of Watershed	Hydrological Component (% of Rainfall)									
		Rainfall (%)	Surface Runoff	Evapotranspiration	Drainage	Lateral flow	Percolation	Base flow	Deep Percolation	Simulated Runoff	Observed Runoff
1.	Hemavathi	100	24.73	38.84	35.97	12.59	23.38	23.82	0.24	61.15	77.91
2.	Hridaynagar	100	14.13	77.33	9.60	1.15	8.45	3.87	4.04	19.15	24.31
3.	Mohegaon	100	15.73	58.81	25.07	15.04	10.03	1.60	11.74	32.37	34.72
4.	Manot	100	24.20	46.09	28.28	15.33	12.95	2.72	10.30	42.25	44.17
5.	Amachi	100	10.74	58.10	34.78	3.48	31.30	15.98	14.75	30.19	28.74
6.	Anthrolli	100	15.77	28.89	54.56	18.01	36.56	3.80	34.13	37.57	35.06
7.	Attigundi	100	11.11	34.35	57.03	11.98	45.06	44.41	0.45	67.50	71.14
8.	Barchi	100	15.31	56.91	27.94	10.34	17.60	6.13	14.30	31.75	33.61
9.	Khanapur	100	15.15	43.64	43.26	14.27	28.99	15.89	12.36	45.31	59.42
10.	Hirehalla	100	9.41	98.81	2.97	2.38	0.59	0.31	2.81	12.10	11.20
11.	Sagar	100	23.71	46.81	29.87	12.81	17.06	16.72	0.17	53.24	64.42
12.	Sorab	100	33.56	46.99	18.65	9.29	9.36	10.94	3.08	53.80	58.40
13.	Dasanakatte	100	20.47	14.79	65.69	35.30	30.39	29.44	0.30	85.21	89.68
14.	Haladi	100	21.43	20.07	60.88	35.76	25.12	24.46	0.25	81.64	93.02
15.	Jadkal	100	31.53	13.67	55.25	33.15	22.10	21.64	0.22	86.32	92.54
16.	Kokkarne	100	26.97	25.96	47.43	28.46	18.97	18.56	0.19	73.99	78.89
17.	Halkal	100	51.14	25.95	24.64	10.32	14.32	13.50	0.14	74.96	88.27

6.5 REMARKS

In this chapter, the sensitivity analysis is carried out to identify the sensitivity of parameters in influencing the model output for simplification of the developed model giving better results (LTHS ASMA II). It is observed that the coefficient (γ) of pre-antecedent soil moisture store level (V_{00}) is the most sensitive (MS) among all parameters for all study watersheds. For majority of the study watersheds, the curve numbers at the starting day of simulation for surface flow (CN_0) and sub-surface drainage flow (CNd_0) are also highly sensitive parameters in addition to the parameters related with soil characteristics, viz., wilting point (θ_w) and field capacity (ψ_f). Hence, an underestimation or overestimation of these parameters will results into large errors in simulation of stream flow and requires a great attention in their estimation. Some parameters like α, β, P_1, ψ_0, λ_d, P_3, P_4, E_g, δ, and K are not sensitive or less sensitive as they do not contribute errors in stream flow estimation. Out of these parameters, some non-measurable and less or not sensitive parameters can be considered first to omit or fix according to the response of model. Thus, the sensitivity analysis helps develop a simplified version to minimize the number of parameters. Among the four LTHS models proposed in this study, the best LTHS ASMA II model is considered for simplification. The 15-parameter LTHS ASMA II model is simplified into 9-parameter LTHS ASMA SIMP model based on statistical analysis. In application, LTHS ASMA SIMP model performs comparably with the LTHS ASMA II model, with little reduction in model efficiency. Thus, the simplified LTHS ASMA SIMP model may be a more viable alternative to LTHS ASMA II model.

CHAPTER 7

MODEL PARAMETERIZATION USING WATERSHED GEOMORPHOLOGY

7.1 GENERAL

Finding the value of parameters of a conceptual model is a challenging task particularly in ungauged basins or basins where very less measurements are available. Hence, it has been the endeavor of many hydrologists to quantify and relate geomorphological parameters of these watersheds to their hydrologic response characteristics (Chandra, 1993). The geomorphological characteristics of a watershed play very important role in generating runoff. Certain physical characteristics of watershed, such as size, shape, orientation, topography, geology, geomorphology, land use and soil characteristics etc. affect significantly the hydrological response of a watershed. Both runoff volumes and rates increase as watershed size increases. Long narrow watersheds are likely to have lower runoff rates than more compact watersheds of the same size. The circular to oval shape of watershed allows quick disposal of runoff and results in a high peaked and narrow hydrograph; while elongated shape of watershed allows slow disposal of water and results in a broad and low peaked hydrograph (Singh and Singh, 1997). A circular basin is more efficient in runoff discharge than an elongated basin (Singh and Singh, 1997). The geological or soil materials determine runoff yield to a large degree. The infiltration rate and capacity thus have their effect on runoff, vegetation and the practice incident and forestry also influence infiltration. Vegetation retains overland flow and increases surface detention to reduce peak runoff rates.

As such, Horton (1945) pioneered the hydro-geomorphologic analysis of watershed and provided a rational and systematic base, rather a framework of outlines of geomorphological characteristics to relate them to various hydrological properties of the watershed. Strahler's (1952) modification of this technique has generally been adopted for use in hydrologic study.

Potter (1953) and Benson (1962) related peak discharge to watershed area, a topographical factor, and a rainfall frequency factor. Boyd (1978) developed a conceptual model using watershed geomorphological properties. Using a probabilistic framework, Rodrguez-Iturbe and Valdés (1979) and Gupta et al. (1980) presented a geomorphological instantaneous unit hydrograph with the exponential probability distribution for the time of travel of water drops which is essentially equivalent to using a linear reservoir. Rosso (1984) derived the Nash IUH parameters as functions of Horton's ratios. Hydro-geomorphological analysis was carried out in a number of Indian watersheds to compute the runoff in water resources development and management projects (Roohani and Gupta, 1988; Chalam et al., 1996; Chaudhary and Sharma, 1998; Kumar et al., 2001; Ali and Singh, 2002; Durbude and Kumar, 2002; Singh et al., 2003; Suresh et al., 2004; Durbude, 2005; Durbude and Chandramohan, 2007; Dabral and Pandey, 2007; etc.).

Shrinivasan (1988) concluded that the geomorphological characteristics such as bifurcation ratio, total stream length, total basin area, drainage density and constant of channel maintenance, etc. substantially contribute in evaluation of the hydrological characteristics of basin. Karnieli et al. (1994), Hsieh and Wang (1999), Durbude (2004) carried out hydrogeomorphological analysis for a watershed and inferred that there exist highly significant relationship between mean annual runoff and watershed characteristics such as watershed area, total stream length, drainage density and first order stream frequency etc. Nourani and Monadjemi (2006) developed geomorphological runoff models using a method similar to Boyd's. Yen and Lee (1997) presented a geomorphological model which was applicable not only to those watersheds lacking enough statistical data but also lacking geomorphological data.

The advantage of incorporating geomorphology in rainfall–runoff models is that the models can be applied to watersheds which lack observations and model parameters can be determined from watershed geomorphology. Agirre et al. (2005) and López et al. (2005) presented unit hydrograph models using watershed geomorphology and linear reservoirs, with a constant calibrated lag time for all reservoirs. The watershed morphology was employed just for determination of sub-basins (linear reservoirs) without any consideration of the sub basin physiographical properties. Nourani and Mano (2007) used TOPMODEL and the kinematic wave approach, wherein all model parameters, except one, were linked to the geomorphologic properties. Recently, Nourani et al. (2009) developed three geomorphological rainfall-runoff models. Thus, there exists a scope to correlate the physical characteristics of the watersheds with its response via various model parameters.

In the previous chapter, the necessity for model simplification was discussed. It is apparent that the model containing too many parameters for simulation of limited components of hydrological processes exhibit difficulty in field applications. Usability of a model can be enhanced if its parameters can be related to measurable catchment characteristics. The physical characteristics of the watersheds which are measurable entities and influencing the runoff characteristics of watershed can be correlated with the model parameters by means of some techniques such as regression analysis. In regression analysis, investigations are made to relate dependent variable (Y) for example model parameters to independent predictors (Xs) such as physical characteristics of watershed. It can be used for modeling causal relationships between model parameters and physical characteristics of watershed.

While performing the regression analysis, certain guidelines should be followed such as visualization correlation between Y and Xs, selecting a model, data gathering on Y and Xs, and then performing the regression analysis. Based on this analysis, the optimized model may be accepted or rejected. A best model should have a high R^2 value (a measure of goodness-of-fit) and the R^2 (adj) should be fairly close. The residuals should be normally distributed with a mean of zero and a standard deviation of one. The data used for analysis should cover the entire range of response value for analysis and prediction. The general computational problem that needs to be solved in multiple regression analysis is to fit a straight line to a number of points. Since more than one independent variables are involved in this analysis, the regression line cannot be visualized in the two dimensional space, but can be computed.

7.2 PHYSICAL CHARACTERISTICS OF WATERSHED

As stated earlier, the physical characteristics of the watersheds that significantly affect the runoff are geographical area, length, slope, shape, land use, and soil characteristics of watershed. Various researchers such as Horton (1945), Miller (1953), Schum (1956) developed an expression to compute geomorphological characteristics of watershed. As mentioned in Chapter 2, with the development of Geographical Information System (GIS) tools, it is now possible to determine hydrological and watershed geomorphological parameters using Digital Elevation Models (DEMs) (Jenson and Domingue, 1988; Maidment et al., 1996; Olivera and Maidment, 1999; Maidment, 2002; Durbude and Kumar, 2002; Pandey et al. 2004; Durbude, 2004, 2005; Durbude and Chandramohan, 2007, etc.). Therefore, in the present study, ILWIS (GIS) was used to determine various physical characteristics of watersheds.

The physical characteristics of study watersheds were extracted from the Survey of India (SOI) toposheets. Relevant toposheets were scanned and projected into Universal Traverse Mercator (UTM) projection system into zone (43-in which the study area lies), using Everest (India, 1956) Ellipsoid and Everest (India, Nepal) datum using image processing utilities of ILWIS software. The rectified toposheets were further used for the delineation of different features in the study watersheds like contour lines and drainage networks etc. The base map of the watershed boundary at 1:50,000 scale was prepared using the location of various contour and drainage lines. Different thematic maps, viz., contour map and drainage map were prepared using the base map. DEMs were created using the contour maps, which were further used for the assessment of relief aspects. The mathematical expressions given by various researchers to compute physical characteristics in terms of geomorphological characteristics of watershed are discussed in the following section.

7.2.1 Geographical Area

The area of watershed is also known as the drainage area and it is the most important watershed characteristic for hydrologic analysis. It reflects the volume of water that can be generated from rainfall. Once the watershed has been delineated, its area can be determined, either by approximate map methods or by GIS. The geographical area of the study watersheds computed by using ILWIS GIS software is presented in Table 7.1.

Table 7.1 Physical Characteristics of Study Watersheds

Sr. No.	Name of Watershed	Physical characteristics of the watershed								
		Area (A) (Km^2)	Perimeter (P) (Km)	Length (Lb) (Km)	Hydrologic length (Lm) (Km)	Form factor (Rf)	Circulatory ratio (Rc)	Elongation ratio (Re)	Total relief (H) (m)	Vegetation (V) (%)
1	Hirehalla	1296.00	162.23	55.49	51.31	0.42	0.62	0.73	150	6
2	Hridaynagar	3370.00	402.42	182.92	215.20	0.10	0.26	0.36	228	65
3	Amachi	87.00	33.74	11.28	11.51	0.68	0.96	0.93	224	70
4	Barchi	4661.00	326.97	148.62	174.85	0.21	0.55	0.52	391	58
5	Mohegaon	14.50	20.81	8.18	8.60	0.22	0.42	0.53	254	94
6	Anthroli	503.00	98.21	35.47	24.23	0.40	0.66	0.71	246	57
7	Manot	5032.00	503.03	228.65	269.00	0.10	0.25	0.35	660	35
8	Sorab	96.00	45.30	15.81	24.61	0.38	0.59	0.70	266	60
9	Khanapur	320.00	143.74	30.83	48.08	0.34	0.19	0.65	146	63
10	Sagar	75.00	33.56	11.84	10.92	0.54	0.84	0.83	108	55
11	Attigundi	4.51	8.81	3.47	2.34	0.37	0.73	0.69	188	85
12	Hemavati	600.00	127.35	57.89	55.13	0.18	0.46	0.48	350	12
13	Kokkarne	343.00	116.94	34.35	53.17	0.29	0.32	0.61	1147	82
14	Halkal	108.00	48.23	18.39	17.64	0.32	0.58	0.64	1101	92
15	Dasanakatte	135.00	57.95	19.92	28.56	0.34	0.50	0.66	869	92
16	Jadkal	90.00	39.45	13.12	18.75	0.52	0.73	0.82	1142	85
17	Haladi	505.00	105.07	34.79	42.75	0.05	0.57	0.73	968	87

7.2.2 Length

Conceptually length of watershed is the distance traveled by the surface drainage and sometimes more appropriately labeled as hydrologic length (Lm). This length is usually used in computing a time parameter, which is a measure of the travel time of water through a watershed. The hydrologic length of watershed (Lm) is therefore measured along the principal flow path from the watershed outlet to its boundary. Since the channel does not extend up to the basin boundary, it is necessary to extend a line from the end of the channel to the basin boundary. The measurement follows a path where the greatest volume of water would generally travel. The watershed characteristics like perimeter of watershed (P) and maximum length of the watershed parallel to the principal drainage lines (Lb) are also calculated using ILWIS GIS software, which can be further used for computing the shape factor. The perimeter (P), length of the watershed (Lb), and hydrologic length (Lm) of various study watersheds are shown in Table 7.1.

7.2.3 Shape

Basin shape is not generally used directly in hydrologic design methods. However, parameters that reflect basin shape are used and have a conceptual basis. Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will "bunch up" at the outlet. A circular watershed would result in runoff from various parts of the watershed reaching the outlet at the same time. An elliptical watershed having the outlet at one end of the major axis and having the same area as the circular watershed would cause the runoff to be spread out over time, thus producing a smaller flood peak than that of the circular watershed. Watershed having circular to oval shape allows quick disposal of runoff and results in a high peaked and narrow hydrograph while elongated shape of sub watershed allows slow disposal of water and results in a broad and low peaked hydrograph.

Circulatory ratio, elongation ratio, and form factor influence watershed shape or outline forms and these factors can be used for evaluation for stream flow characteristics of a watershed. These indices are the measures to compare basin shape, which is a very important factor influencing the peak flow and other hydrological characteristics such as steepness of rising and recession limbs, the time spread of hydrograph etc. If the value of elongation ratio is equal to one, it shows that the watershed is equally elongated from all sides. The circularity and elongation ratio approaches unity as the shape of drainage basin of the watershed approaches a perfect circle. A number of watershed parameters have been developed to reflect basin shape. Following are few typical parameters.

7.2.3.1 Circularity ratio

Circulatory ratio (Rc) as defined by Miller (1953) is the ratio of basin area of the watershed to the area of the circle having circumference equal to the perimeter of basin of the watershed.

$$Rc = A/A_0 \tag{7.1}$$

where A_0 is the area of a circle having a perimeter equal to the perimeter of the basin. In the present study, the circularity ratio (Rc) value ranges from 0.19 to 0.96 for various watersheds (Table 7.1). It is evident from the drainage map of Amachi watershed (Fig. 4.1). The circular shape of this watershed (Rc = 0.96) promote the quick and high peaked runoff.

7.2.3.2 Elongation ratio

Elongation ratio (Re) as given by Schum (1956) is the ratio between the diameter of a circle with the same area as basin of watershed and the maximum length of the basin parallel to the principal drainage lines.

$$R_e = 2/L_m \, (A/\pi)^{0.5} \tag{7.2}$$

where L_m is the maximum length of the watershed parallel to the principal drainage lines. The Re values can be grouped into three categories, namely circular (>0.9), oval (0.7-0.9), and less elongated (<0.7) (Chopra et al., 2005). The values of elongation ratio (Re) are ranges from 0.35 to 0.93 for various watersheds (Table 7.1) in the present study.

7.2.3.3 Form factor

Form factor is the ratio of basin area of watershed in sq. km. to the square of basin length in km and it is given by the following expression:

$$Rf = A/(Lb)^2 \tag{7.3}$$

The form factor for various study watersheds is presented in Table 7.1. Generally, the shape factor is the best descriptor of peak discharge. It is negatively correlated with peak discharge.

7.2.4 Total Relief

The variables involved in the relief aspects of the watershed are the most significant parameters in hydrological studies of the watershed. The total relief (H) is the maximum vertical distance between lowest (outlet) and the highest (divide) points in the watershed. It is a measure of the potential energy available to move water and sediment downstream. The total relief of various study watersheds is presented in Table 7.1.

7.2.5 Vegetation

Land use in terms of vegetation (V) coverage affects both the volume and timing of runoff. During a rainstorm, flow from an impervious, steeply sloped, and smooth surface make a little retardation and no loss to the flow. In comparison, flow along a pervious forested hill of the same size will produce retardation and significant loss to the flow due to infiltration. In the present study percentage of vegetation in the watershed is computed based on the coverage of forest area within that watershed. The percentage vegetation of various study watersheds is presented in Table 7.1.

In the present study, the parameters of the proposed LTHS ASMA II model are correlated with the above measurable physical characteristics of the watershed by using the multiple regression technique as described in the subsequent section.

7.3 Multiple Regression Analysis

The multiple regression analysis is carried out to develop the relation between the LTHS ASMA II model parameters and the physical properties of the watershed. In the multiple regression, the multiple correlation coefficient (R) is Pearson's product moment correlation between the predicted values (Y') and the observed values (Y). Just as coefficient of determination (r^2) is the proportion of the total variance (s^2) of Y that can be explained by the linear regression of Y on X, R^2 is the proportion of the variance explained by multiple regressions. The significance of R is tested by the F-statistic of the analysis of variance for the regression. The basic idea is to select the most significant regression equation, which corresponds to the minimum p-value of F-test. In regression analysis, selecting variables is very important. As a matter of fact, the first problem that has to be solved in practice is to determine which variables should be included in the model. Obviously, the goodness of regression model depends on the selection of variables. How to select variables that can yield the best regression equation? Aitkin (1974) defined a class of "adequate" regression equations, characterized by a lower bound on the multiple correlation coefficients. Here "adequate" means that each member of the class is not significantly poorer than the complete equation. As Aitkin pointed out, this does not solve the problem of finding the "best" equation for prediction. Besides, Spjotvoll (1972) constructed a multiple comparison method, which usually gives a set of many equations none of which is significantly better than any other. Many criteria have been presented (see Draper & Smith, 1981) for the selection of the “best” regression equation, but none of these has been considered as the best one. Using different criteria, one gets different (the "best") regression equations. Among these criteria are residual mean square (s^2), adjusted multiple correlation coefficient (R), Cp-statistic (Mallows, 1964) and so on. In order to develop a good model based on these criteria, it is necessary to select the best subset.

7.3.1 Need for Subset Selection

A problem arises frequently in multiple regression analysis how to predict the value of a dependent variable when there are a number of variables available to choose as independent variables. Though the high speed of modern algorithms is available to perform the multiple linear regression calculations, it is tempting to select a subset instead of just using all the variables in the model. There are several reasons for need of subset selection given as follows:

i. It may be expensive to collect the full complement of variables for future predictions.
ii. It may be possible to measure more accurately the fewer variables.
iii. Parsimony is an important property of good models. It is easy to obtain more insight into the influence of regressors in models with a few parameters.
iv. Estimates of regression coefficients are likely to be unstable due to multicollinearity in models with many variables. One gets better insights into the influence of regressors from models with fewer variables as the coefficients are more stable for parsimonious models.
v. It can be shown that using independent variables that are uncorrelated with the dependent variable will increase the variance of predictions.
vi. It can be shown that dropping independent variables that have small (non-zero) coefficients can reduce the average error of predictions.

Therefore, in such analyses, it is always better to make predictions with models that do not include irrelevant variables. Dropping independent variables that have small (non-zero) coefficients will improve the predictions as it will reduce the mean square error (MSE). Hence, there is a need for selecting subset of the independent parameters to correlate with the dependant parameters. There are several methods for selecting a subset of predictors that produce the "best" regression. Many statisticians discourage general use of these methods because they can detract from the real-world importance of predictors in a model. Examples of predictor selection methods are step-up selection, step-down selection, stepwise regression, and best subset selection. The fact that there is no predominant method indicates that none of them are broadly satisfactory (Draper and Smith, 1998).

7.3.2 Algorithms for Subset Selection

Selecting subsets to improve MSE is a difficult computational problem for large number of independent variables. The most common procedure for more than 20 independent variables is to use heuristics to select “good” subsets rather than to look for the best subset for a given criterion. The heuristics most often used and available in statistics software are step-wise procedures. There are three common procedures: forward selection, backward elimination, and step-wise regression (Draper and Smith 1981). In forward selection procedure, the variables are kept on adding one at a time to construct what we hope is a reasonably good subset (Draper and Smith 1981). Starting with constant term only in subset, compute the reduction in the sum of squares of the residuals (SSR) obtained by including each variable that is not presently in *S*. For the variable, say, *i*, that give the largest reduction in SSR compute as:

$$F_i = Max_{i \notin S} \frac{SSR(S) - SSR(S \cup \{i\})}{\sigma^2(S \cup \{i\})} \qquad (7.4)$$

If *Fi* > *Fin*, where *Fin* is a threshold (typically between 2 and 4) add *i* to *S*. Repeat until no variables can be added.

The backward elimination started with all variables in *S*. Compute the increase in the sum of squares of the residuals (SSR) obtained by excluding each variable that is presently in *S* (Draper and Smith 1981). For the variable, say, i that give the smallest increase in SSR compute as:

$$F_i = Min_{i \notin S} \frac{\sigma^2(S)}{SSR(S - \{i\}) - SSR(S)} \qquad (7.5)$$

If *Fi* < *Fout*, where *Fout* is a threshold (typically between 2 and 4) then drop *i* from *S*. Repeat until no variable can be dropped. Backward Elimination has the advantage that all variables are included in *S* at some stage. This addresses a problem of forward selection that will never select a variable that is better than a previously selected variable that is strongly correlated with it. The disadvantage is that the full model with all variables is required at the start and this can be time-consuming and numerically unstable.

The step-wise regression procedure is like forward selection except that at each step we consider dropping variables as in backward elimination. Convergence is guaranteed if the thresholds Fout and Fin satisfy: Fout < Fin. It is possible, however, for a variable to enter *S* and then leave S at a subsequent step and even rejoin S at a yet later step. As stated above these methods pick one best subset. There are straightforward variations of the methods that do identify several close to best choices for different sizes of independent variable subsets.

None of the above methods guarantees that they yield the best subset for any criterion such as adjusted R^2. These are reasonable methods for situations with large number of independent variables. Hence, in the present study, stepwise multiple regressions with p-value of F-statistic were followed to select the best subset of various combinations of measurable characteristics of study watersheds by using EXCEL 2007: Multiple Regression and statistical software, namely SYSTAT 10.

7.3.3 Stepwise Multiple Regression

Stepwise regression was introduced by Efroymson (1960). This method is an automated procedure used to select the most statistically significant variables from a large pool of explanatory variables. The method does not take into account industrial knowledge about the process, and therefore, other variables of interest may be later added to the model, if necessary. If properly used, the stepwise regression option in EXCEL 2007 and SYSTAT (or other stat packages) puts more power and information than does the ordinary multiple regression option, and it is especially useful for shifting through large number of potential independent variables and/or fine-tuning a model by poking variables in and/or out. If improperly used, it may converge on a poor model while giving a false sense of security.

The stepwise regression option either begins with no variables in the model or proceeds forward (adding one variable at a time) or starts with all potential variables in the model and proceed backward (removing one variable at a time). At each step, the SYSTAT program performs various calculations via for each variable currently in the model, it computes the t-statistic for its estimated coefficient, squares it, and reports this as its "F-to-remove" statistic; for each variable not in the model, it computes the t-statistic that its coefficient would have if it were the next variable added, squares it, and reports this as its "F-to-enter" statistic. At the next step, the program automatically enters the variable with the highest F-to-enter statistic or removes the variable with the lowest F-to-remove statistic in accordance with certain control parameters that have been specified.

Under the forward method, at each step, it enters the variable with the largest F-to-enter statistic, provided that this is greater than the threshold value for F-to-enter. When there are no variables left to enter whose F-to-enter statistics are above the threshold, it checks to see whether the F-to-remove statistics of any variables added previously have fallen below the F-to-remove threshold. If so, it removes the worst of them, and then tries to continue. It finally stops when no variables either in or out of the model have F-statistics on the wrong side of their respective thresholds. The backward method is similar in spirit, except it starts with all variables in the model and successively removes the variable with the smallest F-to-remove statistic, provided that this is less than the threshold value for F-to-remove.

Whenever a variable is entered, its new F-to-remove statistic is initially the same as its old F-to-enter statistic, but the F-to-enter and F-to-remove statistics of the other variables will generally all change. Similarly, when a variable is removed, its new F-to-enter statistic is initially the same as its old F-to-remove statistic. Until the F-to-enter and F-to-remove statistics of the other variables are recomputed, it is impossible to tell what the next variable to enter or remove will be. Hence, this process is myopic, looking only one step forward or backward at any point. There is no guarantee that the best model that can be constructed from the available variables (or even a good model) will be found by this one-step-ahead search procedure. Hence, when the procedure terminates, one should study the sequence of variables added and deleted, think about whether the variables that were included or excluded make sense. For example, the variable with the lowest F-to-remove or highest F-to-enter may have just missed the threshold value, in which case one may wish to tweak the F-values and see what happens. Sometimes adding a variable with a marginal F-to-enter statistic, or removing one with a marginal F-to-remove statistic, can cause the F-to-enter statistics of other variables not in the model to go up and/or the F-to-remove statistics of other variables in the model to go down, triggering a new chain of entries or removals leading to a very different model.

The selection of stepwise forward or backward multiple regression method depends on the set of independent variables. If a very large set of potential independent variables is available from which one has to extract a few, i.e. one is on fishing expedition, one should generally go forward. On the other hand, if one has a modest-sized set of potential variables from which one wishes to eliminate a few, i.e. one is fine-tuning some prior selection of variables, one should generally go backward. As noted above, after SYSTAT completes a forward run based on the F-to-enter threshold, it takes a backward look based on the F-to-remove threshold, and vice versa. Hence, both thresholds come into play regardless of which method are using, and the F-to-enter threshold must be greater than or equal to the F-to-remove threshold (to prevent cycling). Usually the two thresholds are set to the same value. Keeping in mind that the *F*-statistics are squares of corresponding t-statistics, an F-statistic equal to 4 would correspond to a *t*-statistic equal to 2, which is the usual rule-of-thumb value for "significance at the 5% level." (4 is the default value for both thresholds.). It is always better using a somewhat smaller threshold value than 4 for the automatic phase of the search-for example 3.5 or 3. Since the automatic stepwise algorithm is myopic, it is usually OK to let it enter a few too many variables in the model, and then one can weed out the marginal ones later on by hand. However, beware of using too low an F-threshold if the number of variables is large compared to the number of observations or if there is a problem with multicollinearity in data.

In the present study, first the regression matrix was prepared to have an idea about the poorly correlated physical characteristics with model parameters as shown in Table 7.2. This analysis helps take decision for carrying out multiple linear regression analysis. The multiple regressions were performed using the Data Analysis Add-in facilities of EXCEL 2007. The regression matrix (Table 7.2) was used for choosing the best subset of the watershed characteristics to correlate with model parameters. Since EXCEL 2007 has limited facilities and required several trials to select the best subset of watersheds characteristics, the multiple regressions using stepwise backward elimination procedure based on p-value of F- statistics (Zhang and Wang, 1997) is performed in SYSTAT 10. Here, the p-value is the probability (prob(F)) of obtaining a test statistic at least an extreme as the one that was actually observed, assuming that the null hypothesis is true. Generally, one rejects the null hypothesis if the p-value is smaller than or equal to the significance level (α). If the level is 0.05, then results that

Table 7.2 Regression Matrix between LTHS ASMA II Model Parameters and Physical Characteristics of Study Watersheds

Sr. No.	Model Parameters	Regression coefficient (r^2)								
		Area	Perimeter	Length	Hydrologic length	Form factor	Circulatory ratio	Elongation ratio	Total relief	Vegetation
		(A)	(P)	(Lb)	(Lm)	(Rf)	(Rc)	(Re)	(H)	(V)
1	CNd_0	0.178	0.146	0.196	0.145	0.090	0.001	0.170	0.089	0.175
2	α	0.181	0.261	0.244	0.264	0.307	0.366	0.293	0.218	0.003
3	β	0.160	0.154	0.149	0.138	0.000	0.022	0.057	0.628	0.168
4	γ	0.171	0.221	0.212	0.238	0.300	0.310	0.280	0.131	0.000
5	δ	0.014	0.024	0.025	0.022	0.079	0.027	0.016	0.001	0.024
6	P_3	0.001	0.003	0.014	0.010	0.034	0.004	0.075	0.005	0.012
7	P_4	0.173	0.093	0.101	0.068	0.048	0.071	0.003	0.281	0.191
8	K	0.032	0.079	0.060	0.060	0.124	0.166	0.073	0.127	0.060
9	P_1	0.041	0.029	0.026	0.017	0.011	0.014	0.001	0.043	0.120
10	θ_w	0.262	0.385	0.368	0.370	0.142	0.285	0.291	0.028	0.006
11	ψ_f	0.222	0.329	0.283	0.334	0.221	0.324	0.179	0.085	0.001
12	ψ_0	0.094	0.038	0.050	0.045	0.159	0.032	0.084	0.072	0.000
13	E_g	0.147	0.205	0.190	0.207	0.486	0.483	0.418	0.236	0.000
14	CN_0	0.053	0.011	0.036	0.033	0.062	0.001	0.088	0.010	0.001
15	λ_d	0.172	0.163	0.173	0.173	0.028	0.023	0.079	0.021	0.017

are only 30% likely or less are deemed extraordinary, given that the null hypothesis is true. The calculated p-value exceeds 0.05, so the observation is consistent with the null hypothesis. Likewise, if prob(F)<0.05, then the model is considered significantly better that would be expected by chance and reject the null hypothesis of no linear relationship of model parameters to the measurable physical characteristics of the watersheds. Some of the statisticians also considered the model is highly significant if p-value is less than or equal to 0.001.

The various combination of p-value -to enter and p- value-to remove and/or F-value-to enter and F-value to remove were tried in SYSTAT 10 to choose the correct combination to develop the regression equations. The regression statistics along with analysis of variance (ANOVA) for correct combination of physical characteristics of watersheds to estimate the various model parameters is given in appendix H. As seen from the ANOVA (Appendix H), the multiple correlation coefficient (multiple R) for most of the model parameters such as CN_0, α, β, P_3, P_4, θ_w,ψ_f,,ψ_0, E_g, and CNd_0, are more than 0.60, which indicates that there exists a good correlation between model parameters and measurable physical characteristics of the watersheds. A very good correlation (multiple R=0.95) is found between initial ground water content (ψ_0) and physical characteristics of the watershed such as A, P, Lb, Lm, Rf, Rc, and Re. From the p-value of F-statistics (Appendix H), it is found that the regression equation developed for β, θ_w, ψ_0, and E_g parameters are highly significant (level of significance or p- value is more than 0.001), while some parameters such as δ, K, P_1, and λ_d are very poorly significant (or insignificant) at 95% confidence interval (level of significance or p-value is less than 0.05). From the ANOVA (Appendix H), the regression equations for various model parameters were formulated as shown in Table 7.3. As seen from Table 7.3, the multi-linear regression equations developed for some of the model parameters of LTHS ASMA II model are highly significant, while there exists a significant relationship for most of the parameters. Hence, the multi-linear regression equations developed for these model parameters (except for those parameters for which regression equations are found insignificant) may be used for parameter estimation using the measurable physical characteristics of watersheds. Thus, many parameters in the proposed model (LTHS ASMA II) could be estimated from catchment characteristics and could potentially be used for field application when sufficient data for better calibration of parameters of the model do not exist.

Table 7.3 Regression Equations Showing Relationship between LTHS ASMA II Model Parameters and Physical Characteristics of Watersheds

Model Parameter	Multi-linear Regression Equation	Multiple (R^2)
CN_0	$CN_0=31.991-0.317P+0.702Lb$	0.39
α	$\alpha=0.64-0.424Rc+0.0001H$	0.52
β	$\beta=0.022-0.001L+0.0003H$	0.76*
γ	$\gamma=0.751-0.37Rc$	0.31
δ	$\delta=0.023Lb+10.38Rf-2.75$	0.24**
P_3	$P_3=0.45+0.0003A+0.005P-0.02Lb$	0.56
P_4	$P_4=1.38-0.0001A-0.018Lb+0.017Lm-1.125Rf+0.0001H$	0.74
K	$K=1.27-0.011H+0.147V$	0.40**
P_1	$P_1=0.02+0.001P-0.002Lb-0.0002Lm+0.17Rc-0.18Re$	0.24**
θ_w	$\theta_w=10.968Lb-8.248Lm+275.567Rf-481.685Rc+319.221Re+2.709V-133.414$	0.85*
ψ_f	$\theta_f=180.578+0.835Lm-330.33Rc+444.463Re$	0.54
ψ_0	$\psi_0=0.26A-15.69P+48.91Lb-17.0Lm-320.07Rf-3144.86Rc+4051.43Re-207.56$	0.91*
λ_d	$\lambda_d=0.056+0.001Lm$	0.17**
CNd_0	$CNd_0=36.79+1.51Lb-1.19Lm$	0.52
E_g	$E_g=0.242+0.601Rc-0.0001H$	0.65*

Note: * highly significant at 95% confidence interval
** not significant at 95% confidence interval

7.4 REMARKS

The relationship between model parameters and measurable physical characteristics of the watersheds using multiple regression analysis is developed in this chapter. The step-wise regression with backward elimination on p-value of F-statistics is followed to develop regression equations. In most of the cases, a significant relationship is found between the model parameters and physical characteristics of study watersheds at 95% confidence interval. From this analysis, it is concluded that there exists a relationship between LTHS ASMA II model parameters and physical characteristics of study watersheds.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 SUMMARY

In the present study four new/modified Long Term Hydrologic Simulation models are proposed to simulate the stream flow and to understand the stream flow generation process in a watershed. These models are based on modified SMA procedure in SCS-CN concept and operate on daily time step. The first model, LTHS MICHEL I uses the expression for soil moisture store level prior to rainfall occurrence (V_0) for various antecedent moisture conditions (AMCs) proposed by Michel et al.(2005), while the second LTHS MICHEL II is formulated based on antecedent moisture amount (AM) to avoid the sudden jump in CN and further quantum jump in V_0. Since V_0 plays a vital role in the proposed SMA procedure, in the third LTHS ASMA I, the SMA procedure is re-conceptualized by deriving an expression for V_0 based on pre-antecedent moisture level before the onset of rainfall (V_{00}), leading to the advance soil moisture accounting (ASMA) procedure. In the fourth LTHS ASMA II, the subsurface component via sub-surface drainage flow is modified following Yuan et al., (2001).

The proposed models were tested on annual and seasonal data series of 17 watersheds of various shape/size, physical characteristics, located in various agro-climatic zones of India. The performance of these models is quantitatively evaluated using various evaluation criteria viz., Nash-Sutcliffe coefficient of efficiency (NSE), root mean square error (RMSE), standard error (SE), and percent relative error (RE). It is revealed from the analysis that the proposed LTHS ASMA II model yields maximum NSE of 0.92 in calibration for Kokkarne watershed and 0.90 in validation for Hemavathi watershed whereas minimum efficiency of 0.52 is observed in calibration of LTHS MICHEL I model for Hridaynagar watershed and 0.34 in validation for Anthrolli watershed (excluding the most dry watershed, Hirehalla). In general, all the models yield high efficiency for wet (high yielding) watersheds indicating a very good model response for these watersheds, and low efficiency for dry (low yielding) watersheds.

The LTHS ASMA II model produces better results than the others ranked as LTHS ASMA I, LTHS MICHEL II, and LTHS MICHEL I models. This is apparent from the trend analysis by plotting of ascending order of runoff coefficient of various watersheds under study against NSE values in calibration and validation.

On the basis of SE, the performance of the LTHS ASMA II model was adjudged better compared to other models for most of watersheds studied. The range of SE obtained for various proposed LTHS models decreases in the order: LTHS MICHEL I, LTHS MICHEL II, LTHS ASMA I, and LTHS ASMA II in both calibration and validation. The plot of mean value of SE for the proposed models shows the decreasing order of performance as LTHS ASMA II > LTHS ASMA I > LTHS MICHEL II > LTHS MICHEL I. Similar to the trend for NSE, SE also increases with catchment wetness in terms of average runoff coefficient. This may be due to the underestimation of some high peaks of the hydrograph in case of high yielding watershed. The comparative performance based on RE also shows the better performance of LTHS ASMA II model. The trend analysis for RE shows that absolute annual average of RE is decreasing with watershed wetness reflecting a better performance for low yielding watersheds than high yielding watersheds. The existing lumped continuous SCS-CN based long term simulation models such as Michel et al. (2005) and Geetha et al. (2008) models were also tested on annual data series of study watersheds. The performance of the best model among the proposed model in this study (i.e. LTHS ASMA II) is also compared with the existing models and found that the performance of proposed LTHS ASMA II model is better than the existing models. Similarly, the proposed LTHS models were also tested for seasonal data series (June-November) of study watersheds, which also depicts similar results as seen for annual data series. But the model efficiency is better for annual data than seasonal data. This can be mainly attributed to the discontinuity in seasonal data series, which may cause the improper accounting of antecedent moisture.

The performance of the proposed models is also analyzed on the basis of subjective assessment through visual comparison between the observed and simulated runoff. The results were plotted for calibration and validation periods or all models using annual and seasonal data of all watersheds, which shows a close match between simulated and observed stream flows for most of the watersheds except for some deviation in simulating the peak flows. The components of various runoff generating mechanisms are quantified to compare the significance of these components in various watersheds. The base flow is found to be more significant in high runoff producing coastal watersheds than low runoff producing watersheds, while the evapo-transpiration shows reverse trends. All other components except deep percolation show linearly increasing trends with respect to runoff coefficient and are more significant/dominant in high runoff producing watersheds. The deep percolation is dormant in high runoff producing watersheds.

The sensitivity analysis has been carried out to identify the sensitivity of parameters to model output. The model giving better results (i.e. LTHS ASMA II) was considered for sensitivity analysis. The parameter (γ) related with V_{00} is found to be the most sensitive parameter among all parameters. For majority of the study watersheds, the curve numbers at the starting day of simulation for surface flow (CN_0) and subsurface drainage flow (CNd_0) are also highly sensitive parameters in addition to those related with soil characteristics, viz., wilting point (θ_w) and field capacity (ψ_f). Hence, an underestimation or overestimation of these parameters will produce large errors in simulation of stream flows and therefore demands great attention while estimating these parameters.

An effort was also made to minimize the number of parameters involved in this model by fixing the insensitive or less sensitive parameters based on statistical analysis and this, in turn, resulted in formulation of a nine-parameter simplified model (LTHS ASMA SIMP). The performance of this model was also evaluated for all study watersheds by comparing its results with LTHS ASMA II model. The proposed LTHS ASMA SIMP model prformed as well as did ASMA LTHS II model, but with little reduction in model efficiency. Efforts were also made to develop a relationship between model parameters and measurable physical characteristics of the watersheds using multiple regression analysis. Step-wise regression with backward elimination on p-value of F-statistics is followed to develop regression equations. In most of the cases, a significant relationship is found between the model parameters and physical characteristics of study watersheds at 95% confidence interval.

8.2 CONCLUSIONS

The popular and extensively employed SCS-CN method was critically reviewed for its structure, application, and inconsistencies to simulate daily stream flow. Based on the review, the gaps were identified, and consequently, attempt has been made to propose new/modified form of SCS-CN method to use it for long term simulation based on stronger mathematical foundation and hydrologically more realistic perception. On the basis of quantitative assessment for the performance of the proposed LTHS models based on various statistical criteria and further subjective assessment through visual comparison between observed and simulated stream flow, the following conclusions can be drawn:

1. Among the proposed LTHS models, LTHS ASMA II which incorporates the proposed Advance Soil Moisture Accounting procedure and modified SCS-CN based conceptual frame work for sub-surface drainage flow produce better results than to other models when applied to the daily data (annual and seasonal) of rainfall and observed stream flow of 17 study watersheds situated in different agro-climatic zones of India.

2. LTHS ASMA II yields highest efficiency (up to 0.92) in calibration for high runoff producing (wet) watershed indicating a very good model performance. Overall, all the four proposed LTHS models yields high efficiency, and lower RE values for wet (high yielding) watersheds and comparatively lower values of efficiency for dry (low yielding) watersheds indicating a very good model response for wet watersheds and good to satisfactory model response for dry watersheds and poor response to most dry watershed.

3. The proposed models also help understand and identify various process involved in runoff generating mechanism. The base flow is more significant in high runoff producing coastal watersheds than low runoff producing watersheds, while the evapo-transpiration shows reverse trends. All other components, except deep percolation, show linearly increasing trends with runoff coefficient while deep percolation is dormant in high runoff producing watersheds.

4. The parameters sensitivity for LTHS ASMA II model dictates a needs for accuracy in the estimation of the coefficient (γ) of pre-antecedent soil moisture store level (V_{00}) and initial values of curve number values for surface flow and sub-surface drainage flow along with the parameters related with soil characteristics, viz., wilting point and field capacity.

5. The simplified model LTHS ASMA SIMP developed by fixing some of the parameter values through sensitivity analysis produce results comparable with ASMA LTHS II model with minimum reduction in efficiency and significant reduction in number of parameters.

6. Developed relationship between some model parameters and measurable catchment characteristics show highly significant correlation at 95% confidence level, and hence, these relations can be used for parameter estimation with high degree of confidence.

7. The proposed LTHS models are capable of simulating daily stream flow and also of capturing the variability of curve numbers representing hydrological characteristics in complex dynamic watersheds.

The specific conclusions of this study can be summarizes as follows:

1. The modified SMA procedure based on AM instead of different AMCs improves significantly the model performance.

2. The incorporation of the developed ASMA procedure in the LTHS ASMA I improve the model efficiency and produces better results than LTHS MICHEL I and LTHS MICHEL II models due to improvements in surface flow component.

3. An expression for sub-surface drainage flow is proposed based on modified SCS-CN concept. The incorporation of proposed relation along with ASMA procedure (Model-IV) produces better performance among the proposed models.

4. Proposed LTHS models perform very good on the data of wet watersheds, good to satisfactory on less dry watersheds, and poor in most dry watersheds. In general, these models are capable of capturing the variability of curve numbers representing hydrological characteristics of the complex watersheds.

5. The base flow is more significant in high runoff producing coastal watersheds than low runoff producing watersheds.

6. Model parameters such as coefficient of pre-antecedent soil moisture store level (V_{00}), curve number, field capacity, permanent wilting point were highly to most sensitive to runoff estimation, requiring careful assessment.

7. The proposed simplified nine-parameter LTHS ASMA SIMP model can be used for long term hydrologic simulation of stream flow.

8. There exists a relationship between LTHS ASMA II model parameters and physical characteristics of study watersheds.

8.3 MAJOR CONTRIBUTIONS OF THE STUDY

The major contribution of the present study is enumerated as follows;

1. Development of four different SCS-CN-based long term hydrologic simulation models by modifying the SMA procedure in SCS-CN concept to simulate the daily stream of watersheds of various shape/size, physical characteristics and located in various agro-climatic zones of India.

2. An expression for initial soil moisture store level, V_0, is proposed in LTHS ASMA I model which deals for advanced SMA procedure to make the SMA procedure amenable to continuous simulation of daily stream flow and, in turn, SMA procedure

is improved as advance soil moisture accounting (ASMA) procedure to incorporate into the model for long term hydrologic simulation (LTHS) of daily stream flow (Durbude et al., 2010).

3. An expression for ASMA and sub-surface drainage flow is proposed in LTHS ASMA II model based on the modified SCS-CN concept. The incorporation of these relations exhibits an improvement over the existing models of Michel et al. (2005) and Geetha et al. (2008).
4. Simplification of 15-parameter LTHS ASMA II model into a 9-parameter LTHS ASMA SIMP model with little reduction in model efficiency.
5. Development of relationships between LTHS ASMA II model parameters and physical characteristics of study watersheds for field application.

8.4 SCOPE FOR FURTHER RESEARCH WORK

The following may be explored in future for further refinement:

The simulated stream flow showing higher deviation from the observed ones in case of dry and most dry watersheds, like Hirehalla, Hridaynagar, etc. suggest that proposed and existing models lack in some key aspects dominating in relatively dry watersheds and need further investigation for better understanding of runoff generating phenomena in these watersheds.

Rainfall intensity and storm duration are not considered in the proposed LTHS models in this study. The intensity and duration of rainfall may influence the transformation of rainfall into stream flow. This aspect may be studied in context of the proposed modeling framework in future.

GIS could be used for discretization of the watershed in smaller units and proposed modeling framework can be converted into a distributed model for study of sub watershed variability dominating runoff producing processes in future studies.

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ANNUAL VALUES OF RAINFALL, OBSERVED RUNOFF, SIMULATED RUNOFF, AND RE (%) FOR THE PROPOSED MODELS

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	LTHS MICHEL I (M-I)		LTHS MICHEL II (M-II)		LTHS ASMA I (M-III)		LTHS ASMA II (M-IV)	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
1	Hemavathi	1975-76	2940.5	2552.5	2118.4	17.0	2071.7	18.8	2132.4	16.5	2643.34	-3.6
		1976-77	2648.1	1718.0	1728.1	-0.6	1785.9	-4.0	1882.7	-9.6	1463.29	14.8
		1977-78	2728.6	1896.0	1737.4	8.4	1826.8	3.6	1824.7	3.8	1575.92	16.9
		1978-79	2889.5	2935.5	2100.3	28.4	2227.6	24.1	2273.4	22.6	2073.66	29.4
		1979-80	3087.1	2061.8	1992.2	3.4	2256.4	-9.4	2345.1	-13.7	1990.71	3.4
	Average		**2858.7**	**2232.7**	**1935.3**	**11.6**	**2033.7**	**12.0**	**2091.7**	**13.2**	**1949.4**	**13.6**
1	Hridaynagar	1981-82	1586.6	314.4	243.9	22.4	299.9	4.6	272.2	13.4	354.0	-12.6
		1982-83	1461.5	309.3	303.0	2.0	296.1	4.3	283.3	8.4	338.9	-9.6
		1983-84	1937.1	375.1	444.4	-18.5	411.8	-9.8	426.3	-13.6	387.8	-3.4
		1984-85	1300.0	294.6	229.1	22.2	203.9	30.8	219.5	25.5	194.1	34.1
		1985-86	1457.2	254.9	137.6	46.0	167.2	34.4	181.2	28.9	126.3	50.4
		1986-87	1811.5	593.0	398.8	32.7	400.3	32.5	357.5	39.7	443.8	25.2
		1987-88	879.7	179.4	38.5	78.5	23.9	86.7	28.1	84.4	24.5	86.3
		1988-89	1375.2	560.2	182.1	67.5	203.0	63.8	210.0	62.5	156.0	72.2
		1989-90	1167.6	285.4	74.2	74.0	112.6	60.6	108.5	62.0	90.2	68.4
	Average		**1441.8**	**351.8**	**227.9**	**40.4**	**235.4**	**36.4**	**231.8**	**37.6**	**235.1**	**40.2**
3	Barchi	1989-90	998.2	225.9	312.2	-38.2	370.4	-64.0	341.9	-51.4	283.8	-25.6
		1990-91	1602.8	615.2	499.7	18.8	526.2	14.5	536.7	12.8	387.3	37.0
		1991-92	1684.2	666.8	693.2	-4.0	701.4	-5.2	708.2	-6.2	568.5	14.7
		1992-93	1630.4	667.8	632.8	5.2	544.5	18.5	704.2	-5.5	424.1	36.5
		1993-94	1181.6	313.1	332.2	-6.1	247.9	20.8	406.7	-29.9	111.5	64.4
	Average		**1419.4**	**497.7**	**494.0**	**14.5**	**478.1**	**24.6**	**539.5**	**21.1**	**355.0**	**35.7**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
4	Manot	1981-82	1135.5	386.8	379.4	1.9	360.8	6.7	419.3	-8.4	430.6	-11.3
		1982-83	1023.9	374.8	426.2	-13.7	415.0	-10.7	414.0	-10.5	411.7	-9.9
		1983-84	1391.1	572.8	591.6	-3.3	612.1	-6.9	599.4	-4.7	596.8	-4.2
		1984-85	1303.4	622.5	574.1	7.8	653.7	-5.0	616.9	0.9	619.4	0.5
		1985-86	1263.6	720.0	552.5	23.3	536.5	25.5	532.5	26.0	476.0	33.9
		1986-87	1378.7	715.0	539.5	24.5	555.7	22.3	617.7	13.6	471.4	34.1
		1987-88	1347.4	775.0	598.5	22.8	524.0	32.4	668.4	13.8	520.2	32.9
		1988-89	1308.7	637.2	631.7	0.9	629.5	1.2	732.4	-14.9	544.9	14.5
		1989-90	1220.0	279.5	455.3	-62.9	449.3	-60.8	524.6	-87.7	351.8	-25.9
	Average		**1263.6**	**564.8**	**527.6**	**17.9**	**526.3**	**19.1**	**569.5**	**20.1**	**491.4**	**18.6**
5	Amachi	1985-86	1513.6	445.9	333.2	25.3	397.1	10.9	529.5	-18.8	332.6	25.4
		1986-87	1254.5	390.2	268.6	31.2	241.8	38.0	290.0	25.7	219.9	43.7
		1987-88	1360.4	304.9	306.5	-0.5	264.8	13.1	312.6	-2.5	211.9	30.5
		1988-89	1800.5	458.4	568.7	-24.1	546.0	-19.1	557.4	-21.6	433.3	5.5
		1989-90	1722.6	494.1	396.9	19.7	439.3	11.1	446.7	9.6	330.8	33.0
		1990-91	1838.4	602.3	318.7	47.1	507.5	15.7	509.9	15.3	350.5	41.8
		1991-92	1823.3	529.9	393.1	25.8	561.6	-6.0	558.9	-5.5	382.0	27.9
		1992-93	2315.7	651.1	698.2	-7.2	765.1	-17.5	775.0	-19.0	606.7	6.8
		1993-94	1737.1	548.2	331.4	39.5	451.0	17.7	469.0	14.4	298.4	45.6
	Average		**1707.3**	**491.7**	**401.7**	**24.5**	**463.8**	**16.6**	**494.3**	**14.7**	**351.8**	**28.9**
6	Anthrolli	1985-86	755.6	256.2	248.6	3.0	192.5	24.9	207.6	19.0	237.9	7.2
		1986-87	709.2	147.7	209.8	-42.1	157.1	-6.4	183.2	-24.1	193.2	-30.9
		1987-88	733.0	200.5	187.4	6.5	157.4	21.5	181.7	9.4	195.9	2.3
		1988-89	1011.8	341.9	360.7	-5.5	336.4	1.6	371.5	-8.7	360.7	-5.5
		1989-90	832.5	287.0	235.1	18.1	190.1	33.8	218.8	23.8	224.6	21.8
		1990-91	1086.8	405.0	385.0	4.9	327.9	19.0	361.6	10.7	406.3	-0.3
		1991-92	1200.2	444.3	516.9	-16.3	442.2	0.5	472.2	-6.3	479.7	-8.0
		1992-93	1365.4	503.5	513.7	-2.0	455.0	9.6	489.5	2.8	522.3	-3.8
		1993-94	1295.9	700.5	499.7	28.7	431.7	38.4	478.6	31.7	495.4	29.3
	Average		**998.9**	**365.2**	**350.8**	**14.1**	**298.9**	**17.3**	**329.4**	**15.1**	**346.2**	**12.1**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
7	Attigundi	1985-86	1868.0	1274.3	1091.8	14.3	1227.4	3.7	1395.2	-9.5	1254.2	1.6
		1986-87	2285.6	1681.0	1666.8	0.8	1595.6	5.1	1559.5	7.2	1870.8	-11.3
		1987-88	1607.1	1131.8	1079.5	4.6	1004.1	11.3	1113.8	1.6	1137.1	-0.5
		1988-89	1567.8	1086.4	1107.9	-2.0	1041.1	4.2	1047.1	3.6	1195.5	-10.0
		1989-90	1457.4	985.2	736.4	25.3	716	27.3	836.3	15.1	944.1	4.2
		1990-91	2073.7	1309.4	1482.5	-13.2	1407.8	-7.5	1446.6	-10.5	1584.2	-21.0
		1991-92	1709.0	1284.0	1197.2	6.8	1068.7	16.8	1137.9	11.4	1220.5	4.9
		1992-93	2682.2	2091.6	1972.4	5.7	1887.4	9.8	1879.5	10.1	1988.5	4.9
		1993-94	2394.8	1793.7	1703.9	5.0	1590.1	11.3	1610.6	10.2	1686.8	6.0
	Average		**1960.6**	**1404.2**	**1337.6**	**8.6**	**1282.0**	**10.8**	**1336.3**	**8.8**	**1431.3**	**7.2**
8	Mohegaon	1981-82	1240.0	333.6	308.9	7.4	263.9	20.9	307.2	7.9	367.6	-10.2
		1982-83	1112.9	338.6	297.0	12.3	316.9	6.4	253.8	25.1	299.8	11.5
		1983-84	1533.1	485.7	436.2	10.2	480.0	1.2	427.6	12.0	453.6	6.6
		1984-85	1294.9	518.0	409.5	20.9	486.4	6.1	531.5	-2.6	481.7	7.0
		1985-86	1329.1	578.5	319.0	44.9	361.5	37.5	437.8	24.3	349.7	39.5
		1986-87	1356.1	470.5	380.3	19.2	429.6	8.7	484.4	-2.9	388.9	17.4
		1987-88	1125.2	377.5	222.5	41.1	255.1	32.4	339.5	10.1	243.3	35.6
		1988-89	1165.9	550.3	317.9	42.2	356.7	35.2	432.2	21.5	334.2	39.3
		1989-90	925.9	227.0	149.6	34.1	184.7	18.6	231.2	-1.8	174.1	23.3
	Average		**1231.5**	**431.1**	**315.7**	**25.8**	**348.3**	**18.6**	**382.8**	**12.0**	**343.6**	**21.1**
9	Khanapur	1985-86	3935.0	1665.4	2164.7	-30.0	2138.2	-28.4	2046.4	-22.9	2237.9	-34.4
		1986-87	3175.7	1736.4	1438.6	17.2	1439.5	17.1	1497.9	13.7	1455.3	16.2
		1987-88	3371.1	1475.2	1336.2	9.4	1536.8	-4.2	1598.3	-8.3	1549.2	-5.0
		1988-89	4517.6	2498.9	2483.9	0.6	2402.9	3.8	2469.0	1.2	2507.3	-0.3
		1989-90	3832.1	1788.1	1829.7	-2.3	1854.4	-3.7	1919.0	-7.3	1894.3	-5.9
		1990-91	4219.0	2697.4	2142.2	20.6	2026.2	24.9	2128.6	21.1	2291.0	15.1
		1991-92	3997.3	2822.2	2192.7	22.3	1988.3	29.5	2074.0	26.5	2288.6	18.9
		1992-93	4214.4	3375.2	2153.0	36.2	2009.2	40.5	2101.5	37.7	2316.6	31.4
		1993-94	4560.7	3530.9	2269.3	35.7	2192.6	37.9	2290.2	35.1	2532.4	28.3
	Average		**3980.3**	**2398.8**	**2001.2**	**19.4**	**1954.2**	**21.1**	**2013.9**	**19.3**	**2119.2**	**17.3**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
10	Hirehalla	1985-86	435.9	30.4	2.1	93.2	39.7	-30.5	44.2	-45.2	51.6	-69.6
		1986-87	398.4	33.4	0.3	99.2	34.3	-2.6	27.0	19.4	43.0	-28.6
		1987-88	672.0	66.7	9.4	85.9	61.6	7.6	47.3	29.1	67.7	-1.5
		1988-89	712.0	89.4	58.6	34.5	66.1	26.0	74.9	16.2	73.9	17.3
		1989-90	561.9	51.7	20.1	61.2	48.5	6.1	41.0	20.6	59.7	-15.4
		1990-91	592.1	62.3	26.7	57.1	56.8	8.9	45.3	27.3	64.5	-3.6
		1991-92	515.6	78.1	20.8	73.4	51.5	34.0	43.9	43.7	63.1	19.2
		1992-93	613.6	106.0	26.5	75.0	61.8	41.7	55.9	47.2	78.3	26.1
		1993-94	849.3	92.1	100.0	-8.6	85.4	7.2	107.4	-16.7	106.2	-15.3
	Average		**594.5**	**67.8**	**29.4**	**65.3**	**56.2**	**18.3**	**54.1**	**29.5**	**67.6**	**21.8**
11	Sagar	1985-86	1625.7	952.4	787.2	17.3	765.8	19.6	1019.5	-7.0	1056.3	-10.9
		1986-87	1340.6	788.6	658.9	16.4	595.8	24.4	661.5	16.1	725.2	8.0
		1987-88	1417.7	791.4	642.2	18.9	668.7	15.5	683.4	13.6	724.3	8.5
		1988-89	1871.3	1191.2	1006.6	15.5	1122.6	5.8	1152.5	3.2	1131.1	5.0
		1989-90	1797.0	976.4	874.0	10.5	954.7	2.2	999.9	-2.4	1007.2	-3.2
		1990-91	2120.5	1471.5	1136.5	22.8	1274.0	13.4	1269.6	13.7	1254.8	14.7
		1991-92	2040.9	1474.0	1125.2	23.7	1257.8	14.7	1264.8	14.2	1246.5	15.4
		1992-93	2528.4	1847.5	1394.0	24.5	1638.8	11.3	1659.5	10.2	1581.9	14.4
		1993-94	2037.4	1505.1	1016.9	32.4	1115.4	25.9	1175.7	21.9	1169.3	22.3
	Average		**1864.4**	**1222.0**	**960.2**	**20.2**	**1043.7**	**14.8**	**1098.5**	**11.4**	**1099.6**	**11.4**
12	Sorab	1985-86	824.8	481.9	546.0	-13.3	337.6	29.9	452.8	6.0	484.9	-0.6
		1986-87	725.5	430.3	258.6	39.9	259.5	39.7	245.7	42.9	325.2	24.4
		1987-88	1004.7	556.9	392.3	29.6	470.8	15.5	434.3	22.0	506.2	9.1
		1988-89	1368.7	852.4	780.0	8.5	868.8	-1.9	849.3	0.4	892.5	-4.7
		1989-90	1265.3	645.6	574.8	11.0	666.2	-3.2	611.0	5.4	648.3	-0.4
		1990-91	1556.3	914.5	748.6	18.1	829.9	9.2	813.6	11.0	835.5	8.6
		1991-92	1605.7	1057.7	919.8	13.0	998.3	5.6	1005.4	4.9	1062.0	-0.4
		1992-93	2102.9	987.8	1189.0	-20.4	1311.9	-32.8	1322.4	-33.9	1442.3	-46.0
		1993-94	1436.7	970.2	652.6	32.7	758.2	21.9	731.5	24.6	741.6	23.6
	Average		**1321.2**	**766.4**	**673.5**	**20.7**	**722.3**	**17.7**	**718.4**	**16.8**	**770.9**	**13.1**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
13	Dasanakatte	1985-86	4926.3	4101.0	3831.7	6.6	3988.4	2.7	4196.1	-2.3	4463.0	-8.8
		1986-87	4447.3	3937.1	3417.8	13.2	3457.3	12.2	3846.9	2.3	3699.3	6.0
		1987-88	3534.6	3050.4	2484.2	18.6	2531.7	17.0	2963.6	2.8	2864.3	6.1
		1988-89	4317.1	3894.7	3375.4	13.3	3442.6	11.6	3784.5	2.8	4211.0	-8.1
		1989-90	4257.7	3901.6	2960.4	24.1	2967.7	23.9	3376.2	13.5	3251.2	16.7
		1990-91	4992.0	4423.2	4132.7	6.6	4241.9	4.1	4666.5	-5.5	4809.0	-8.7
		1991-92	3992.4	3506.1	3085.7	12.0	3233.3	7.8	3629.1	-3.5	3219.2	8.2
		1992-93	4648.1	4407.5	3690.1	16.3	3823.4	13.3	4192.7	4.9	3892.4	11.7
		1993-94	6542.9	6277.2	5326.8	15.1	5828.5	7.1	6129.7	2.3	5995.0	4.5
	Average		**4628.7**	**4166.5**	**3589.4**	**14.0**	**3723.9**	**11.1**	**4087.3**	**4.4**	**4044.9**	**8.8**
14	Haladi	1985-86	4679.8	4470.4	3733.8	16.5	3805.8	14.9	3743.3	16.3	4408.8	1.4
		1986-87	4615.5	4277.6	3650.1	14.7	3852.2	9.9	3870.0	9.5	4617.7	-8.0
		1987-88	3551.5	3214.7	2534.7	21.2	2815.5	12.4	2839.2	11.7	2829.5	12.0
		1988-89	4356.2	3901.6	3500.1	10.3	3670.1	5.9	3681.1	5.7	4254.8	-9.1
		1989-90	4417.8	3906.8	3131.1	19.9	3370.9	13.7	3389.5	13.2	3604.2	7.7
		1990-91	5838.6	5574.5	4980.2	10.7	5258.8	5.7	5263.8	5.6	5932.9	-6.4
		1991-92	4308.7	4058.6	3436.4	15.3	3755.2	7.5	3776.3	7.0	2761.1	32.0
		1992-93	5242.3	4987.3	4348.0	12.8	4538.8	9.0	4553.9	8.7	3589.8	28.0
		1993-94	5453.8	5214.2	4391.2	15.8	4595.1	11.9	4622.8	11.3	3584.1	31.3
	Average		**4718.2**	**4400.6**	**3745.1**	**15.2**	**3962.5**	**10.1**	**3971.1**	**9.9**	**3953.7**	**15.1**
15	Jadkal	1985-86	4552.6	4324.3	3507.4	18.9	4187.7	3.2	4187.9	3.2	4396.8	-1.7
		1986-87	4216.4	3896.9	3202.8	17.8	3667.4	5.9	3845.5	1.3	3913.4	-0.4
		1987-88	4140.3	3877.9	3009.0	22.4	3563.1	8.1	3810.3	1.7	3505.2	9.6
		1988-89	5469.5	5285.3	4295.7	18.7	4899.7	7.3	5111.5	3.3	5448.1	-3.1
		1989-90	4866.0	4454.0	3599.9	19.2	4147.2	6.9	4321.8	3.0	4256.8	4.4
		1990-91	6493.1	5819.9	5547.8	4.7	6187.5	-6.3	6403.3	-10.0	7058.1	-21.3
		1991-92	5310.1	4726.5	4366.2	7.6	4855.1	-2.7	5032.1	-6.5	3951.6	16.4
		1992-93	6373.2	5936.4	5227.4	11.9	5895.1	0.7	6113.7	-3.0	4691.3	21.0
		1993-94	5462.8	5015.0	4272.3	14.8	4831.2	3.7	5053.9	-0.8	3713.1	26.0
	Average		**5209.3**	**4815.1**	**4114.3**	**15.1**	**4692.7**	**5.0**	**4875.6**	**3.6**	**4548.3**	**11.5**

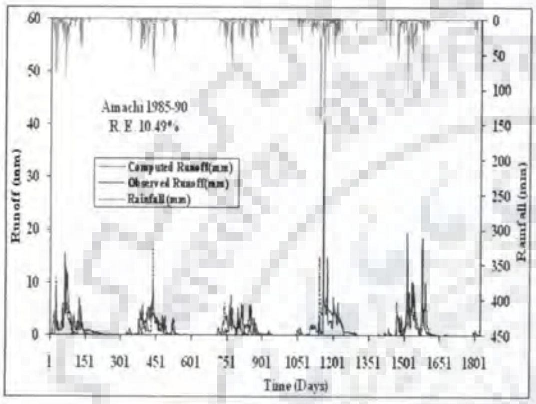
Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
16	Kokkarne	1985-86	4937.7	3932.4	3962.3	-0.8	3656.0	7.0	3689.7	6.2	4210.8	-7.1
		1986-87	4555.9	3521.7	3592.9	-2.0	3594.9	-2.1	3501.8	0.6	3284.1	6.7
		1987-88	3752.2	2538.8	2770.3	-9.1	2771.9	-9.2	2668.9	-5.1	2513.9	1.0
		1988-89	4803.9	3955.0	3934.4	0.5	4046.8	-2.3	3844.0	2.8	3968.7	-0.3
		1989-90	5203.8	4119.9	3924.6	4.7	4010.7	2.6	3790.7	8.0	3786.0	8.1
		1990-91	5608.5	4742.0	4807.2	-1.4	4908.0	-3.5	4704.7	0.8	4893.8	-3.2
		1991-92	4821.9	3998.1	3922.9	1.9	4151.4	-3.8	3902.7	2.4	4114.0	-2.9
		1992-93	5492.0	4271.4	4474.0	-4.7	4483.4	-5.0	4382.0	-2.6	4495.8	-5.3
		1993-94	6378.5	5016.1	5245.2	-4.6	5384.0	-7.3	5127.3	-2.2	5404.8	-7.7
	Average		**5061.6**	**4010.6**	**4070.4**	**3.3**	**4111.9**	**4.8**	**3956.9**	**3.4**	**4074.7**	**4.7**
17	Halkal	1985-86	4552.6	4013.2	3444.3	14.2	3840.3	4.3	3502.4	12.7	4117.1	-2.6
		1986-87	4216.4	3603.2	3371.3	6.4	3345.9	7.1	3335.4	7.4	3418.9	5.1
		1987-88	4140.3	3466.1	3222.7	7.0	3261.8	5.9	3260.4	5.9	3007.7	13.2
		1988-89	5469.5	4729.8	4503.8	4.8	4572.5	3.3	4544.7	3.9	4672.1	1.2
		1989-90	4866.0	4048.8	3751.5	7.3	3820.0	5.7	3811.8	5.9	3675.1	9.2
		1990-91	6493.1	5909.8	5706.0	3.4	5839.3	1.2	5862.3	0.8	6539.7	-10.7
		1991-92	5310.1	4778.4	4455.5	6.8	4476.1	6.3	4465.5	6.5	4902.8	-2.6
		1992-93	6648.1	6270.6	5593.5	10.8	5720.8	8.8	5697.8	9.1	6071.6	3.2
		1993-94	5462.8	5031.9	4469.6	11.2	4510.5	10.4	4499.5	10.6	4567.8	9.2
	Average		**5239.9**	**4650.2**	**4279.8**	**8.0**	**4376.3**	**5.9**	**4650.2**	**7.0**	**4552.5**	**6.3**

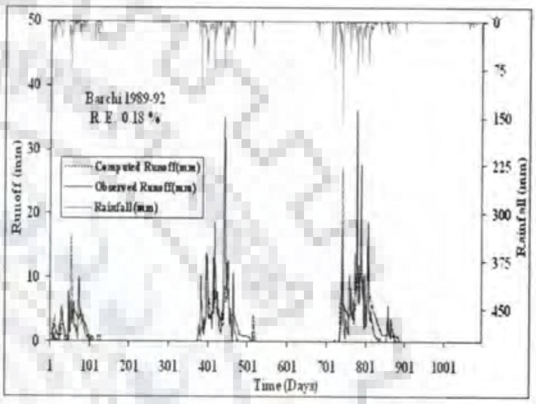
*** Average Relative Error (%) is absolute value (Average RE = $\sum_{i=1}^{n} |RE(\%)| / n$, n=no. of years)**

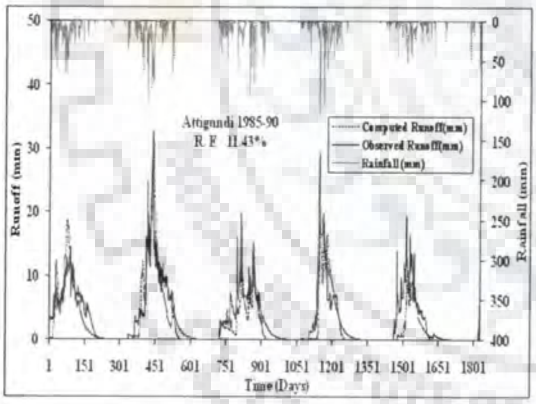
APPENDIX B

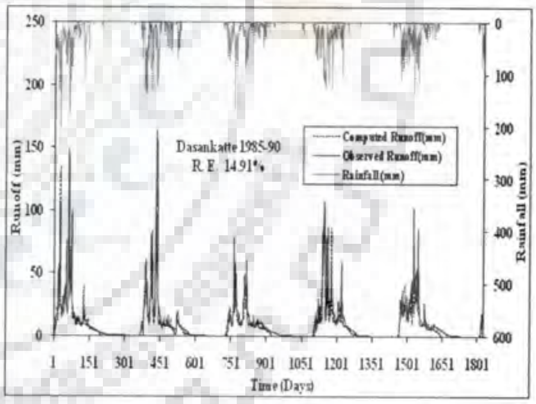
PLOTS OF DAILY VARIATION OF RAINFALL, OBSERVED RUNOFF, COMPUTED RUNOFF, AND RE IN CALIBRATION OF THE PROPOSED MODELS

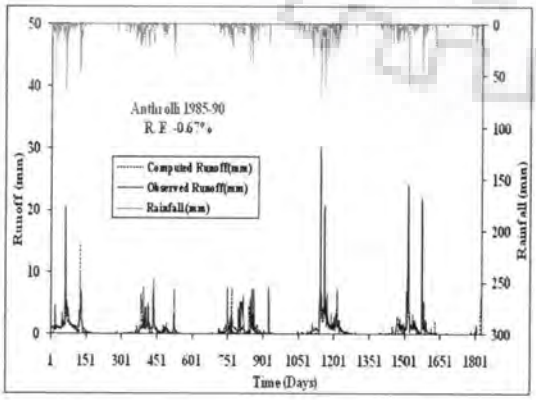
B-I LTHS MICHEL I MODEL

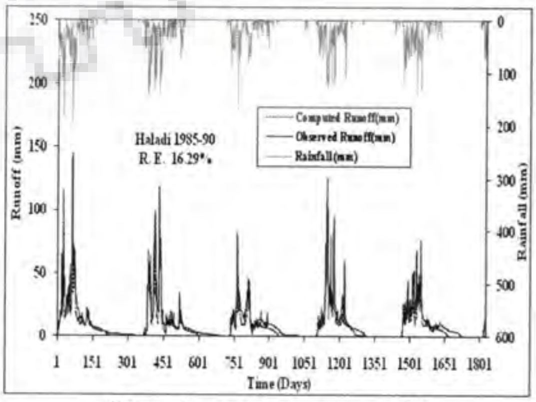






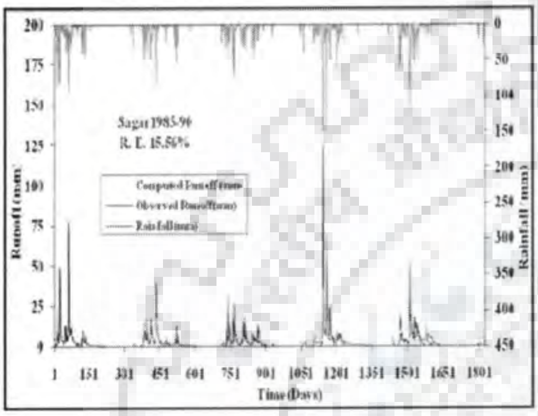


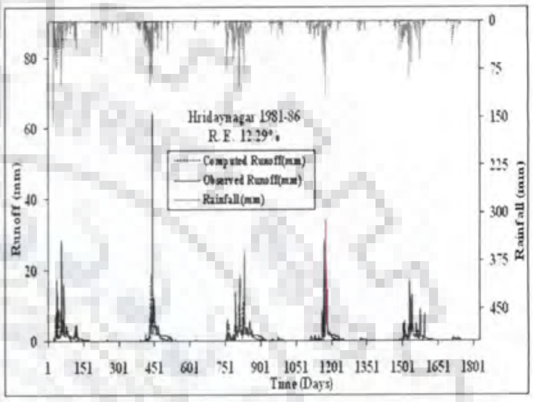


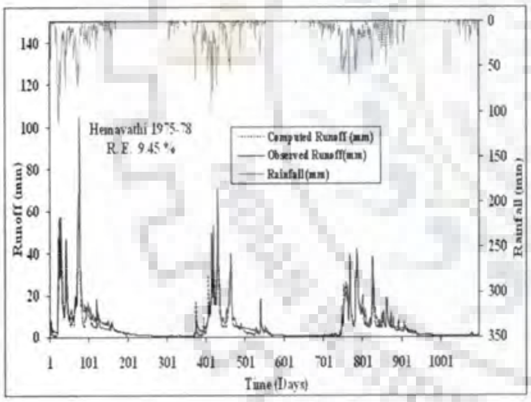


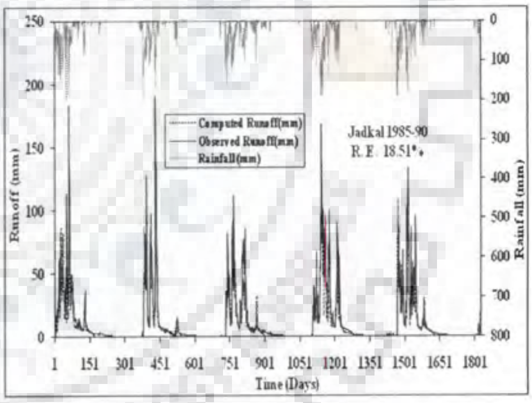
(Day 1 represents June 1)

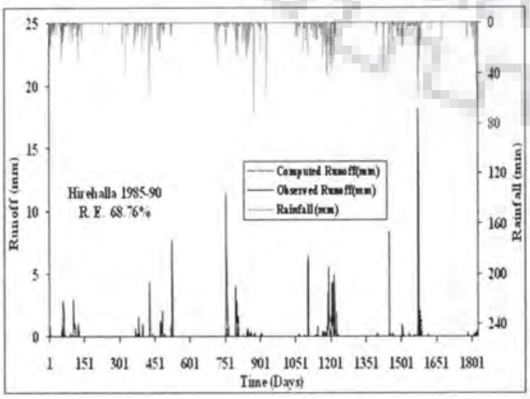
Appendix B continued……

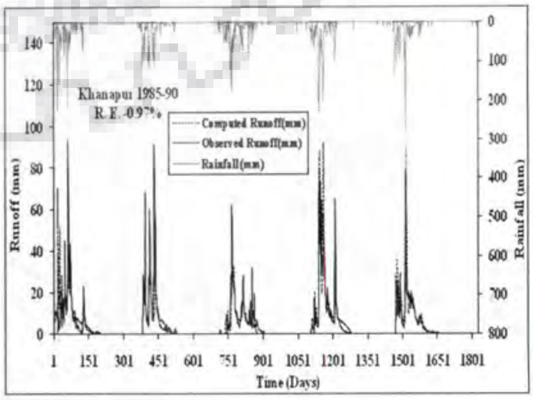






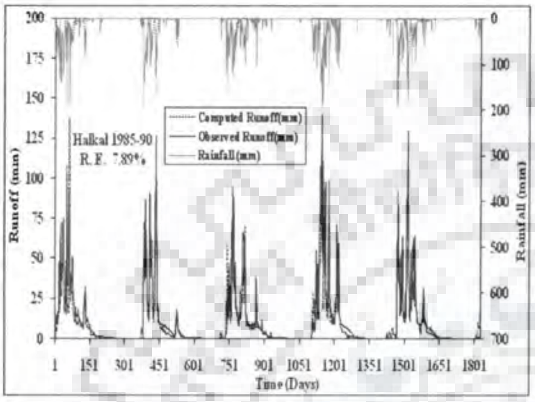


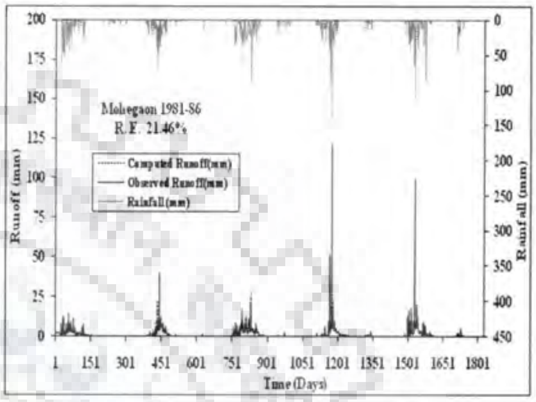


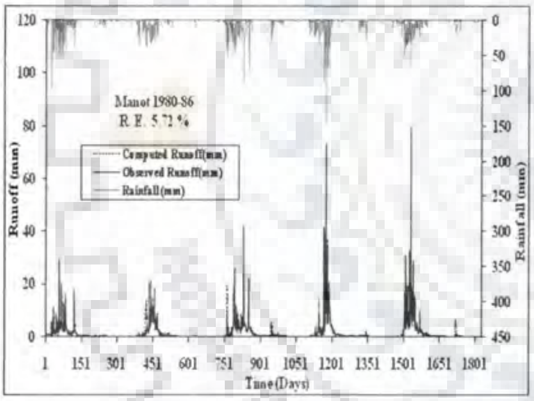


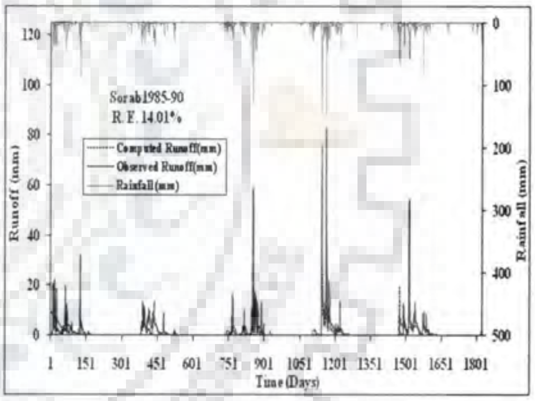
(Day 1 represents June 1)

Appendix B continued…….

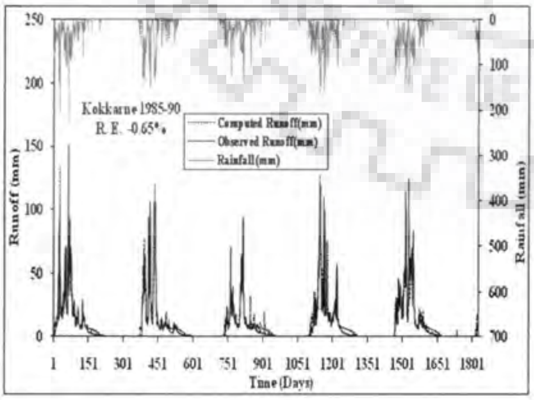






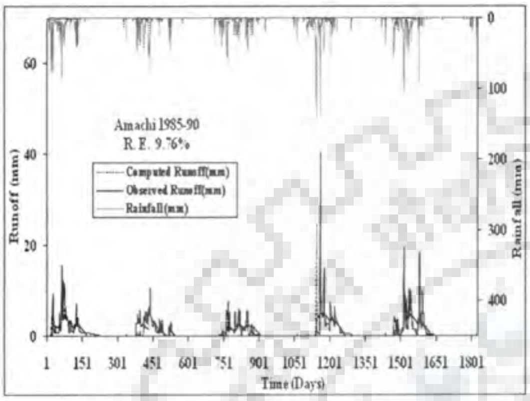


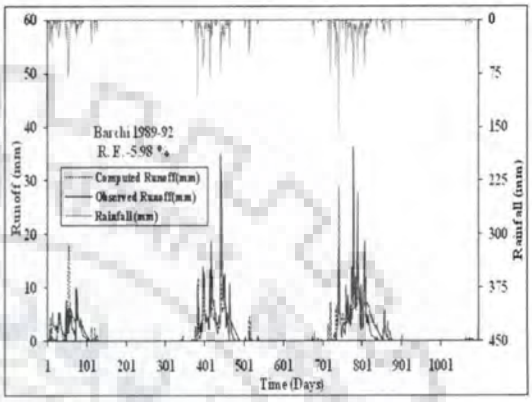
(Day 1 represents June 1)

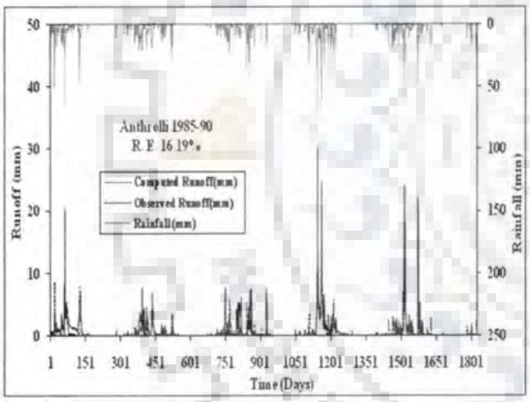


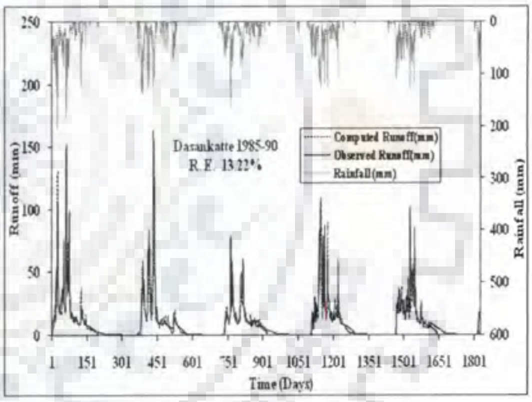
Appendix B continued.......

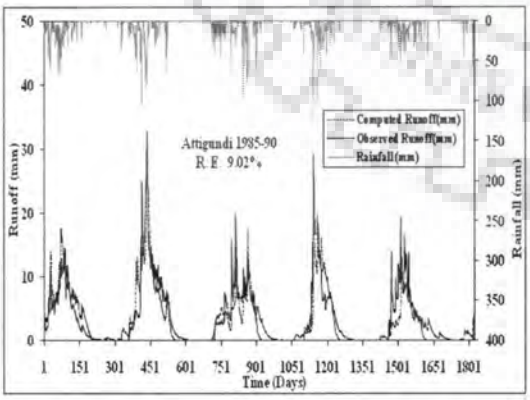
B-II LTHS MICHEL II MODEL

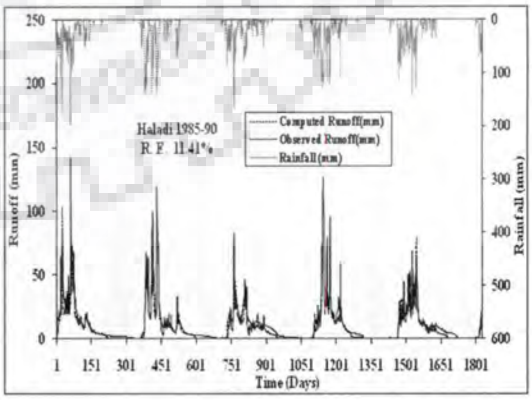






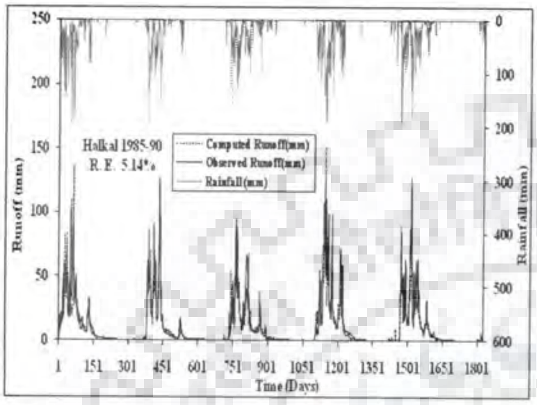


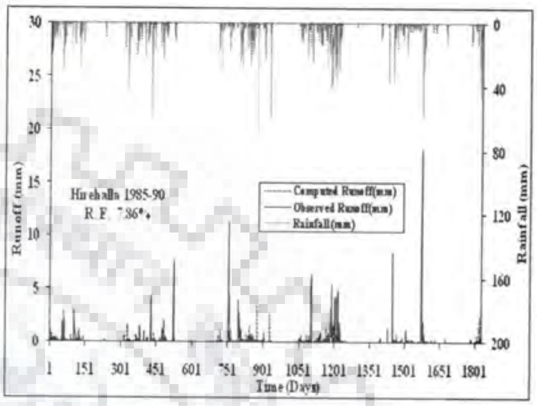


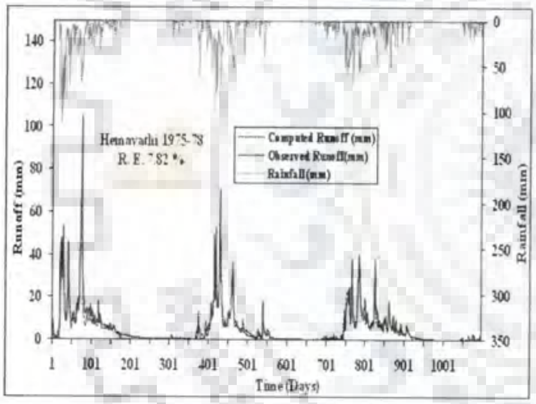


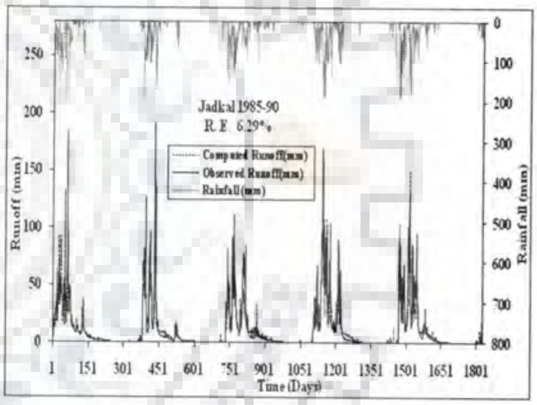
(Day 1 represents June 1)

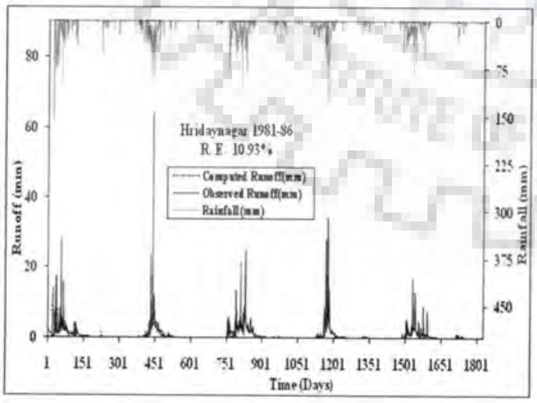
Appendix B continued.......

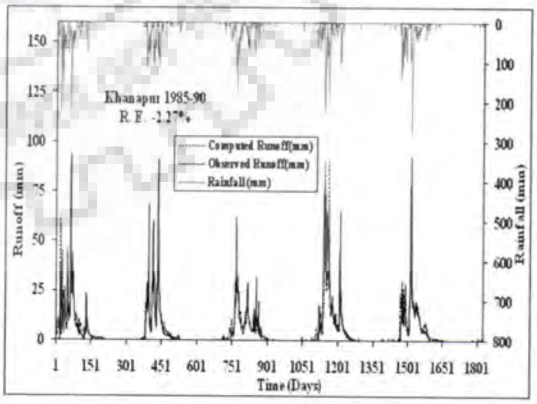






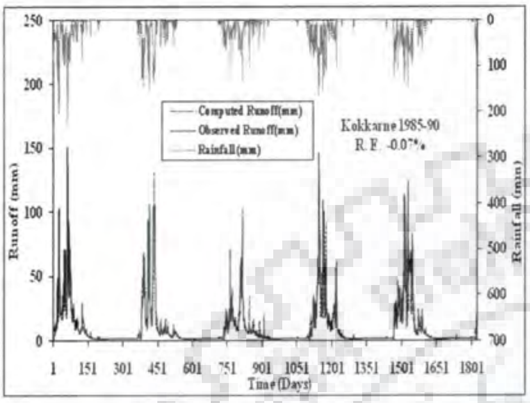


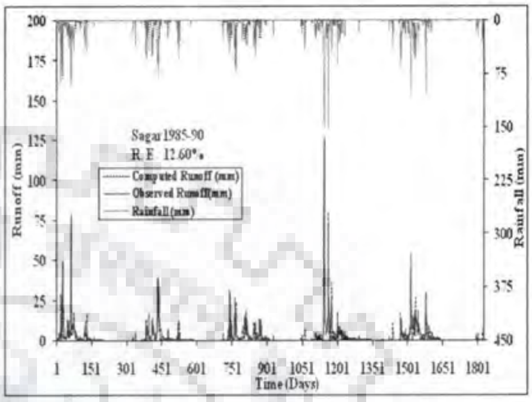


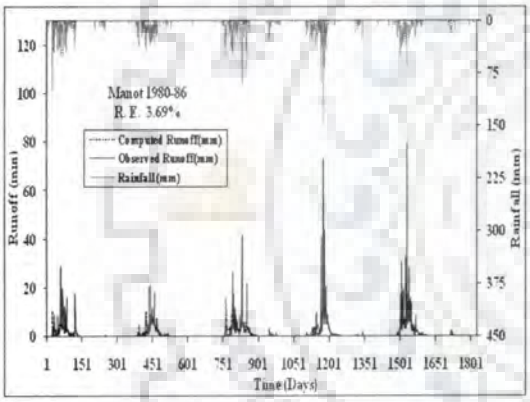


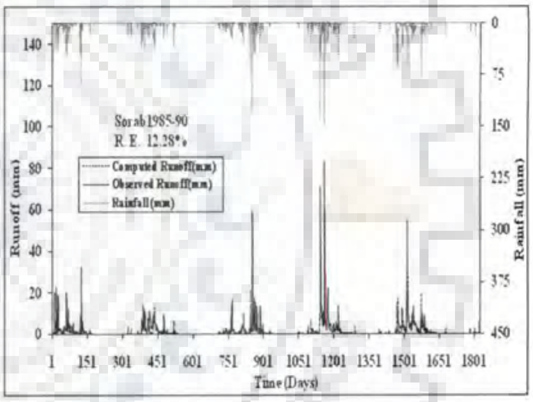
(Day 1 represents June 1)

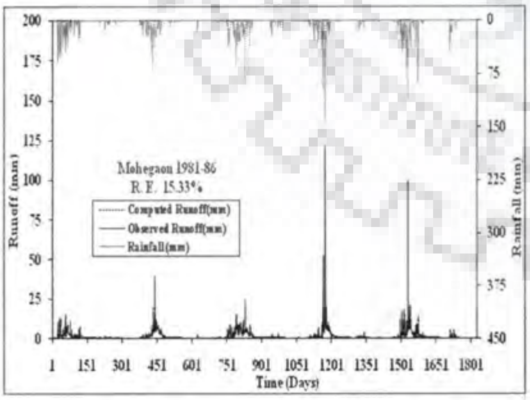
Appendix B continued.......







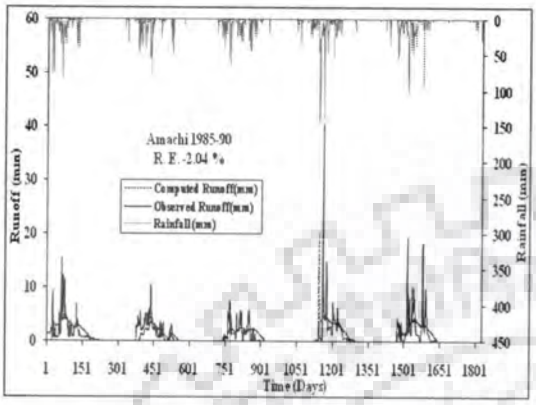


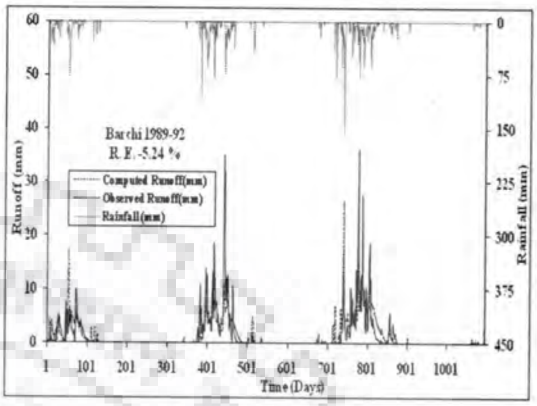


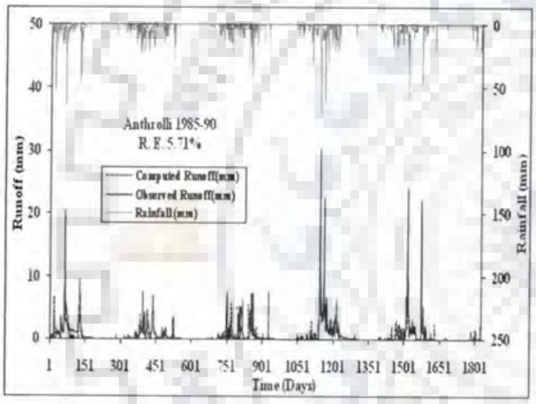
(Day 1 represents June 1)

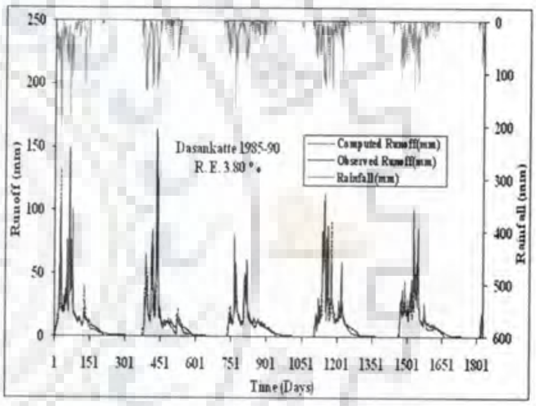
Appendix B continued.......

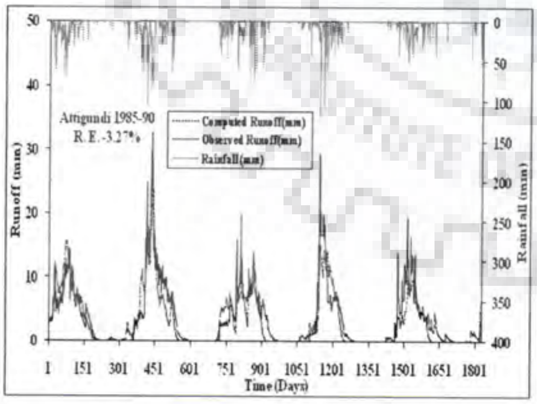
B-III LTHS ASMA I MODEL

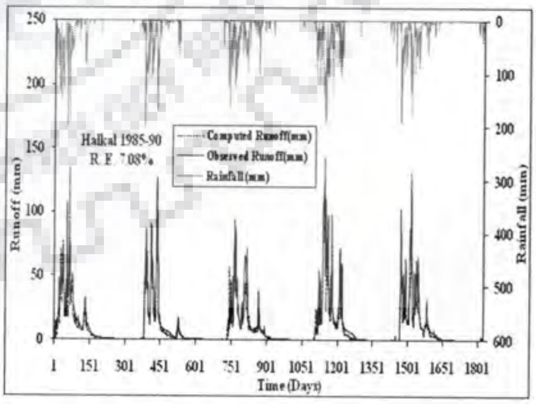






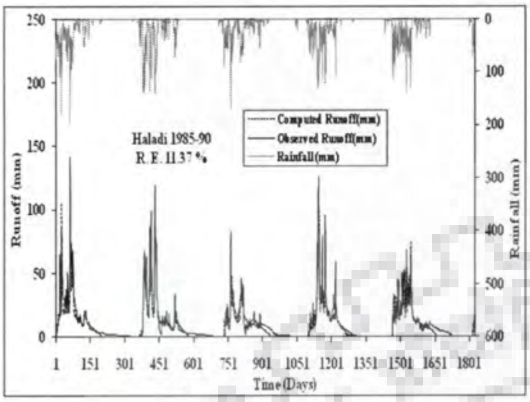


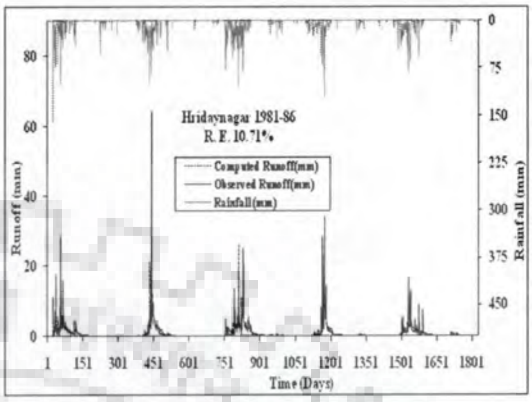


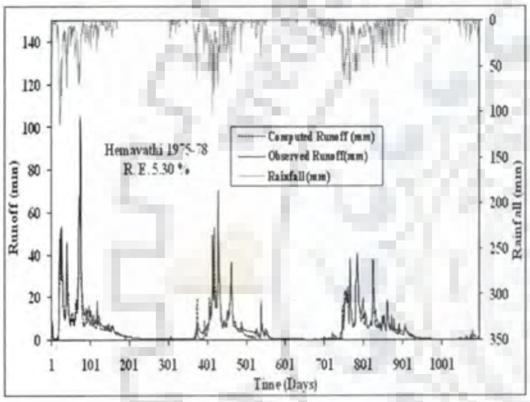


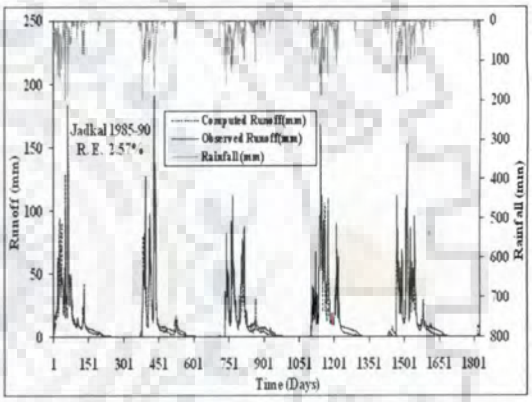
(Day 1 represents June 1)

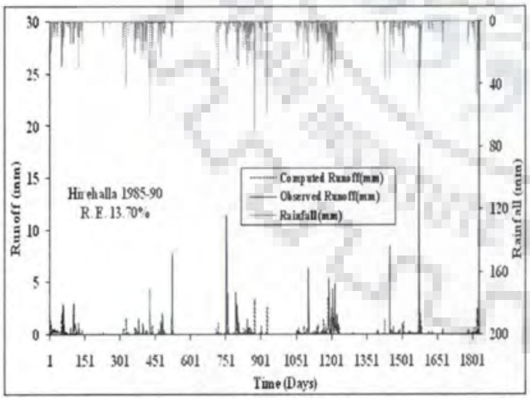
Appendix B continued.......

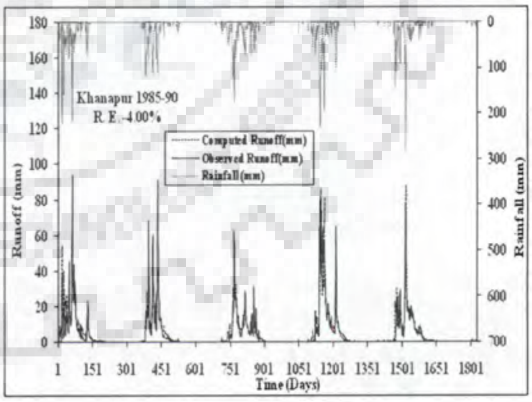






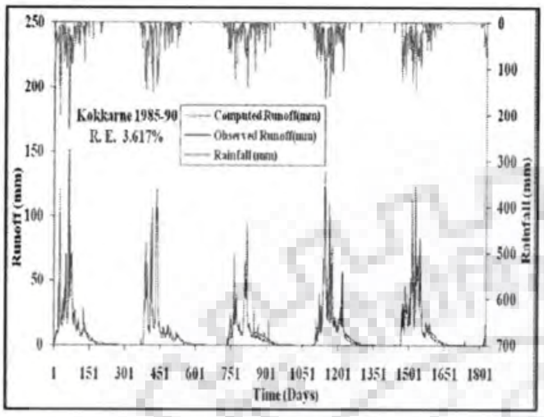


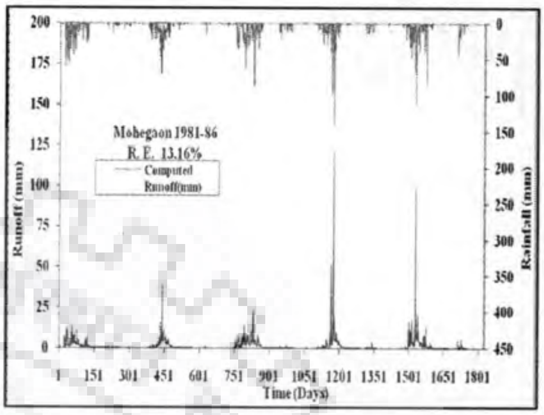


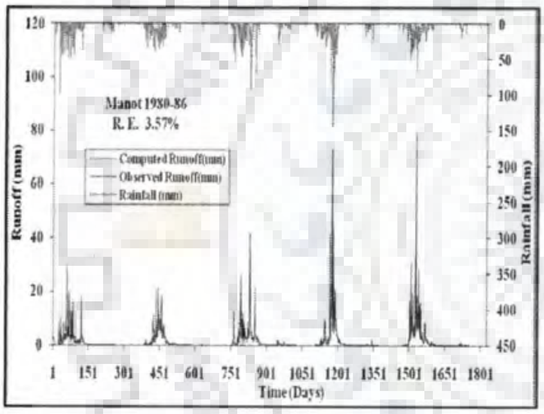


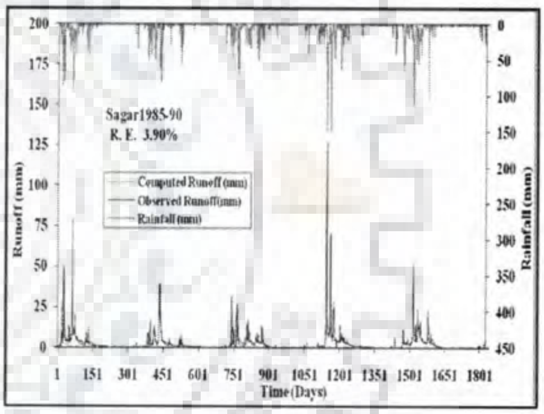
(Day 1 represents June 1)

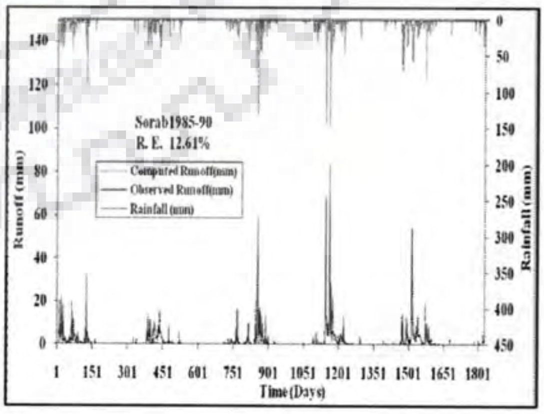
Appendix B continued…….







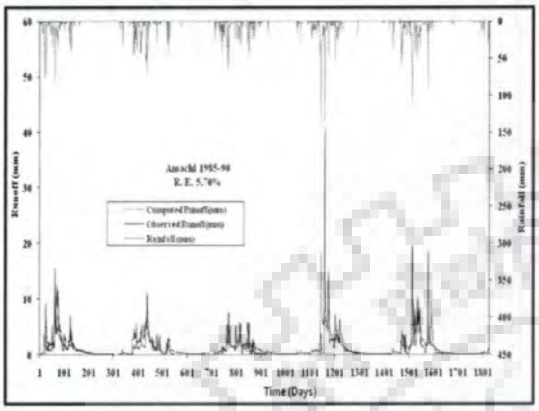


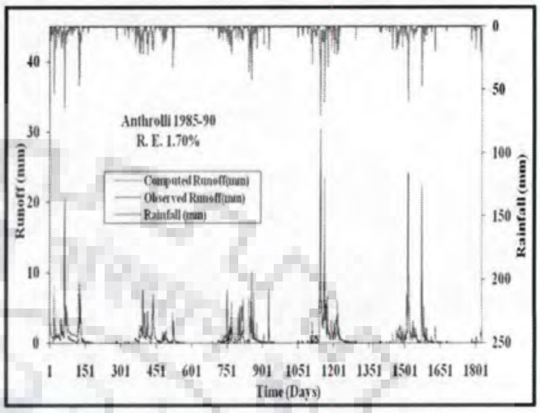


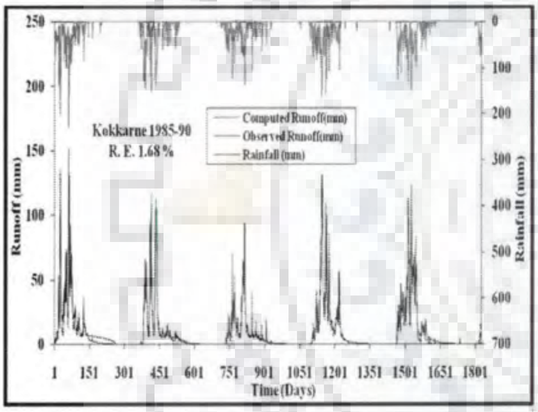
(Day 1 represents June 1)

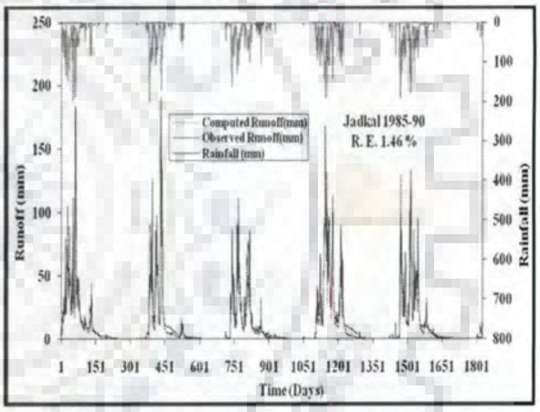
Appendix B continued.......

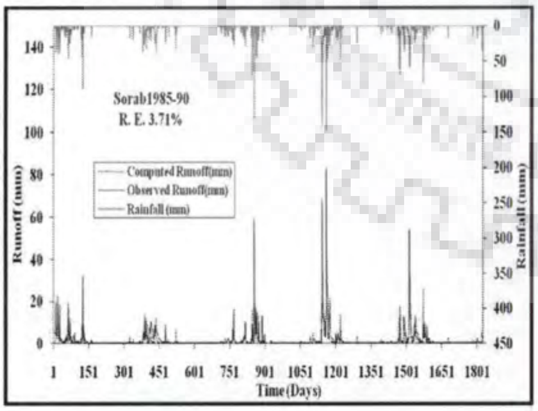
B-IV LTHS ASMA II MODEL

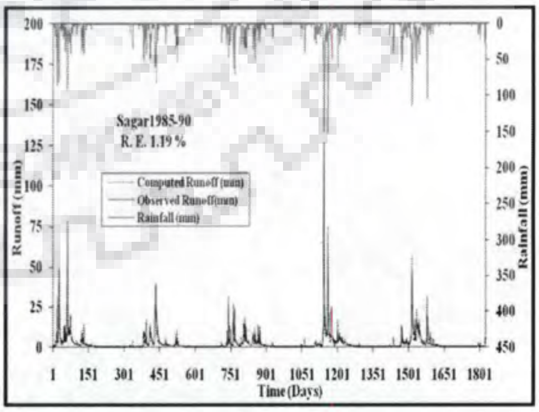






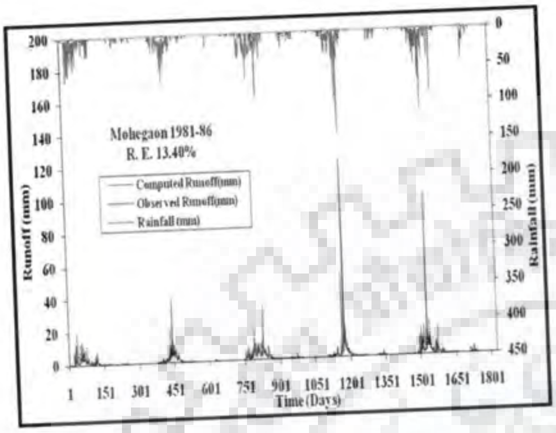


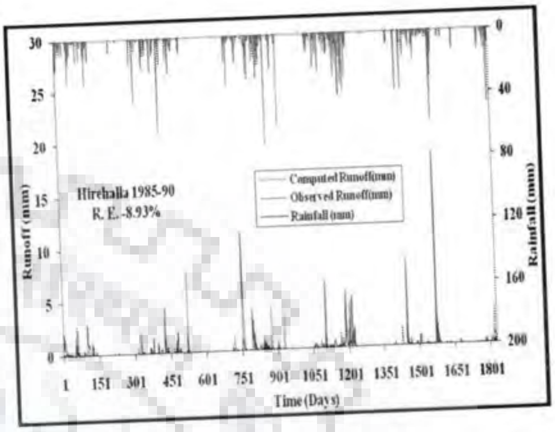


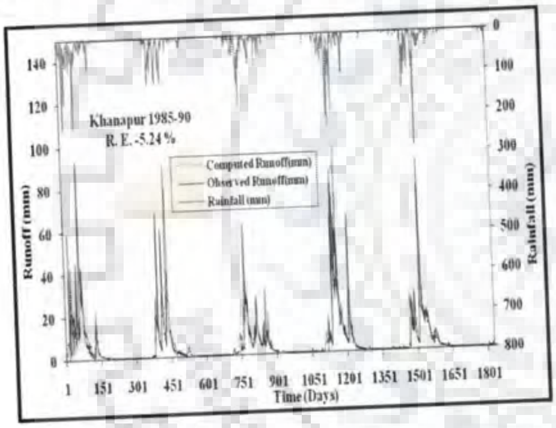


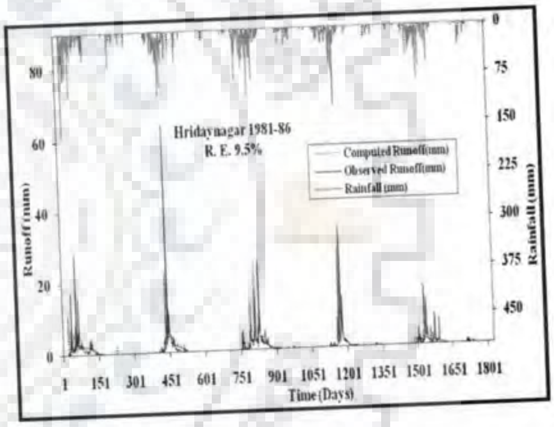
(Day 1 represents June 1)

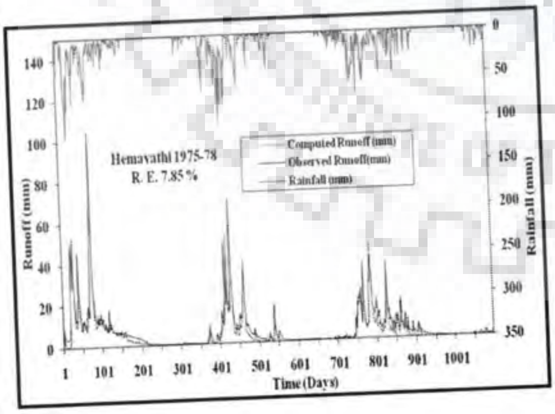
Appendix B continued…….

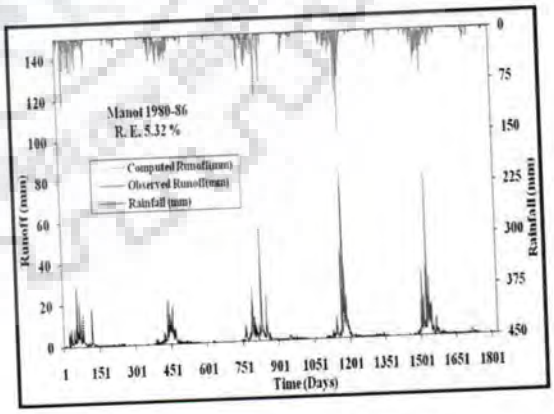






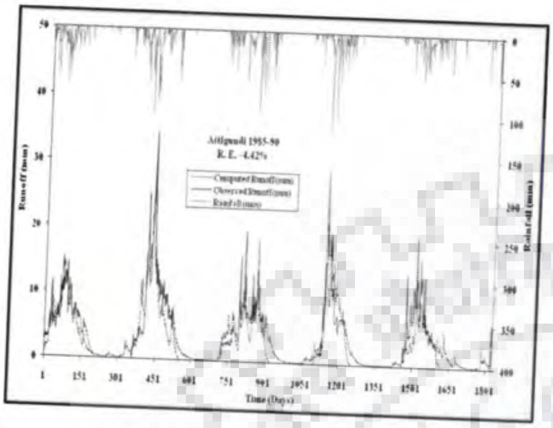


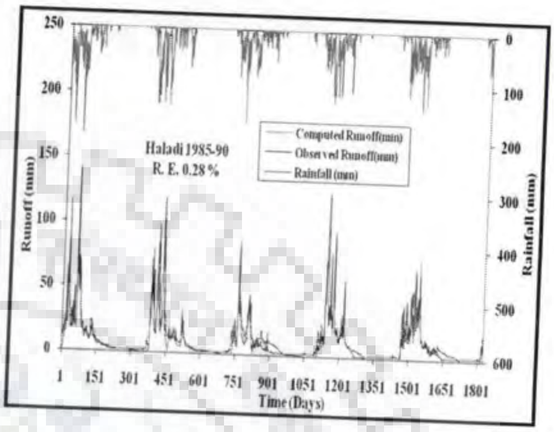


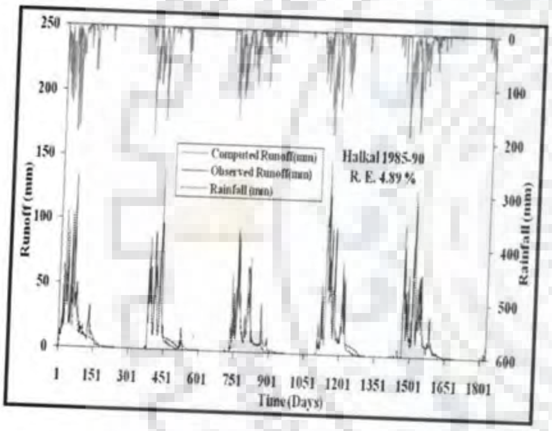


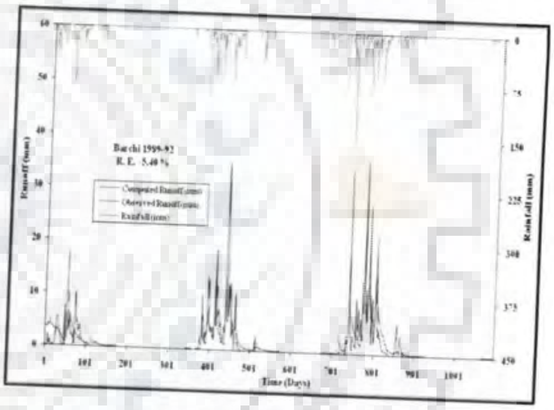
(Day 1 represents June 1)

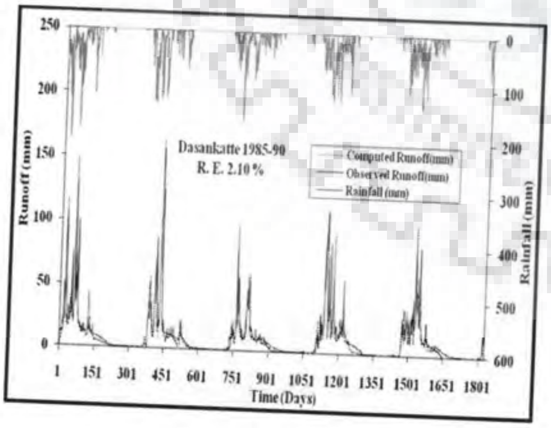
Appendix B continued…….









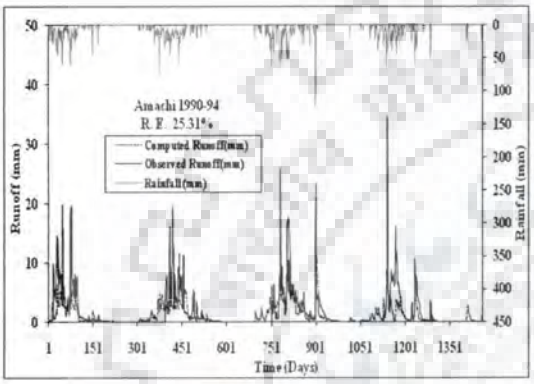


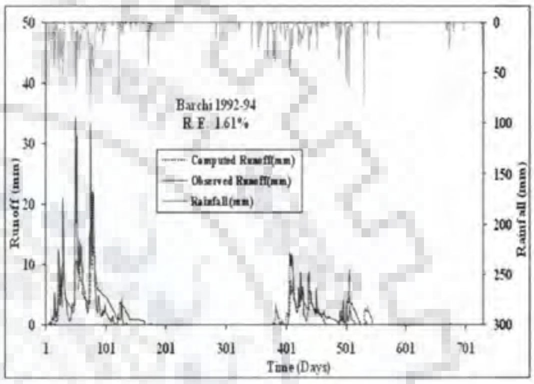
(Day 1 represents June 1)

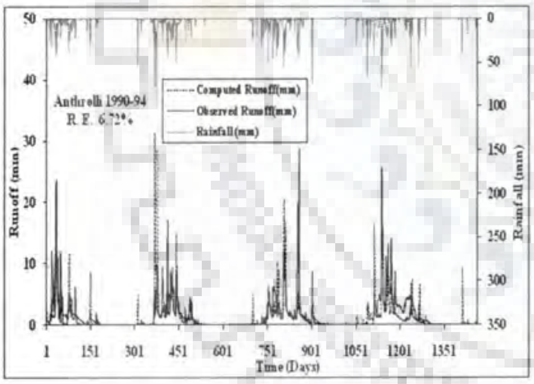
APPENDIX C

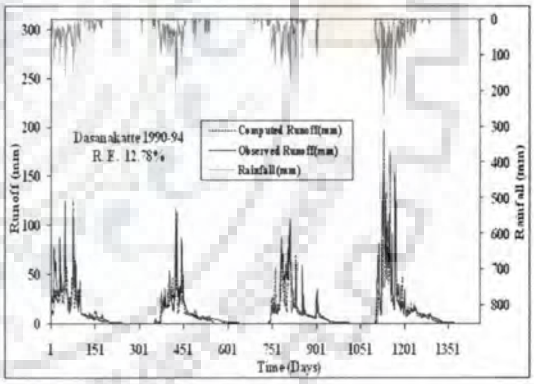
PLOTS OF DAILY VARIATION OF RAINFALL, OBSERVED RUNOFF, CMPUTED RUNOFF, AND RE IN VALIDATION OF THE PROPOSED MODELS

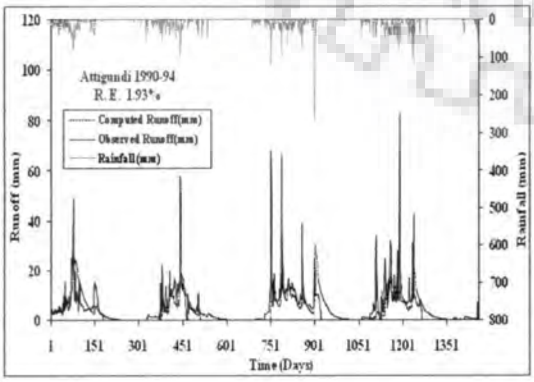
C-I LTHS MICHEL I MODEL

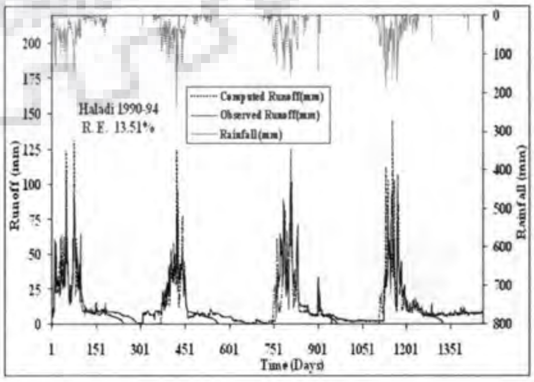






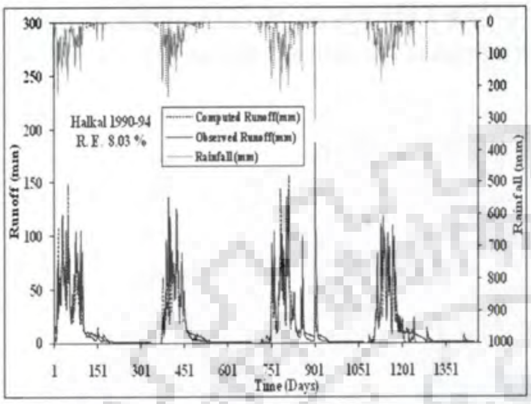


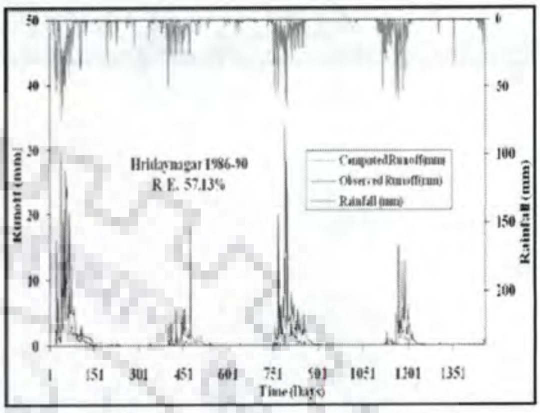


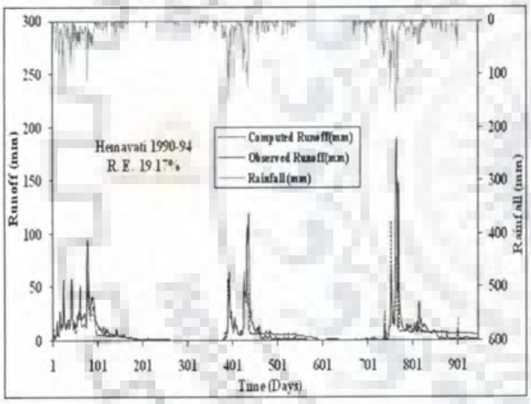


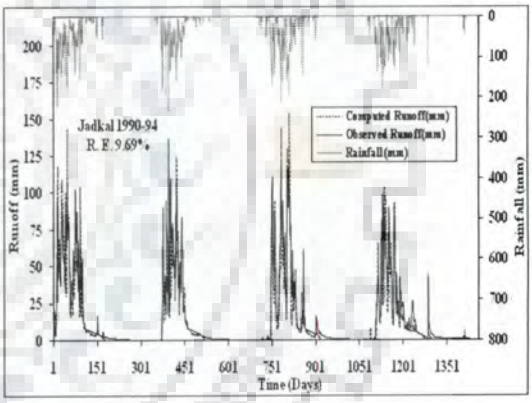
(Day 1 represents June 1)

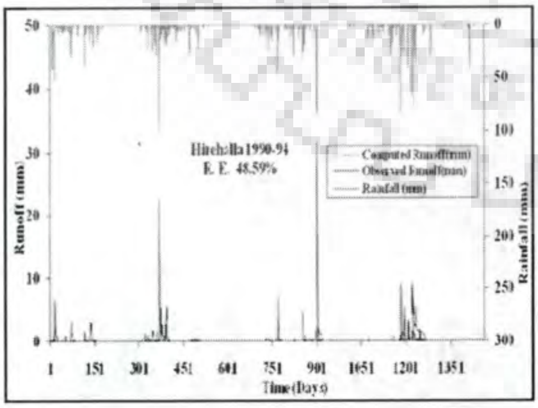
Appendix C continued…….

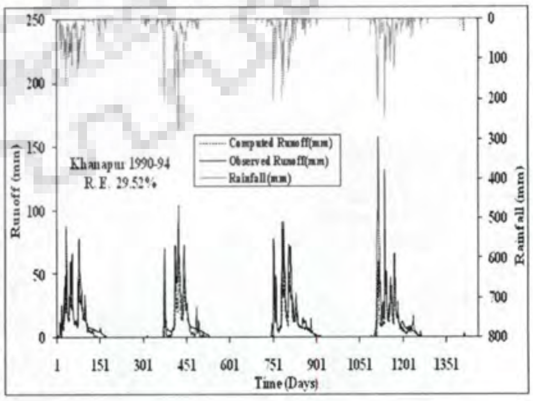






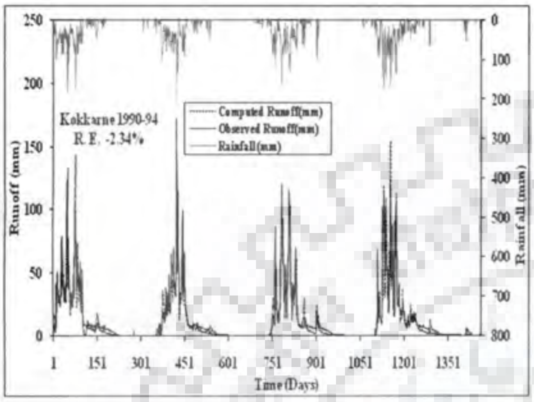


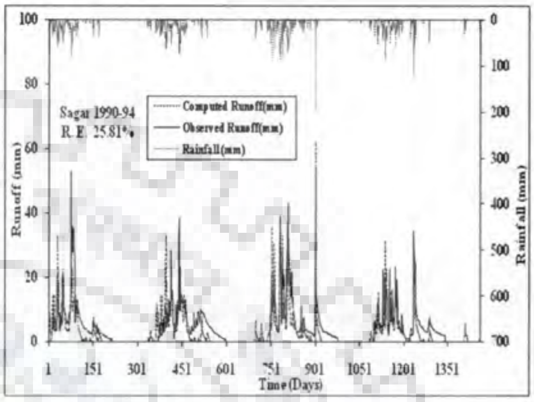


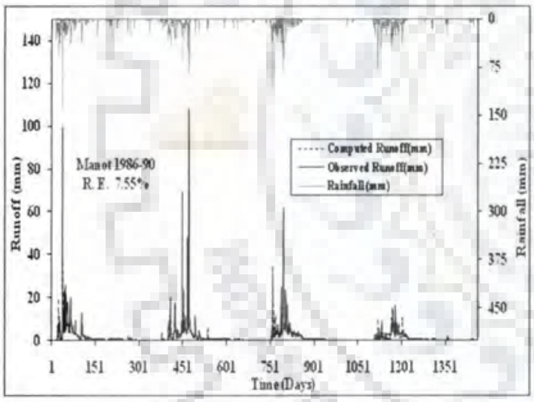


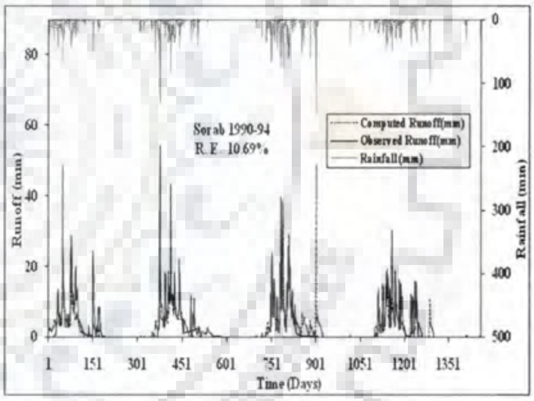
(Day 1 represents June 1)

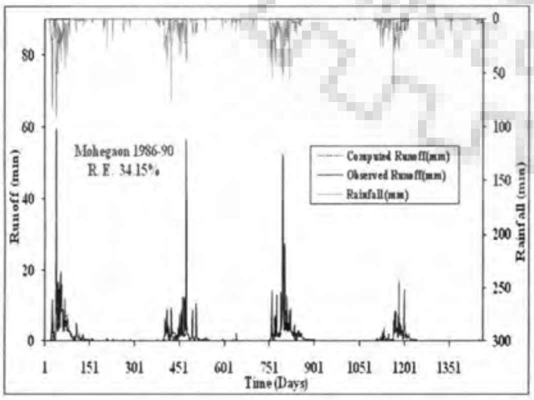
Appendix C continued.......







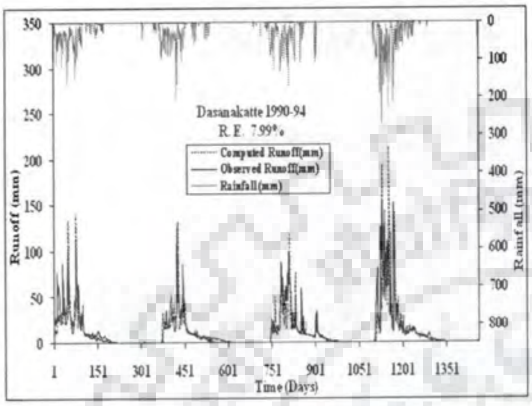


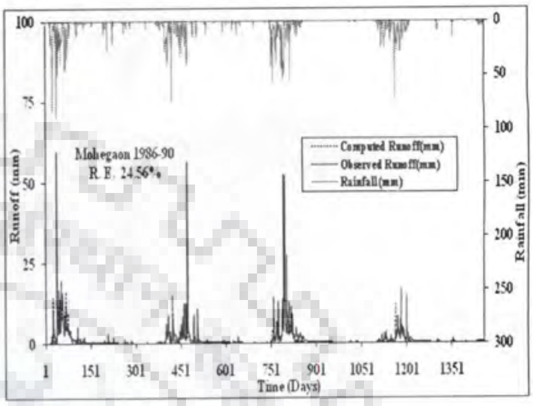


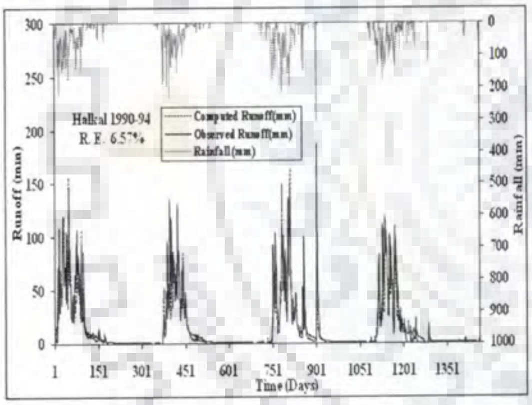
(Day 1 represents June 1)

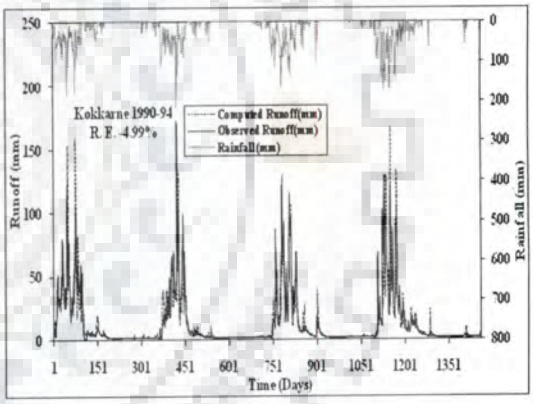
Appendix C continued……

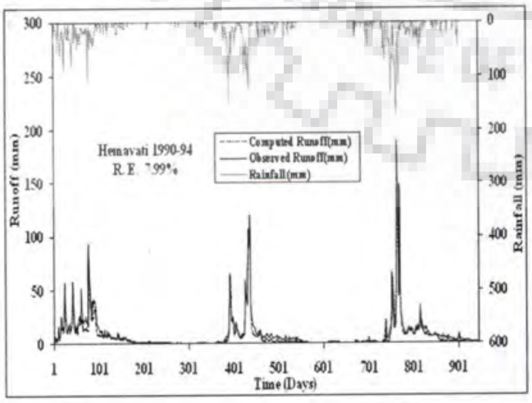
C-II LTHS MICHEL II MODEL

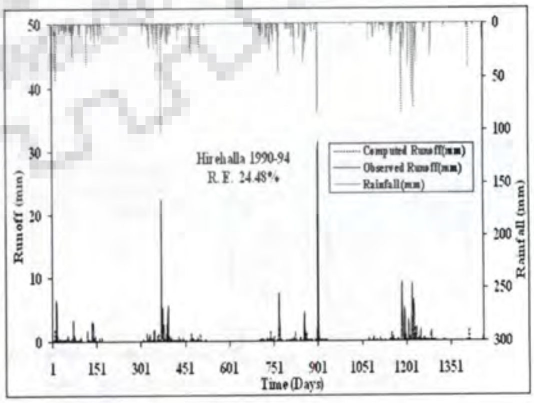






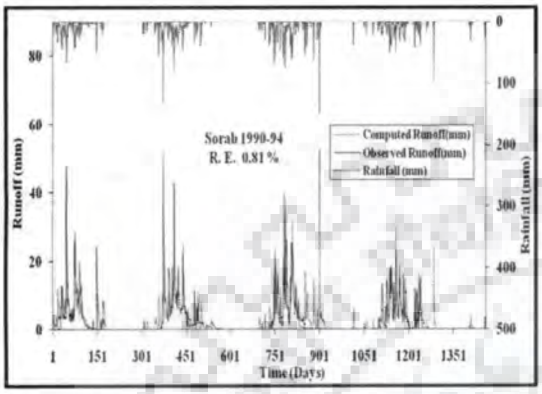


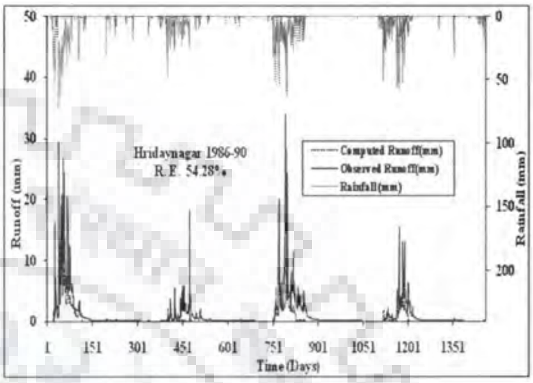


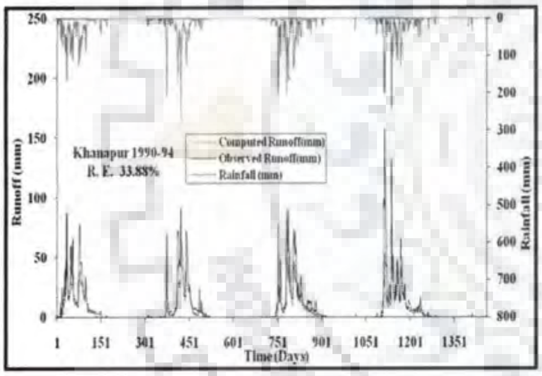


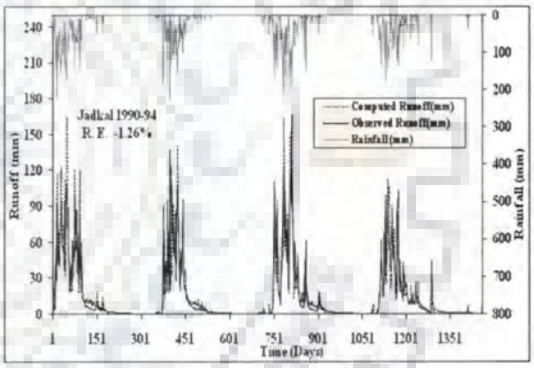
(Day 1 represents June 1)

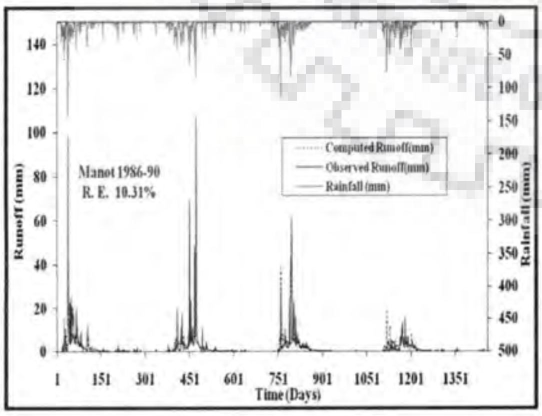
Appendix C continued…….

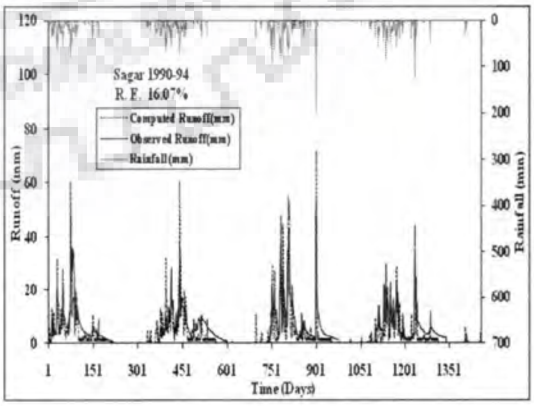






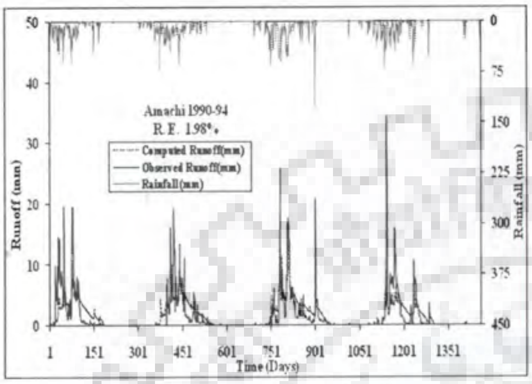


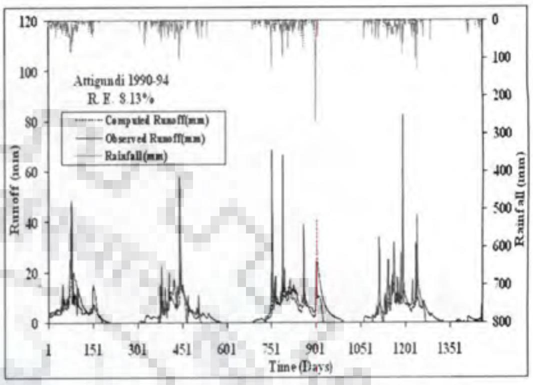


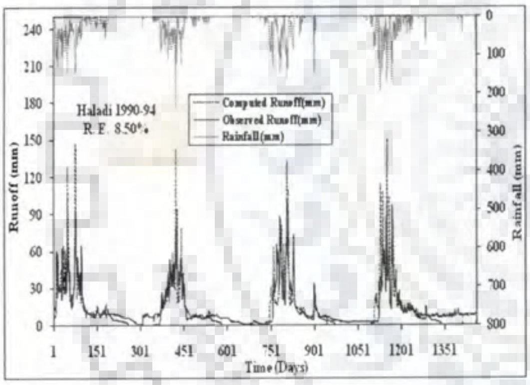


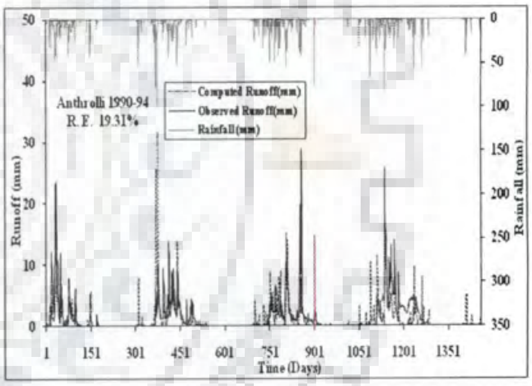
(Day 1 represents June 1)

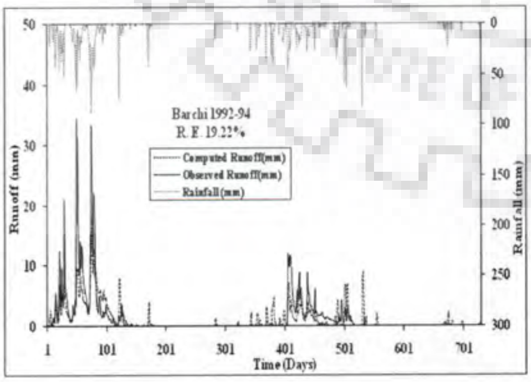
Appendix C continued.......







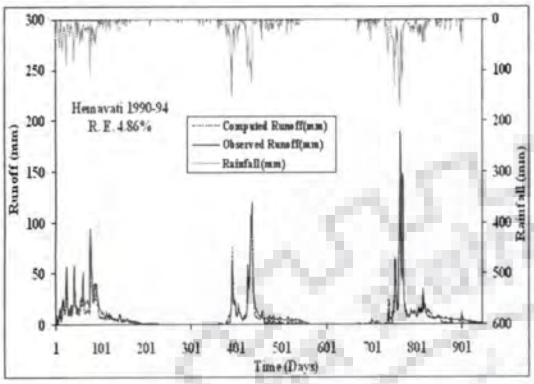


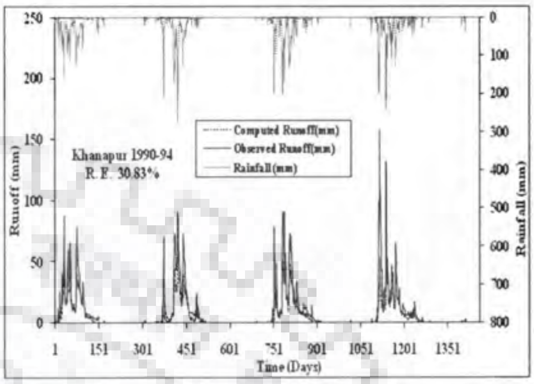


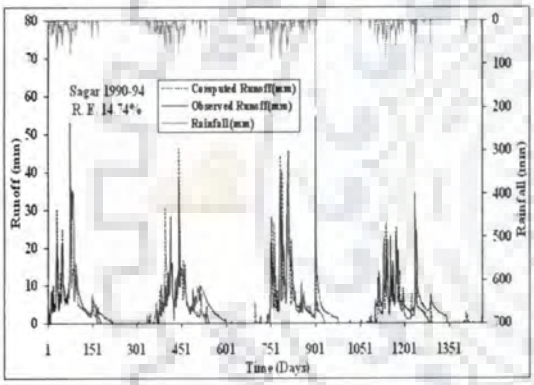
(Day 1 represents June 1)

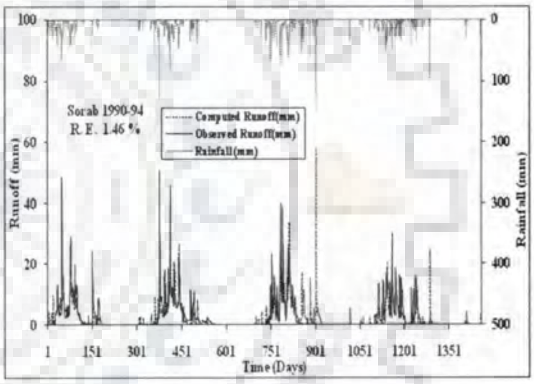
Appendix C continued.......

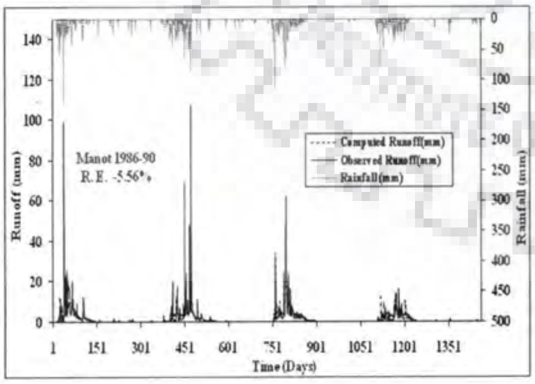
C-III LTHS ASMA I MODEL

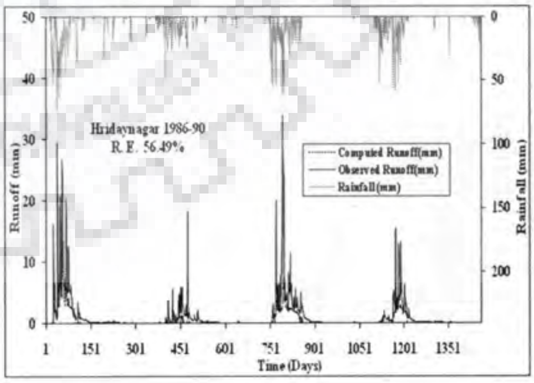






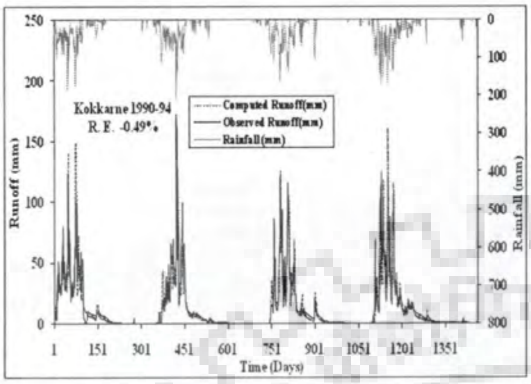


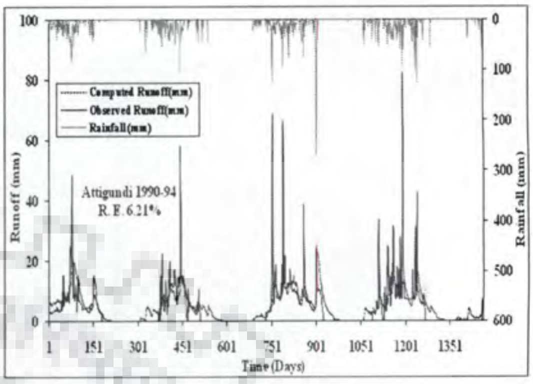


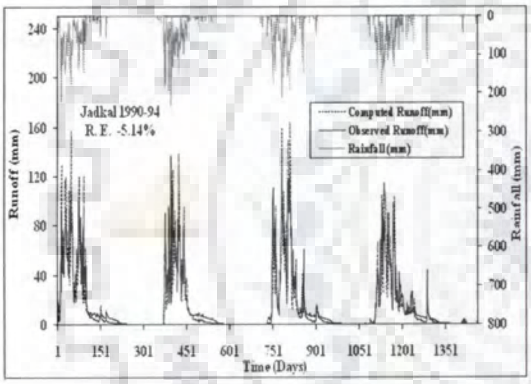


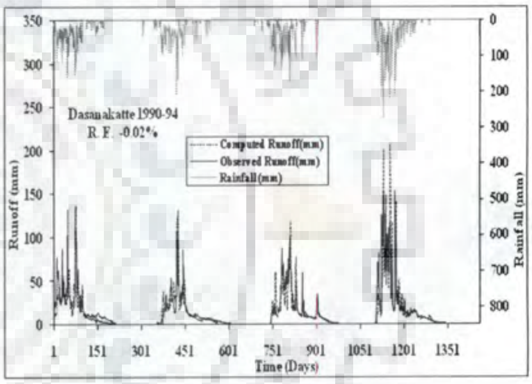
(Day 1 represents June 1)

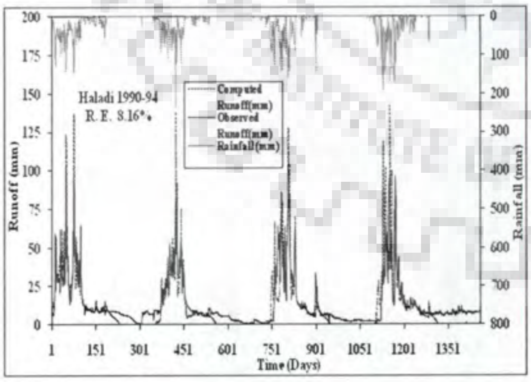
Appendix C continued…….

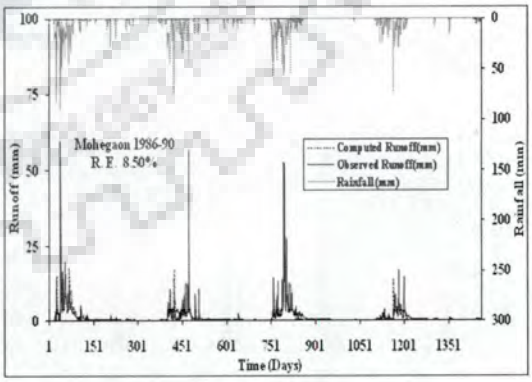






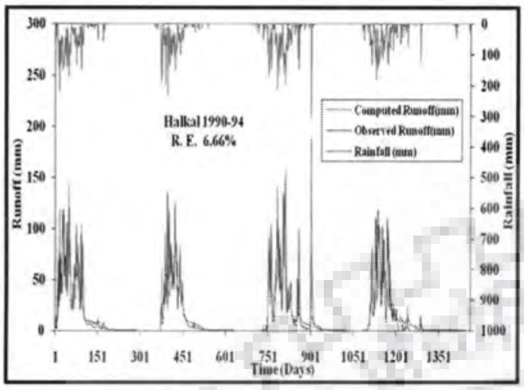


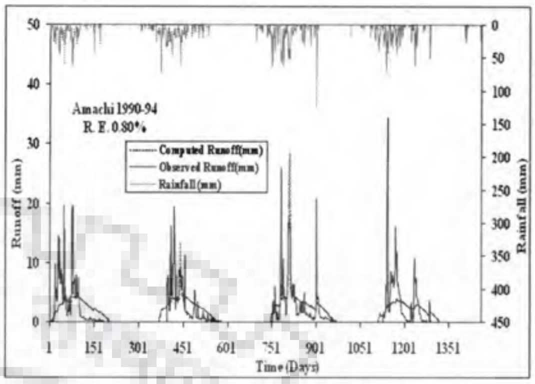


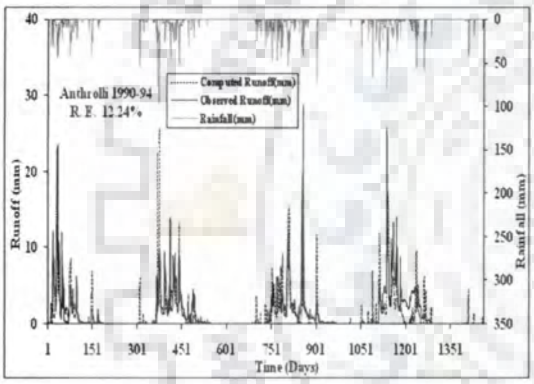


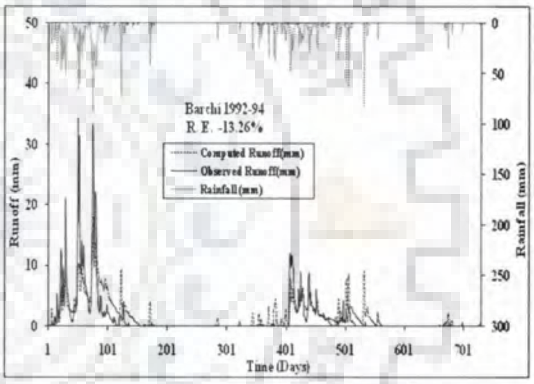
(Day 1 represents June 1)

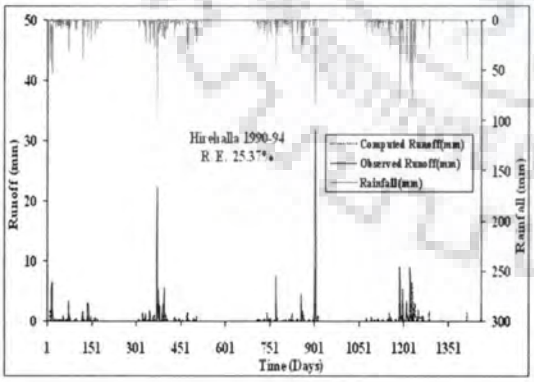
Appendix C continued…….







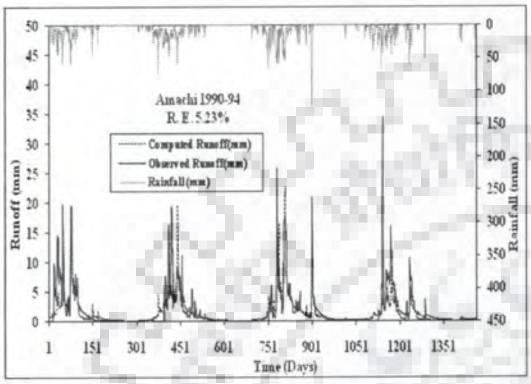


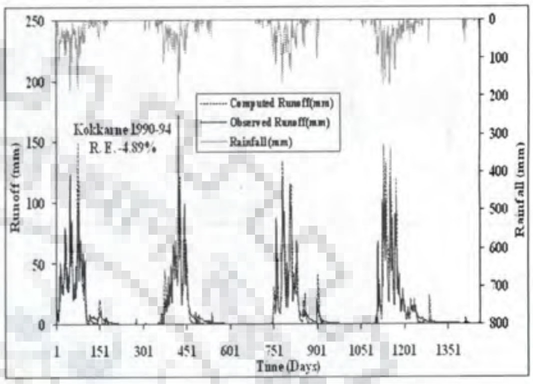


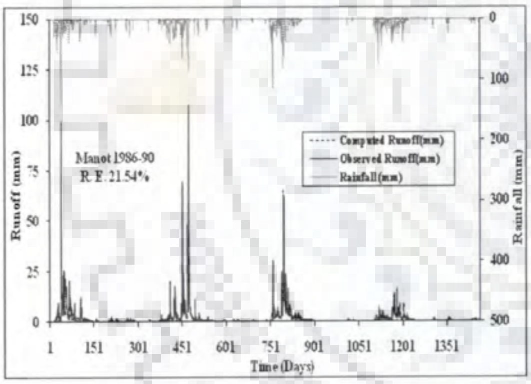
(Day 1 represents June 1)

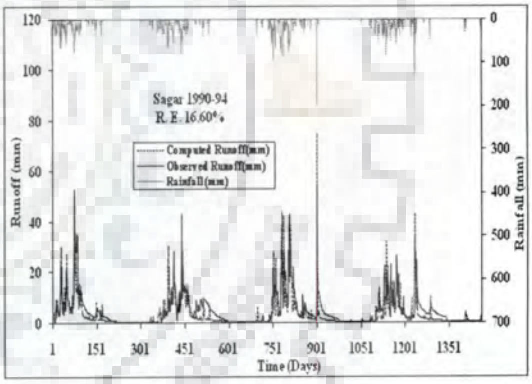
Appendix C continued…….

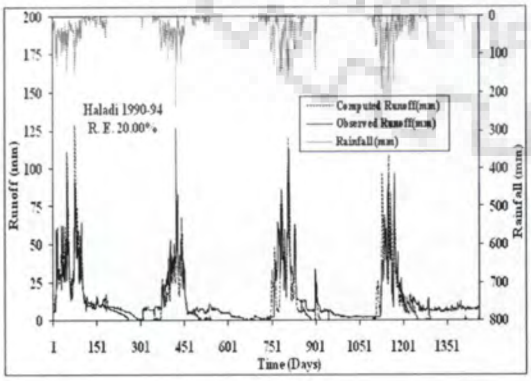
C-IV LTHS ASMA II MODEL

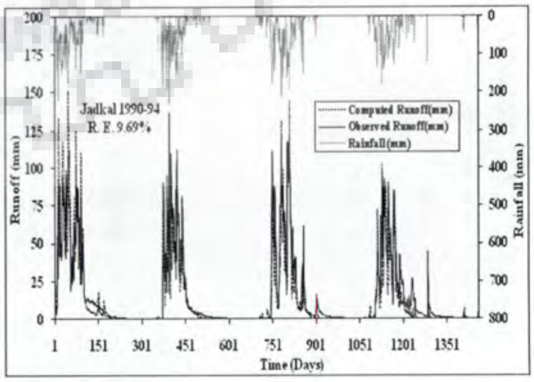






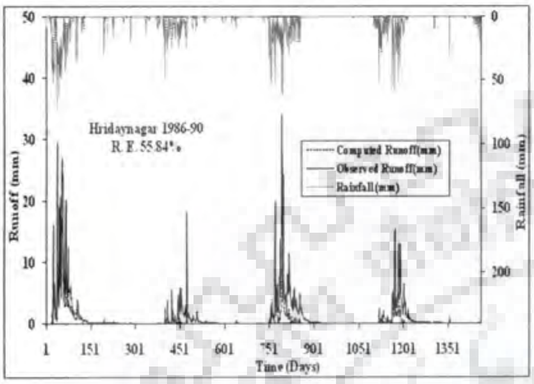


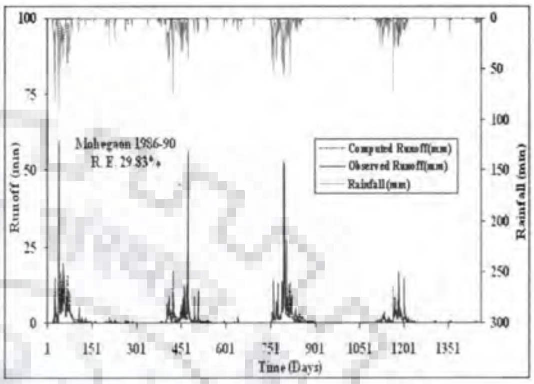


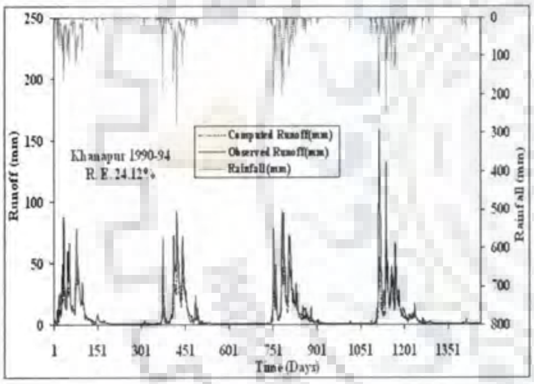


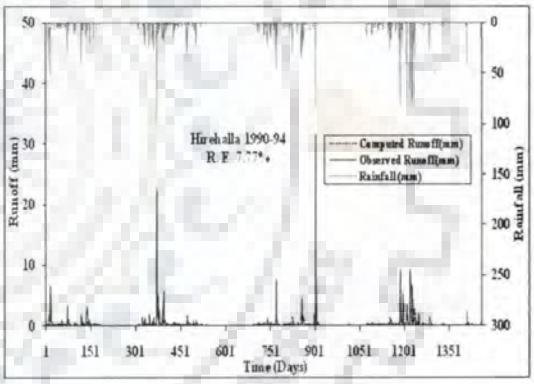
(Day 1 represents June 1)

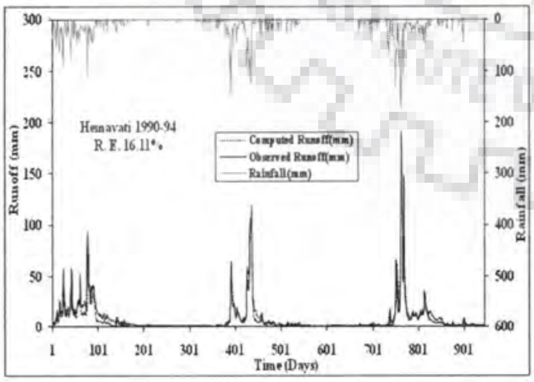
Appendix C continued.......

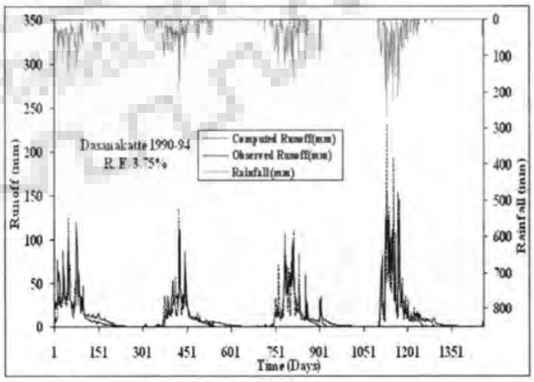






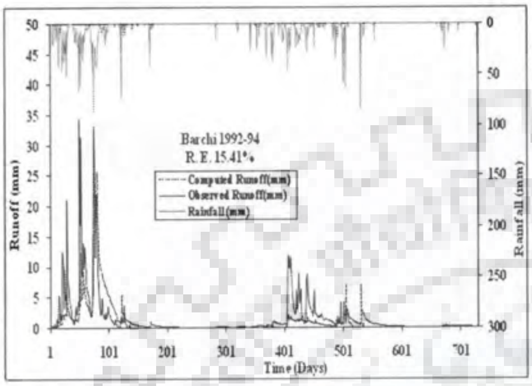


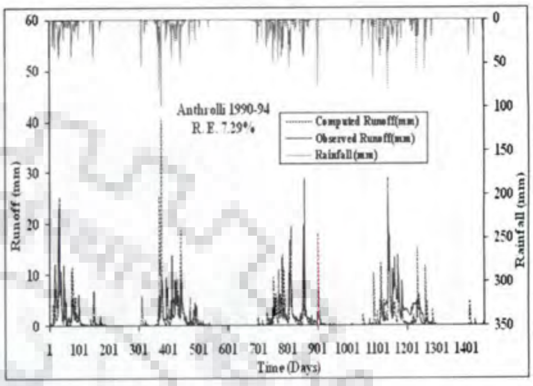


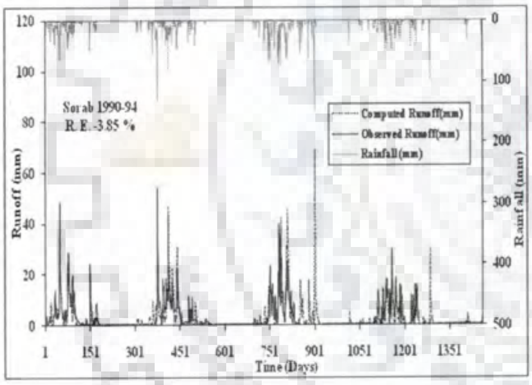


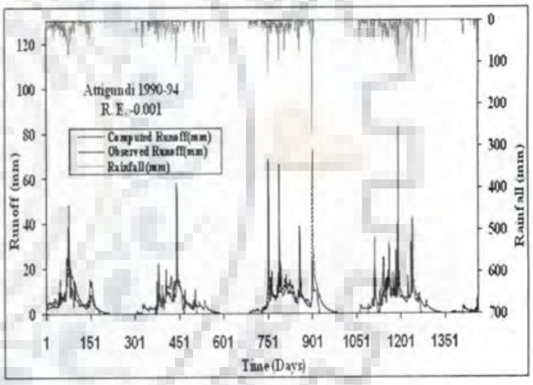
(Day 1 represents June 1)

Appendix C continued…….









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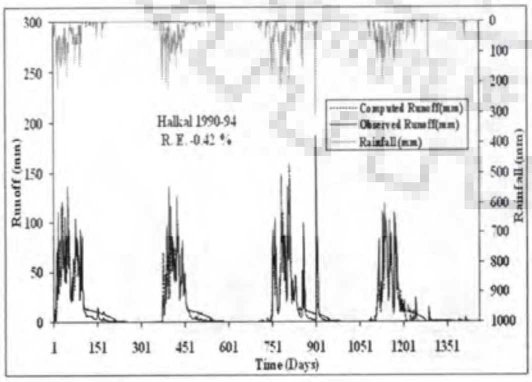


APPENDIX D

SEASONAL VALUES OF RAINFALL, OBSERVED RUNOFF, SIMULATED RUNOFF, AND RE (%) FOR THE PROPOSED MODELS

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	LTHS MICHEL I (M-I)		LTHS MICHEL II (M-II)		LTHS ASMA I (M-III)		LTHS ASMA II (M-IV)	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
1	Hemavathi	1975	2827.4	2420.6	2183.7	9.8	2124.7	12.2	2119.9	12.4	2257.5	6.7
		1976	2396.3	1605.0	1868.7	-16.4	1805.5	-12.5	1732.9	-8.0	1690.3	-5.3
		1977	2471.1	1806.6	1899.5	-5.1	1781.4	1.4	1746.5	3.3	1616.4	10.5
		1978	2730.2	2830.5	2325.3	17.8	2238.1	20.9	2217.5	21.7	2209.4	21.9
		1979	2795.1	1987.7	2117.2	-6.5	2248.9	-13.1	2178.1	-9.6	2134.9	-7.4
	Average		**2644.0**	**2130.1**	**2078.9**	**11.3**	**2039.7**	**10.2**	**1999.0**	**9.5**	**2077.3**	**9.9**
2	Hridaynagar	1981	1432.9	307.7	249.7	18.9	255.9	16.9	282.1	8.3	297.8	3.2
		1982	1399.6	305.9	307.5	-0.5	283.7	7.3	309.1	-1.0	379.4	-24.0
		1983	1754.5	364.0	447.0	-22.8	395.5	-8.7	459.4	-26.2	386.1	-6.1
		1984	1179.2	287.1	234.1	18.5	208.4	27.4	236.9	17.5	200.7	30.1
		1985	1187.2	237.4	138.9	41.5	159.4	32.9	187.8	20.9	122.1	48.6
		1986	1632.0	584.4	441.2	24.5	373.7	36.1	423.4	27.6	426.7	27.0
		1987	834.2	173.4	37.9	78.1	15.3	91.2	58.4	66.3	21.2	87.8
		1988	1370.4	556.6	210.1	62.3	211.8	62.0	251.8	54.8	148.1	73.4
		1989	1024.7	280.1	87.8	68.6	108.2	61.4	141.6	49.5	83.7	70.1
	Average		**1312.7**	**344.1**	**239.4**	**37.3**	**223.5**	**38.2**	**261.2**	**30.2**	**229.5**	**41.1**
3	Barchi	1989	1061.8	225.9	245.3	-8.6	377.8	-67.3	380.1	-68.3	313.4	-38.7
		1990	1391.6	615.2	491.8	20.1	506.1	17.7	511.4	16.9	464.5	24.5
		1991	1621.9	666.8	619.8	7.0	680.4	-2.0	660.5	0.9	723.3	-8.5
		1992	1583	667.8	539.0	19.3	595.0	10.9	591.7	11.4	658.2	1.4
		1993	1165.8	313.1	333.2	-6.4	288.0	8.0	285.6	8.8	231.6	26.0
	Average		**1364.8**	**497.7**	**445.8**	**12.3**	**489.4**	**21.2**	**485.9**	**21.3**	**478.2**	**19.8**

Appendix D continued ------

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
4	Manot	1981	1045.1	373.7	299.7	19.8	380.5	-1.8	436.1	-16.7	390.4	-4.5
		1982	1001.9	366.5	391.5	-6.8	415.3	-13.3	400.4	-9.2	409.7	-11.8
		1983	1256.9	529.0	565.8	-7.0	587.0	-11.0	572.7	-8.3	577.4	-9.2
		1984	1190.4	600.9	634.6	-5.6	628.6	-4.6	612.9	-2.0	633.1	-5.4
		1985	1122.2	700.8	504.0	28.1	513.6	26.7	495.7	29.3	478.5	31.7
		1986	1136.3	690.9	500.2	27.6	506.6	26.7	481.3	30.3	472.9	31.5
		1987	1248.5	751.5	504.1	32.9	527.0	29.9	497.5	33.8	522.6	30.5
		1988	1267.3	624.7	618.8	1.0	642.6	-2.9	619.7	0.8	607.0	2.8
		1989	1056.1	265.2	401.6	-51.4	431.0	-62.5	406.5	-53.3	378.7	-42.8
	Average		**1147.2**	**544.8**	**491.1**	**20.0**	**514.7**	**19.9**	**502.5**	**20.4**	**496.7**	**18.9**
5	Amachi	1985	1459.5	432.4	413.5	4.4	330.6	23.6	485.4	-12.3	471.5	-9.0
		1986	1189.4	390.2	281.6	27.8	303.4	22.2	321.8	17.5	288.2	26.1
		1987	1239.4	303.8	359.6	-18.4	335.4	-10.4	356.4	-17.3	273.8	9.9
		1988	1674.3	452.9	449.2	0.8	554.7	-22.5	583.2	-28.8	657.7	-45.2
		1989	1530.6	494.1	456.6	7.6	475.0	3.8	461.8	6.5	405.0	18.0
		1990	1635.1	600.8	431.1	28.2	476.7	20.7	460.6	23.3	440.9	26.6
		1991	1722.5	525.7	509.4	3.1	541.7	-3.1	524.3	0.3	549.8	-4.6
		1992	2229.8	625.9	660.9	-5.6	704.1	-12.5	694.0	-10.9	789.5	-26.1
		1993	1562.4	539.8	514.1	4.8	545.0	-1.0	520.2	3.6	383.0	29.0
	Average		**1582.5**	**485.0**	**452.9**	**11.2**	**474.1**	**13.3**	**489.8**	**13.4**	**473.3**	**21.6**
6	Anthrolli	1985	678.5	256.2	171.9	32.9	207.1	19.2	209.0	18.5	222.1	13.3
		1986	645.5	147.4	156.5	-6.2	159.8	-8.5	179.2	-21.6	173.4	-17.6
		1987	637.0	186.3	147.3	20.9	162.5	12.8	177.4	4.8	171.3	8.1
		1988	935.7	341.1	334.8	1.8	362.3	-6.2	376.9	-10.5	368.5	-8.0
		1989	687.2	287.0	178.7	37.7	184.0	35.9	205.5	28.4	206.1	28.2
		1990	925.4	404.6	301.9	25.4	324.0	19.9	339.4	16.1	330.0	18.4
		1991	1083.4	444.1	413.6	6.9	443.9	0.1	458.1	-3.1	457.1	-2.9
		1992	1189.1	476.9	423.6	14.7	451.6	9.1	464.7	6.5	464.2	6.6
		1993	1136.9	698.7	408.3	41.6	441.4	36.8	458.9	34.3	456.4	34.7
	Average		**879.9**	**360.3**	**281.9**	**20.9**	**304.1**	**16.5**	**318.8**	**16.0**	**316.6**	**15.3**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
7	Attigundi	1985	1708.9	1239.7	1154.0	6.9	1108.5	10.6	1254.8	-1.2	1088.8	12.2
		1986	2127.1	1661.2	1351.2	18.7	1452.7	12.5	1559.0	6.1	1717.4	-3.4
		1987	1503.7	1129.6	867.2	23.2	843.2	25.4	1110.9	1.6	1055.7	6.5
		1988	1522.6	1084.9	958.9	11.6	977.5	9.9	1153.8	-6.4	1187.6	-9.5
		1989	1182.9	966.4	644.4	33.3	578.6	40.1	885.3	8.4	859.6	11.1
		1990	1821.2	1309.4	1128.5	13.8	1179.9	9.9	1344.3	-2.7	1355.0	-3.5
		1991	1589.0	1281.3	947.0	26.1	942.3	26.5	1181.1	7.8	1132.1	11.6
		1992	2488.8	2022.6	1498.5	25.9	1519.4	24.9	1708.7	15.5	1661.0	17.9
		1993	2122.2	1761.9	1478.7	16.1	1597.4	9.3	1712.3	2.8	1685.7	4.3
	Average		**1785.2**	**1379.7**	**1114.3**	**19.5**	**1133.3**	**18.8**	**1323.4**	**5.8**	**1304.8**	**8.9**
8	Mohegaon	1981	1148.6	323.7	293.6	9.3	318.8	1.5	343.6	-6.2	381.9	-18.0
		1982	1178.7	331.1	338.7	-2.3	313.4	5.3	282.6	14.6	312.1	5.7
		1983	1395.6	463.5	500.8	-8.1	477.4	-3.0	524.1	-13.1	498.4	-7.5
		1984	1180.2	494.3	486.2	1.6	471.9	4.5	506.8	-2.5	495.2	-0.2
		1985	1167.7	552.7	372.8	32.6	329.9	40.3	393.1	28.9	331.4	40.0
		1986	1182.4	459.3	438.6	4.5	411.1	10.5	442.5	3.6	405.3	11.7
		1987	1080.1	363.7	292.8	19.5	235.4	35.3	313.5	13.8	237.8	34.6
		1988	1172.8	543.6	407.5	25.1	362.1	33.4	422.5	22.3	374.8	31.1
		1989	829.3	221	210.5	4.8	167.6	24.2	220.7	0.1	165.9	24.9
	Average		**1148.4**	**417.0**	**371.3**	**12.0**	**343.1**	**17.6**	**383.3**	**11.7**	**355.9**	**19.3**
9	Khanapur	1985	3916.8	1648.9	1999.3	-21.3	2054.3	-24.6	2003.5	-21.5	2056.8	-24.7
		1986	3049.2	1736.4	1390.0	20.0	1472.9	15.2	1467.4	15.5	1433.1	17.5
		1987	3300.8	1475.2	1436.4	2.6	1456.7	1.3	1597.4	-8.3	1465.0	0.7
		1988	4424.9	2498.9	2345.2	6.2	2359.4	5.6	2364.2	5.4	2474.5	1.0
		1989	3705.8	1782.8	1789.2	-0.4	1852.1	-3.9	1888.7	-5.9	1885.2	-5.7
		1990	4070.6	2697.4	2003.5	25.7	2085.1	22.7	1997.3	26.0	2035.1	24.6
		1991	3947.7	2822.2	1995.9	29.3	2064.1	26.9	2049.3	27.4	2212.4	21.6
		1992	4101.4	3372.5	2012.2	40.3	2089.1	38.1	2065.3	38.8	2154.9	36.1
		1993	4419.9	3530.7	2192.5	37.9	2224.7	37.0	2268.5	35.8	2313.4	34.5
	Average		**3881.9**	**2396.1**	**1907.1**	**20.4**	**1962.0**	**19.5**	**1966.8**	**20.5**	**2003.4**	**18.5**

Appendix D continued ------

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
10	Hirehalla	1985	334.8	30.6	31.4	-2.7	40.1	-31.0	41.6	-35.9	55.8	-82.3
		1986	331.8	33.1	0.1	99.6	33.5	-1.1	29.4	11.1	40.6	-22.8
		1987	500.8	66.3	8.2	87.7	53.9	18.7	45.1	32.0	61.1	7.8
		1988	588.5	71.5	39.2	45.1	64.2	10.1	61.9	13.5	73.7	-3.1
		1989	378.0	49.4	17.4	64.9	38.6	21.9	36.2	26.7	48.8	1.3
		1990	448.6	52.4	8.7	83.4	48.8	6.9	40.0	23.7	53.7	-2.5
		1991	459.3	78.1	6.2	92.1	51.8	33.6	44.1	43.5	62.6	19.9
		1992	571.3	106.0	15.7	85.2	62.1	41.3	57.1	46.1	82.8	21.9
		1993	724.2	92.1	80.5	12.6	84.1	8.6	82.0	10.9	108.9	-18.3
	Average		**481.9**	**64.4**	**23.0**	**63.7**	**53.0**	**19.2**	**48.6**	**27.0**	**65.3**	**20.0**
11	Sagar	1985	1570.7	934.2	690.8	26.1	868.2	7.1	1021.4	-9.3	1136.1	-21.6
		1986	1271.6	757.6	539.7	28.8	671.0	11.4	712.4	6.0	838.9	-10.7
		1987	1288.6	791.4	477.5	39.7	651.8	17.6	752.7	4.9	654.3	17.3
		1988	1735.8	1155.1	845.0	26.8	1146.1	0.8	1189.5	-3.0	1080.2	6.5
		1989	1596.2	976.4	705.2	27.8	889.5	8.9	1005.8	-3.0	880.4	9.8
		1990	1919.7	1435.9	892.6	37.8	1100.0	23.4	1223.4	14.8	1010.4	29.6
		1991	1919.7	1380.5	900.7	34.8	1133.9	17.9	1263.0	8.5	1016.3	26.4
		1992	2449.8	1692.9	1208.8	28.6	1583.6	6.5	1683.1	0.6	1461.7	13.7
		1993	1881.4	1305.4	842.5	35.5	1134.2	13.1	1289.9	1.2	1075.6	17.6
	Average		**1737.1**	**1158.8**	**789.2**	**31.8**	**1019.8**	**11.8**	**1126.8**	**5.7**	**1017.1**	**17.0**
12	Sorab	1985	776.5	481.9	186.0	61.4	376.7	21.8	306.1	36.5	496.7	-3.1
		1986	684.3	430.3	290.9	32.4	270.5	37.1	297.8	30.8	339.2	21.2
		1987	937.5	552.1	481.4	12.8	421.6	23.6	457.2	17.2	505.7	8.4
		1988	1300.0	852.4	930.6	-9.2	853.4	-0.1	898.9	-5.5	872.4	-2.4
		1989	1127.5	645.6	646.2	-0.1	610.4	5.5	660.8	-2.3	620.9	3.8
		1990	1350.4	913.7	765.0	16.3	820.0	10.3	778.6	14.8	726.9	20.4
		1991	1525.2	1050.1	997.2	5.0	1030.0	1.9	1023.4	2.5	956.8	8.9
		1992	2009.7	987.8	1263.6	-27.9	1366.2	-38.3	1327.5	-34.4	1289.7	-30.6
		1993	1243.3	970.2	786.2	19.0	768.3	20.8	790.0	18.6	660.1	32.0
	Average		**1217.2**	**764.9**	**705.2**	**20.5**	**724.1**	**17.7**	**726.7**	**18.1**	**718.7**	**14.5**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
13	Dasanakatte	1985	4874.5	3951.1	3840.8	2.8	4064.5	-2.9	4090.5	-3.5	3778.8	4.4
		1986	4368.8	3831.0	3446.1	10.0	3835.1	-0.1	3769.2	1.6	3742.5	2.3
		1987	3426.4	2889.4	2694.8	6.7	3026.5	-4.7	3034.0	-5.0	2993.0	-3.6
		1988	4226.5	3831.5	3485.9	9.0	3849.1	-0.5	3811.4	0.5	3751.4	2.1
		1989	3753.4	3589.6	2964.8	17.4	3374.2	6.0	3278.1	8.7	3567.5	0.6
		1990	4811.2	4357.1	3906.6	10.3	4266.1	2.1	4234.6	2.8	4748.8	-9.0
		1991	3935.9	3332.4	3227.5	3.1	3683.6	-10.5	3651.9	-9.6	3336.0	-0.1
		1992	4648.1	4187.6	3677.7	12.2	3983.2	4.9	4025.2	3.9	2284.2	45.5
		1993	6437.4	6063.8	5505.9	9.2	6240.8	-2.9	6294.2	-3.8	4347.1	28.3
	Average		**4498.0**	**4003.7**	**3638.9**	**9.0**	**4035.9**	**3.8**	**4021.0**	**4.4**	**3616.6**	**10.6**
14	Haladi	1985	4626.6	4213.5	3635.9	13.7	3805.0	9.7	3804.0	9.7	4335.8	-2.9
		1986	4542.6	3987.4	3713.3	6.9	3842.9	3.6	3890.3	2.4	4136.3	-3.7
		1987	3435.3	2899.3	2848.1	1.8	2907.5	-0.3	2988.6	-3.1	2604.1	10.2
		1988	4268.9	3876.0	3632.1	6.3	3694.3	4.7	3777.4	2.5	3878.0	-0.1
		1989	3906.1	3457.7	3220.1	6.9	3274.0	5.3	3352.0	3.1	3241.3	6.3
		1990	5640.3	4432.3	4618.1	-4.2	4743.3	-7.0	4769.6	-7.6	5302.6	-19.6
		1991	4258.1	3517.3	3893.9	-10.7	3950.6	-12.3	4044.5	-15.0	3370.9	4.2
		1992	5213.8	4369.2	4326.9	1.0	4471.8	-2.3	4528.6	-3.6	3276.2	25.0
		1993	5194.7	3869.1	4581.4	-18.4	4673.2	-20.8	4756.6	-22.9	3278.1	15.3
	Average		**4565.1**	**3846.9**	**3830.0**	**7.8**	**3929.2**	**7.3**	**3990.2**	**7.8**	**3713.7**	**9.7**
15	Jadkal	1985	4509.2	4215.8	3687.9	12.5	4173.8	1.0	4188.5	0.6	4207.6	0.2
		1986	4132.2	3815.3	3452.9	9.5	3773.7	1.1	3720.8	2.5	3863.9	-1.3
		1987	4065.4	3768.4	3311.1	12.1	3668.0	2.7	3656.0	3.0	3464.2	8.1
		1988	5239.1	5221.3	4599.9	11.9	4971.4	4.8	4931.3	5.6	5186.7	0.7
		1989	4483.8	4366.6	3784.8	13.3	4068.5	6.8	4054.4	7.2	4218.8	3.4
		1990	6456.6	5732.4	5661.1	1.2	6088.8	-6.2	6011.3	-4.9	6631.4	-15.7
		1991	5237.3	4681.9	4641.5	0.9	4998.4	-6.8	4877.8	-4.2	4148.3	11.4
		1992	6274.4	5805.3	5417.7	6.7	5948.7	-2.5	5814.2	-0.2	4811.6	17.1
		1993	5187.4	4716.2	4553.6	3.4	4863.8	-3.1	4855.0	-2.9	3746.0	20.6
	Average		**5065.0**	**4702.6**	**4345.6**	**8.0**	**4728.3**	**3.9**	**4678.8**	**3.4**	**4475.4**	**8.7**

Appendix D continued ------

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	M-I		M-II		M-III		M-IV	
					Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)	Simulated Runoff (mm)	RE* (%)
16	Kokkarne	1985	4875.5	3890.3	3715.1	4.5	3694.8	5.0	3795.6	2.4	3985.5	-2.4
		1986	4468.6	3464.8	3525.8	-1.8	3634.3	-4.9	3563.9	-2.9	3532.9	-2.0
		1987	3640.4	2480.5	2660.2	-7.2	2733.4	-10.2	2684.8	-8.2	2260.0	8.9
		1988	4723.5	3919.3	3960.3	-1.0	4020.2	-2.6	3940.8	-0.5	3924.7	-0.1
		1989	4680.6	4042.5	3772.8	6.7	3805.9	5.9	3748.0	7.3	3592.1	11.1
		1990	5388.6	4651.3	4367.3	6.1	4495.2	3.4	4380.6	5.8	4137.3	11.1
		1991	4742.5	3957.6	3939.8	0.4	4001.3	-1.1	3941.0	0.4	3540.4	10.5
		1992	5393.2	4176.3	4309.3	-3.2	4438.7	-6.3	4348.2	-4.1	3808.0	8.8
		1993	6013.0	4865.6	5158.0	-6.0	5305.7	-9.0	5174.7	-6.4	4422.2	9.1
	Average		**4880.7**	**3938.7**	**3934.3**	**4.1**	**4014.4**	**5.4**	**3953.1**	**4.2**	**3689.2**	**7.1**
17	Halkal	1985	4509.2	3946.8	3551.6	10.0	3759.1	4.8	3796.6	3.8	3923.9	0.6
		1986	4132.2	3547.2	3452.1	2.7	3581.3	-1.0	3505.7	1.2	3555.7	-0.2
		1987	4065.4	3409.9	3358.4	1.5	3479.2	-2.0	3442.2	-0.9	3061.6	10.2
		1988	5239.1	4689.8	4522.8	3.6	4779.0	-1.9	4698.7	-0.2	4855.5	-3.5
		1989	4483.8	3993.6	3770.6	5.6	3882.8	2.8	3849.9	3.6	4090.9	-2.4
		1990	6456.6	5846.2	5632.4	3.7	5864.6	-0.3	5760.4	1.5	6548.0	-12.0
		1991	5237.3	4749.0	4575.7	3.6	4817.9	-1.4	4688.9	1.3	4636.5	2.4
		1992	6549.3	6173.5	5522.2	10.6	5876.4	4.8	5698.6	7.7	4333.4	29.8
		1993	5187.4	4925.3	4634.5	5.9	4779.9	3.0	4758.4	3.4	3372.2	31.5
	Average		**5095.6**	**4586.8**	**4335.6**	**5.2**	**4535.6**	**2.4**	**4466.6**	**2.6**	**4264.2**	**10.3**

*** Average Relative Error (%) is absolute value (Average RE = $\sum_{i=1}^{n} |RE(\%)| / n$, n=no. of years)**

APPENDIX E

RS VALUES OF SIMULATED STREAM FLOW

E-I Manot Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	35.320	75	100	1.868	MS
2	δ	6.633	75	100	No change	N
3	α	0.854	75	10	No change	N
4	β	0.001	75	100	0.002	N
5	γ	0.952	75	0	5.352	MS
6	K	3.016	75	100	0.019	L
7	P_1	0.017	75	100	No change	N
8	P_3	0.597	75	50	0.338	M
9	P_4	0.483	75	100	0.119	L
10	θ_w	298.930	75	50	0.786	H
11	ψ_f	413.790	75	75	0.965	VH
12	E_g	0.360	75	100	No change	N
13	ψ_0	377.140	50	75	No change	N
14	CNd_0	56.590	75	75	1.571	MS
15	λ_d	0.568	75	75	No change	N

E-II Mohegaon Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	37.000	75	100	0.852	VH
2	δ	0.050	75	100	No change	N
3	α	0.460	75	100	No change	N
4	β	0.010	75	100	0.033	L
5	γ	0.500	75	100	6.973	MS
6	K	5.000	75	100	0.023	L
7	P_1	0.026	75	100	No change	N
8	P_3	0.600	75	50	0.550	H
9	P_4	0.160	75	100	0.076	L
10	θ_w	119.660	50	100	0.431	H
11	ψ_f	395.330	75	75	1.153	MS
12	E_g	0.320	75	100	No change	N
13	ψ_0	469.370	75	25	No change	N
14	CNd_0	58.250	75	50	1.415	MS
15	λ_d	0.070	75	100	No change	N

E-III Sagar Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	21.360	75	100	0.415	H
2	δ	0.210	75	100	No change	N
3	α	0.500	75	100	No change	N
4	β	0.012	75	100	0.012	L
5	γ	0.540	75	100	17.929	MS
6	K	0.640	75	100	0.003	N
7	P_1	0.010	75	100	No change	N
8	P_3	0.590	75	50	0.288	M
9	P_4	0.540	75	75	0.276	M
10	θ_w	45.460	10	100	0.101	L
11	ψ_f	400.000	50	50	0.735	H
12	E_g	0.900	75	100	No change	N
13	ψ_0	190.980	50	100	No change	N
14	CNd_0	50.800	75	75	2.303	MS
15	λ_d	0.090	75	100	No change	N

Appendix E continued…..

E-IV Sorab Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	52.760	75	75	0.354	M
2	δ	0.133	75	100	0.003	N
3	α	0.531	75	75	No change	N
4	β	0.010	75	100	0.006	N
5	γ	0.613	75	50	5.683	MS
6	K	1.633	75	100	0.026	L
7	P_1	0.010	75	100	No change	N
8	P_3	0.500	75	100	0.027	L
9	P_4	0.839	75	10	0.190	L
10	θ_w	105.000	50	100	0.177	L
11	ψ_f	302.343	75	100	0.400	M
12	E_g	0.401	75	100	No change	N
13	ψ_0	396.980	75	100	No change	N
14	CNd_0	51.938	75	75	1.227	MS
15	λ_d	0.046	75	100	No change	N

E-V Amachi Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	17.364	75	100	1.600	MS
2	δ	0.420	75	100	0.020	L
3	α	0.399	75	100	No change	N
4	β	0.020	75	100	0.024	L
5	γ	0.100	75	100	2.931	MS
6	K	2.000	75	100	0.019	L
7	P_1	0.006	75	100	No change	N
8	P_3	0.197	75	100	0.373	M
9	P_4	0.437	75	100	0.183	L
10	θ_w	80.000	50	100	0.119	L
11	ψ_f	310.003	50	100	0.229	M
12	E_g	0.339	75	100	0.006	N
13	ψ_0	242.860	50	100	No change	N
14	CNd_0	32.330	75	100	1.133	MS
15	λ_d	0.018	75	100	No change	N

Appendix E continued…..

E-VI Attigundi Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	20.000	75	100	No change	N
2	δ	0.019	75	100	No change	N
3	α	0.449	75	100	No change	N
4	β	0.001	75	100	0.088	L
5	γ	0.584	75	75	5.527	MS
6	K	5.977	75	100	0.019	L
7	P_1	0.050	75	100	No change	N
8	P_3	0.237	75	100	No change	N
9	P_4	0.979	75	0	0.064	L
10	θ_w	162.467	50	100	0.056	L
11	ψ_f	373.848	50	100	0.097	L
12	E_g	0.375	75	100	No change	N
13	ψ_0	199.356	50	100	No change	N
14	CNd_0	44.788	75	100	3.860	MS
15	λ_d	0.255	75	100	No change	N

E-VII Barchi Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	38.119	75	100	1.291	MS
2	δ	0.010	75	100	0.001	N
3	α	0.540	75	75	No change	N
4	β	0.010	75	100	0.018	L
5	γ	0.540	75	75	4.111	MS
6	K	2.000	75	100	0.085	L
7	P_1	0.010	75	100	No change	N
8	P_3	0.349	75	100	0.168	L
9	P_4	0.500	75	100	0.293	M
10	θ_w	148.943	75	75	0.369	M
11	ψ_f	279.162	50	100	0.510	H
12	E_g	0.378	75	100	No change	N
13	ψ_0	551.527	75	100	No change	N
14	CNd_0	55.359	75	100	0.690	H
15	λ_d	0.090	75	100	No change	N

E-VIII Khanapur Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	11.272	75	100	No change	N
2	δ	0.142	75	100	No change	N
3	α	0.463	75	100	No change	N
4	β	0.020	75	100	0.029	L
5	γ	0.570	75	50	8.482	MS
6	K	3.177	75	100	0.014	L
7	P_1	0.012	75	100	No change	N
8	P_3	0.602	75	50	No change	N
9	P_4	0.990	75	0	0.191	L
10	θ_w	179.876	75	100	0.166	L
11	ψ_f	404.990	50	50	0.338	M
12	E_g	0.500	75	100	No change	N
13	ψ_0	198.328	25	100	No change	N
14	CNd_0	18.339	75	100	2.417	MS
15	λ_d	0.146	75	100	No change	N

E-IX Jadkal Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	30.835	75	100	0.806	VH
2	δ	0.981	75	100	0.046	L
3	α	0.474	75	100	No change	N
4	β	0.337	75	100	0.462	H
5	γ	0.532	75	75	2.705	MS
6	K	0.533	75	100	0.051	L
7	P_1	0.050	75	100	No change	N
8	P_3	0.479	75	100	0.991	VH
9	P_4	0.990	75	0	0.244	M
10	θ_w	160.000	75	100	0.240	M
11	ψ_f	400.000	75	50	0.305	M
12	E_g	0.388	75	100	1.098	MS
13	ψ_0	405.663	75	100	0.192	L
14	CNd_0	42.214	75	100	0.926	VH
15	λ_d	0.061	75	100	No change	N

Appendix E continued…..

E-X Kokkarne Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	15.763	75	100	0.798	H
2	δ	4.990	75	100	0.018	L
3	α	0.575	75	50	No change	N
4	β	0.185	75	100	0.275	M
5	γ	0.557	75	75	2.649	MS
6	K	2.059	75	100	0.008	N
7	P_1	0.002	75	100	No change	N
8	P_3	0.547	75	75	0.125	L
9	P_4	0.990	75	0	0.137	L
10	θ_w	127.419	50	100	0.032	L
11	ψ_f	407.900	75	50	0.081	L
12	E_g	0.303	75	100	No change	N
13	ψ_0	220.191	50	100	No change	N
14	CNd_0	25.940	75	100	0.095	L
15	λ_d	0.012	75	100	No change	N

E-XI Halkal Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	26.483	75	100	0.314	M
2	δ	0.010	75	100	No change	N
3	α	0.653	75	50	No change	N
4	β	0.297	75	100	0.488	H
5	γ	0.658	75	50	2.909	MS
6	K	1.337	75	100	0.001	N
7	P_1	0.010	75	100	No change	N
8	P_3	0.465	75	100	0.354	M
9	P_4	0.990	75	0	0.274	M
10	θ_w	240.000	75	75	0.049	L
11	ψ_f	262.852	50	75	0.048	L
12	E_g	0.379	75	100	0.184	L
13	ψ_0	303.380	50	100	No change	N
14	CNd_0	33.460	75	100	0.704	H
15	λ_d	0.011	75	100	No change	N

E-XII Dasanakatte Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	15.580	75	100	0.133	L
2	δ	0.110	75	100	0.001	N
3	α	0.589	75	50	No change	N
4	β	0.240	75	100	0.291	M
5	γ	0.610	75	50	4.197	MS
6	K	0.760	75	100	0.001	N
7	P_1	0.001	75	100	No change	N
8	P_3	0.404	75	100	0.204	L
9	P_4	0.990	75	0	0.327	M
10	θ_w	123.630	50	100	0.013	L
11	ψ_f	399.870	75	75	0.041	L
12	E_g	0.380	75	100	0.109	L
13	ψ_0	394.380	50	100	No change	N
14	CNd_0	20.400	75	100	0.387	M
15	λ_d	0.016	75	100	No change	N

E-XIII Haladi Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	25.639	75	100	0.499	H
2	δ	0.015	75	100	No change	N
3	α	0.556	75	75	No change	N
4	β	0.234	75	100	0.306	M
5	γ	0.602	75	50	2.860	MS
6	K	1.656	75	100	0.070	L
7	P_1	0.010	75	100	No change	N
8	P_3	0.469	75	100	0.613	H
9	P_4	0.990	75	0	0.285	M
10	θ_w	103.796	50	75	0.054	L
11	ψ_f	399.982	50	25	0.148	L
12	E_g	0.350	75	100	0.651	H
13	ψ_0	389.113	50	100	0.060	L
14	CNd_0	37.109	75	100	0.684	H
15	λ_d	0.047	75	100	No change	N

E-XIV Hirehalla Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	14.552	75	100	No change	N
2	δ	0.061	75	100	No change	N
3	α	0.482	75	100	No change	N
4	β	0.105	75	100	0.235	M
5	γ	0.503	75	75	10.737	MS
6	K	2.071	75	100	0.009	N
7	P_1	0.090	75	100	No change	N
8	P_3	0.798	75	100	0.551	H
9	P_4	0.060	75	100	0.023	L
10	θ_w	130.341	50	100	0.279	M
11	ψ_f	299.952	75	100	0.487	H
12	E_g	0.492	75	100	0.002	N
13	ψ_0	350.000	50	100	No change	N
14	CNd_0	35.782	75	100	2.137	MS
15	λ_d	0.034	75	100	No change	N

E-XV Anthrolli Watershed

Sr. No.	Independent Variables	Optimized Values	Lower Boundary (% decrease)	Upper Boundary (% increase)	RS of Simulated Stream Flow	Symbol
1	CN_0	28.570	75	100	0.837	VH
2	δ	4.920	75	100	No change	N
3	α	0.430	75	100	No change	N
4	β	0.010	75	100	0.020	L
5	γ	0.460	75	100	13.576	MS
6	K	1.690	75	100	No change	N
7	P_1	0.005	75	100	No change	N
8	P_3	0.390	75	100	0.808	VH
9	P_4	0.100	75	100	0.149	L
10	θ_w	220.000	75	75	0.390	M
11	ψ_f	259.770	50	75	0.480	H
12	E_g	0.540	75	75	0.112	L
13	ψ_0	358.800	50	100	No change	N
14	CNd_0	78.190	75	25	0.868	VH
15	λ_d	0.130	75	100	No change	N

APPENDIX F

RS PLOTS OF STREAM FLOW

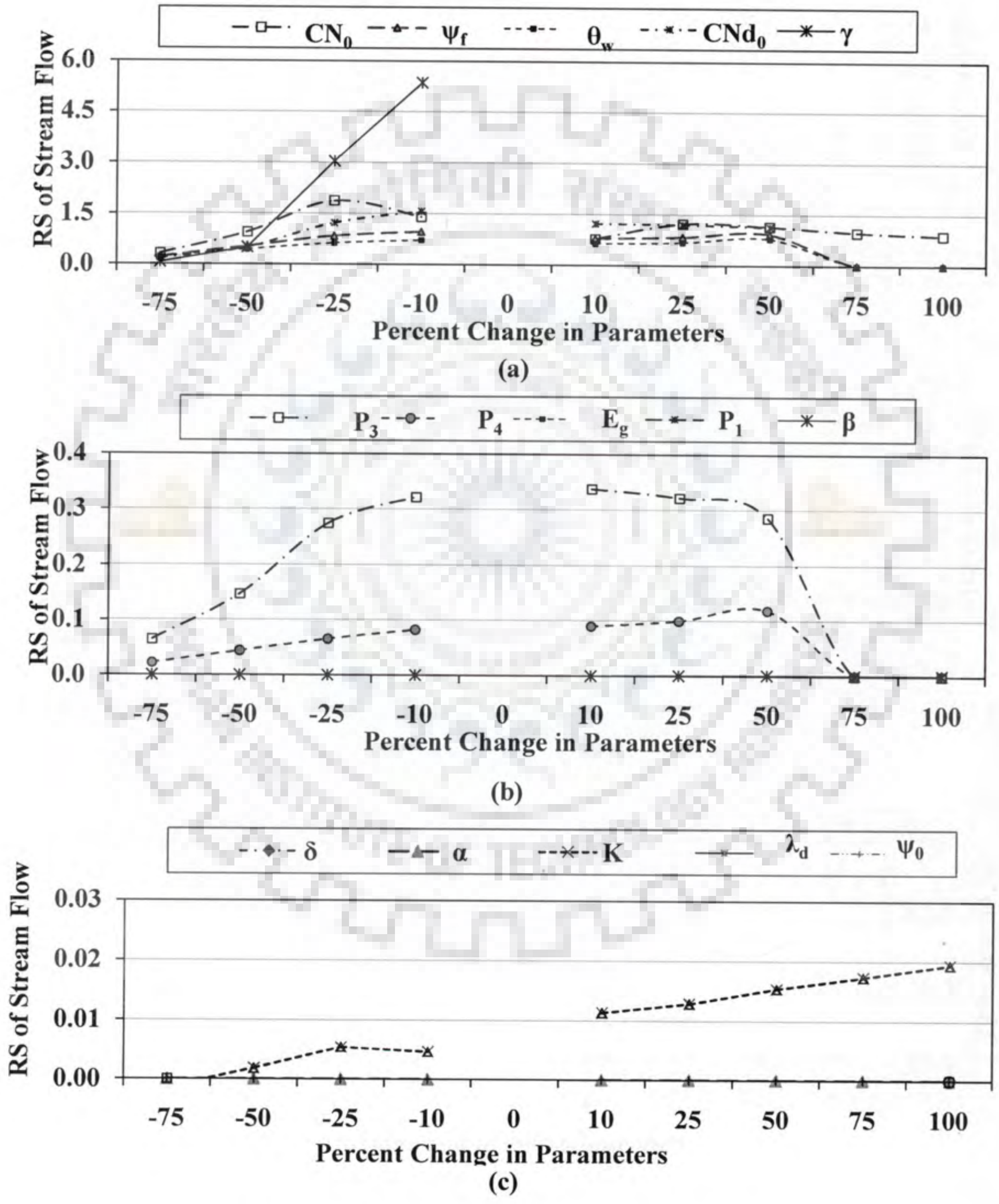
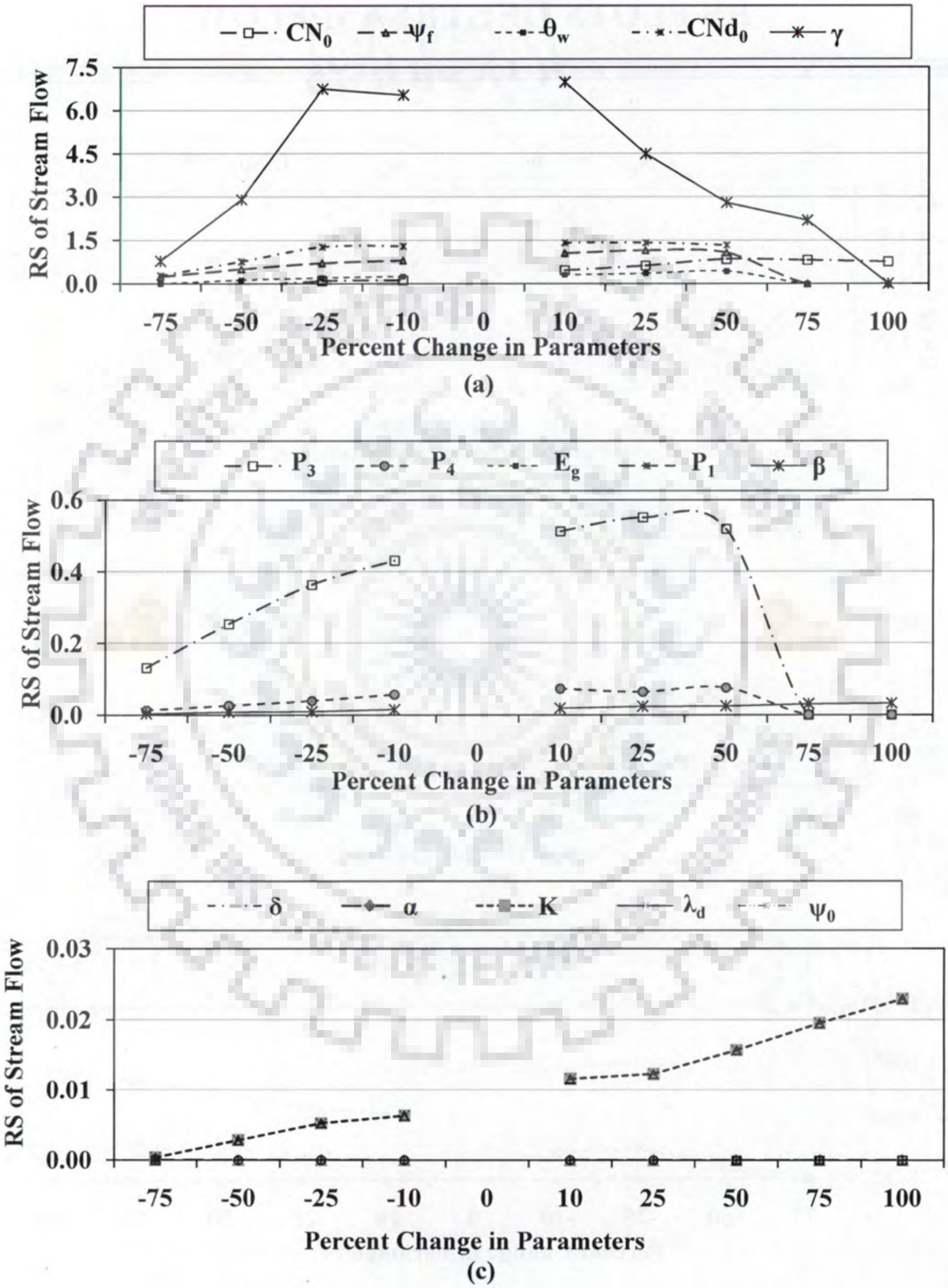


Fig. F-1 RS Plots of Stream Flow for Manot Watershed



(a)

(b)

(c)

Fig. F-2 RS Plots of Stream Flow for Mohegaon Watershed

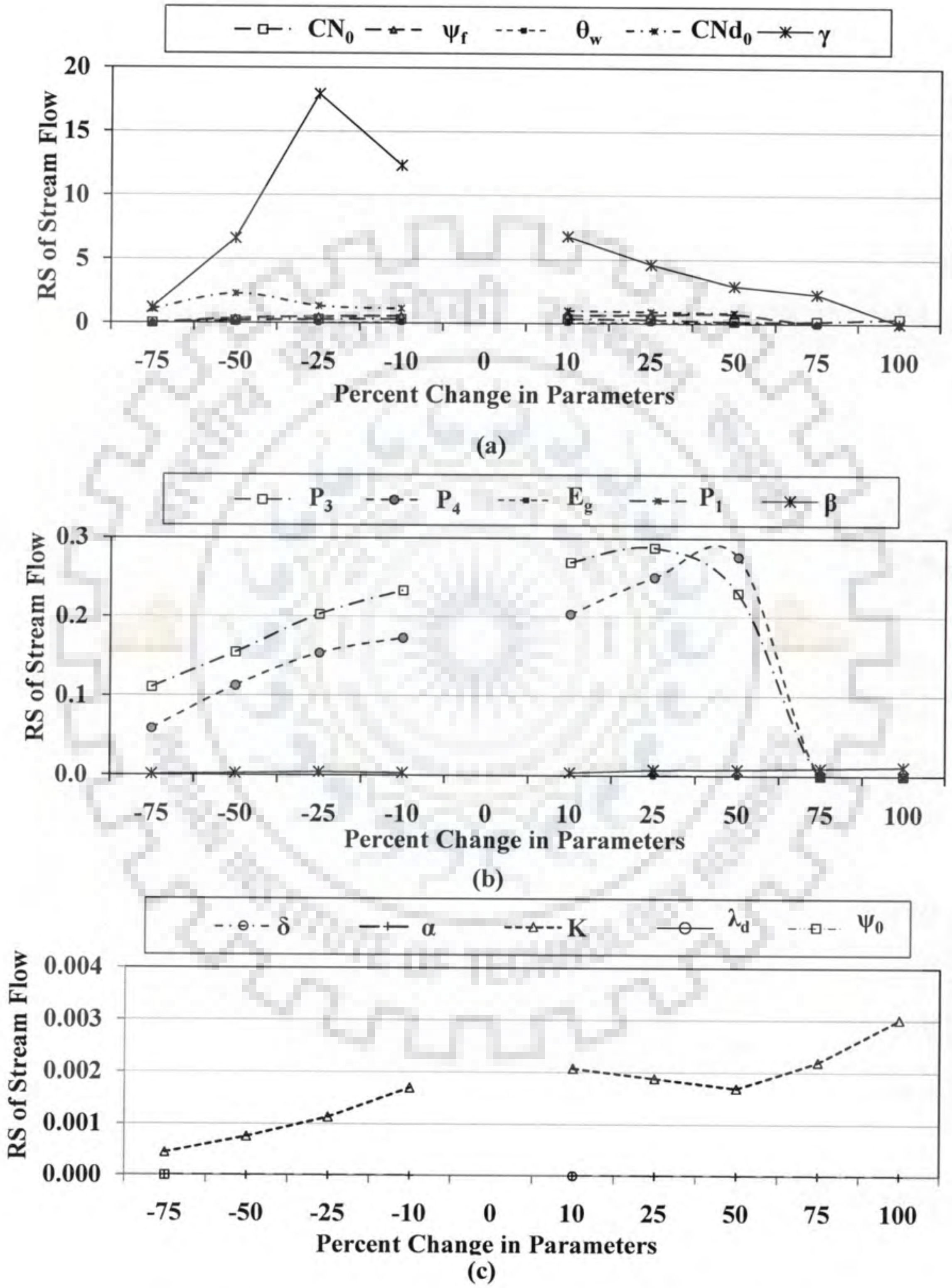


Fig. F-3 RS Plots of Stream Flow for Sagar Watershed

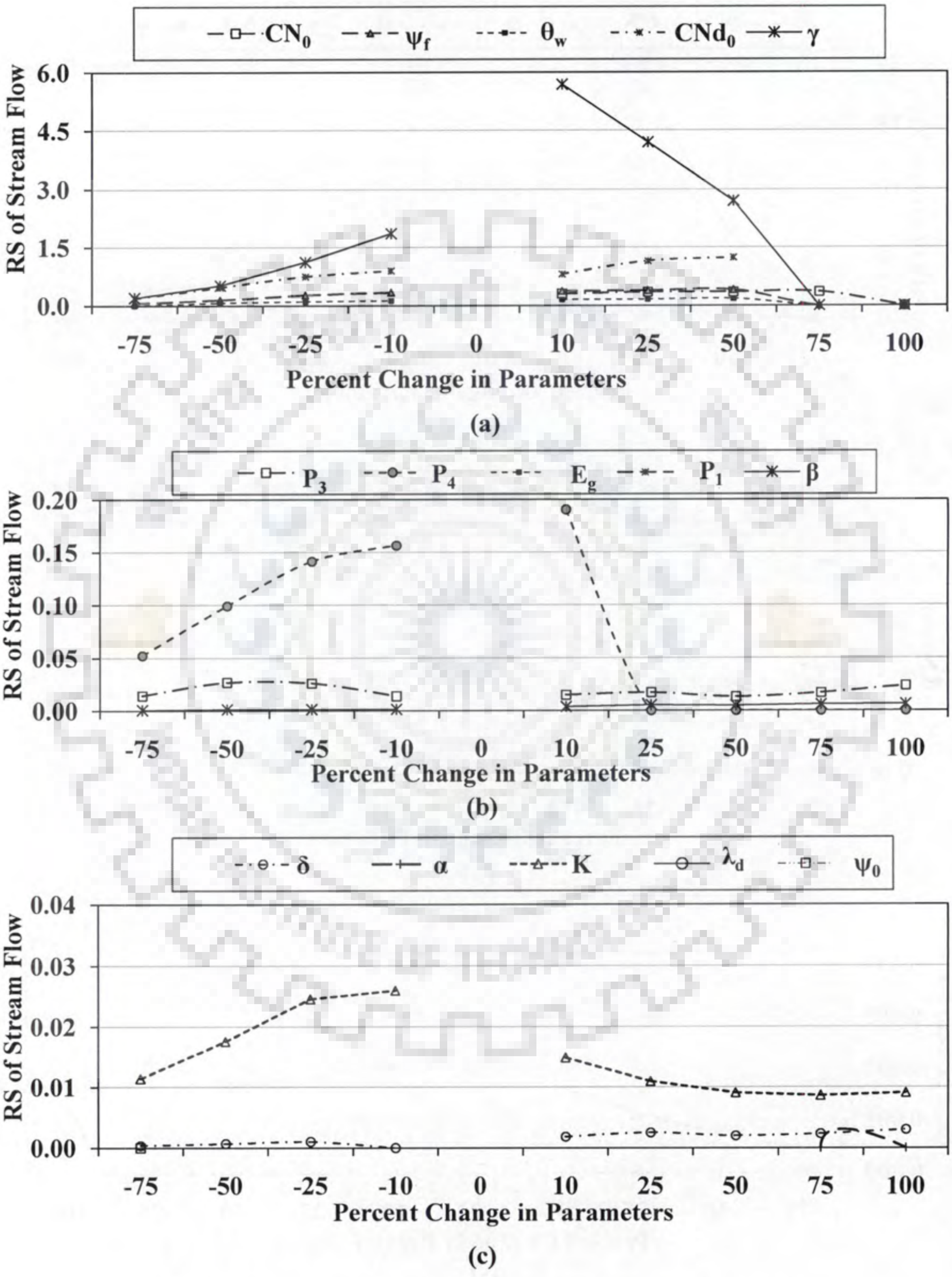


Fig. F-4 RS Plots of Stream Flow for Sorab Watershed

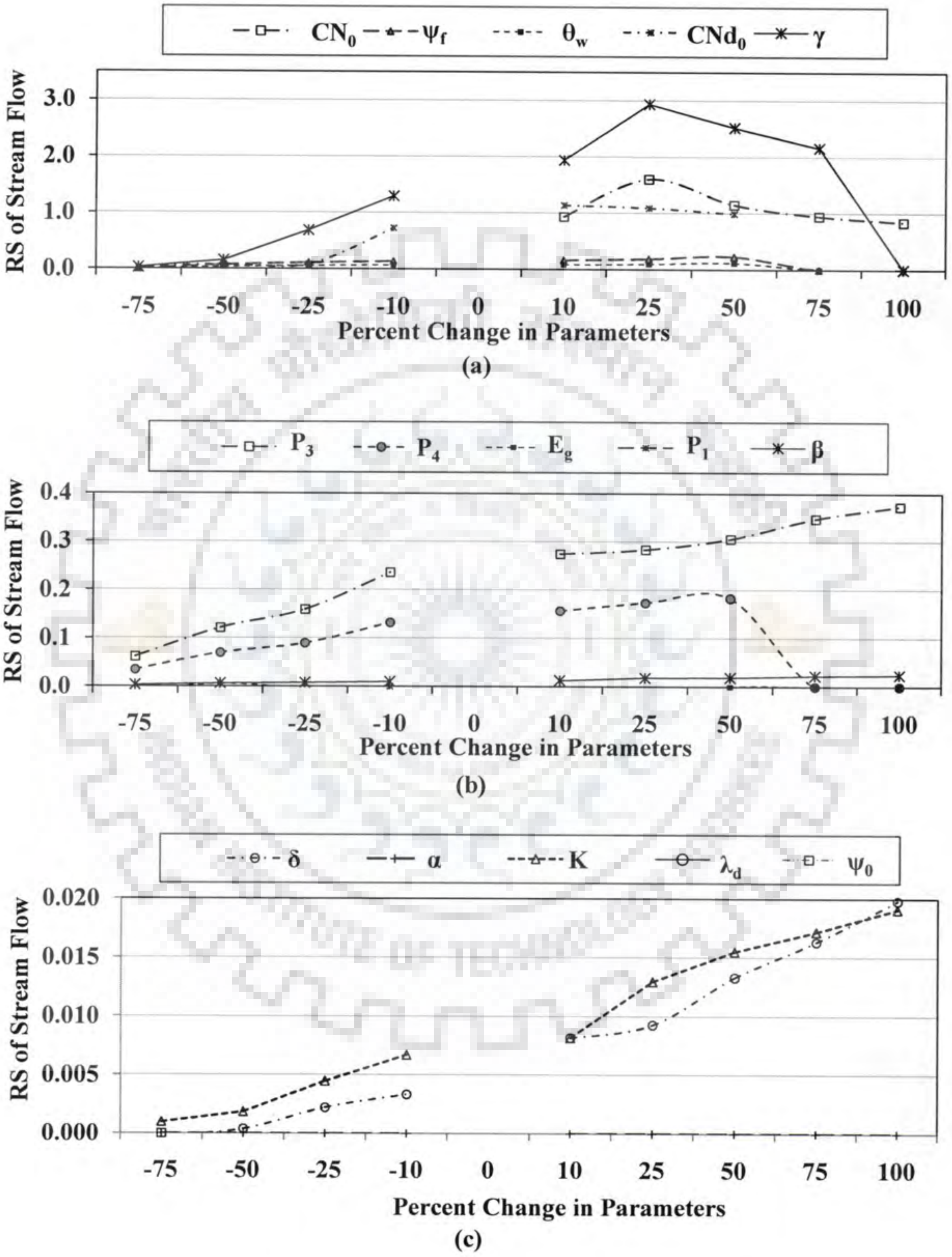
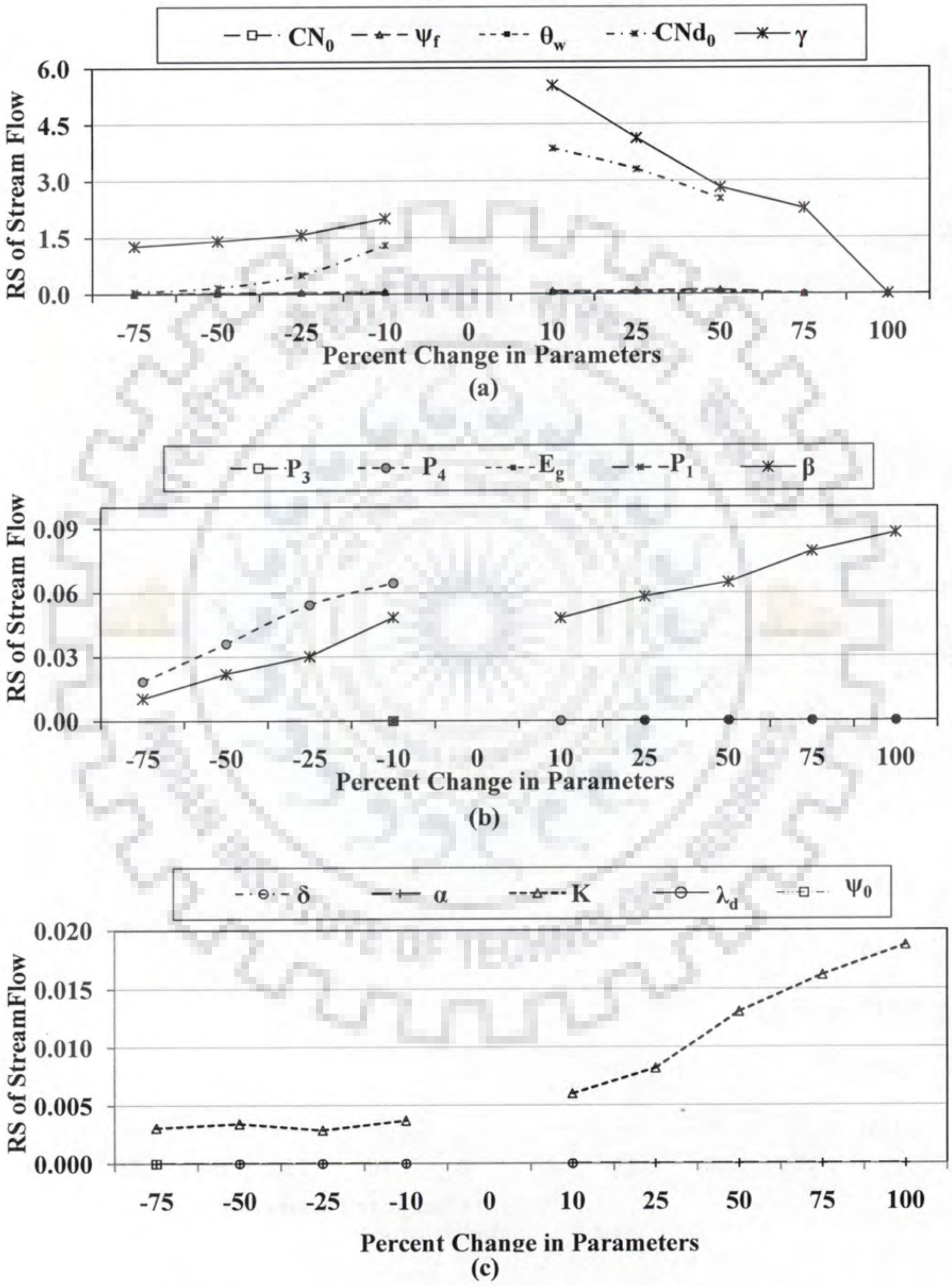


Fig. F-5 RS Plots of Stream Flow for Amachi Watershed



(a)

(b)

(c)

Fig. F-6 RS plots of Stream Flow for Attigundi Watershed

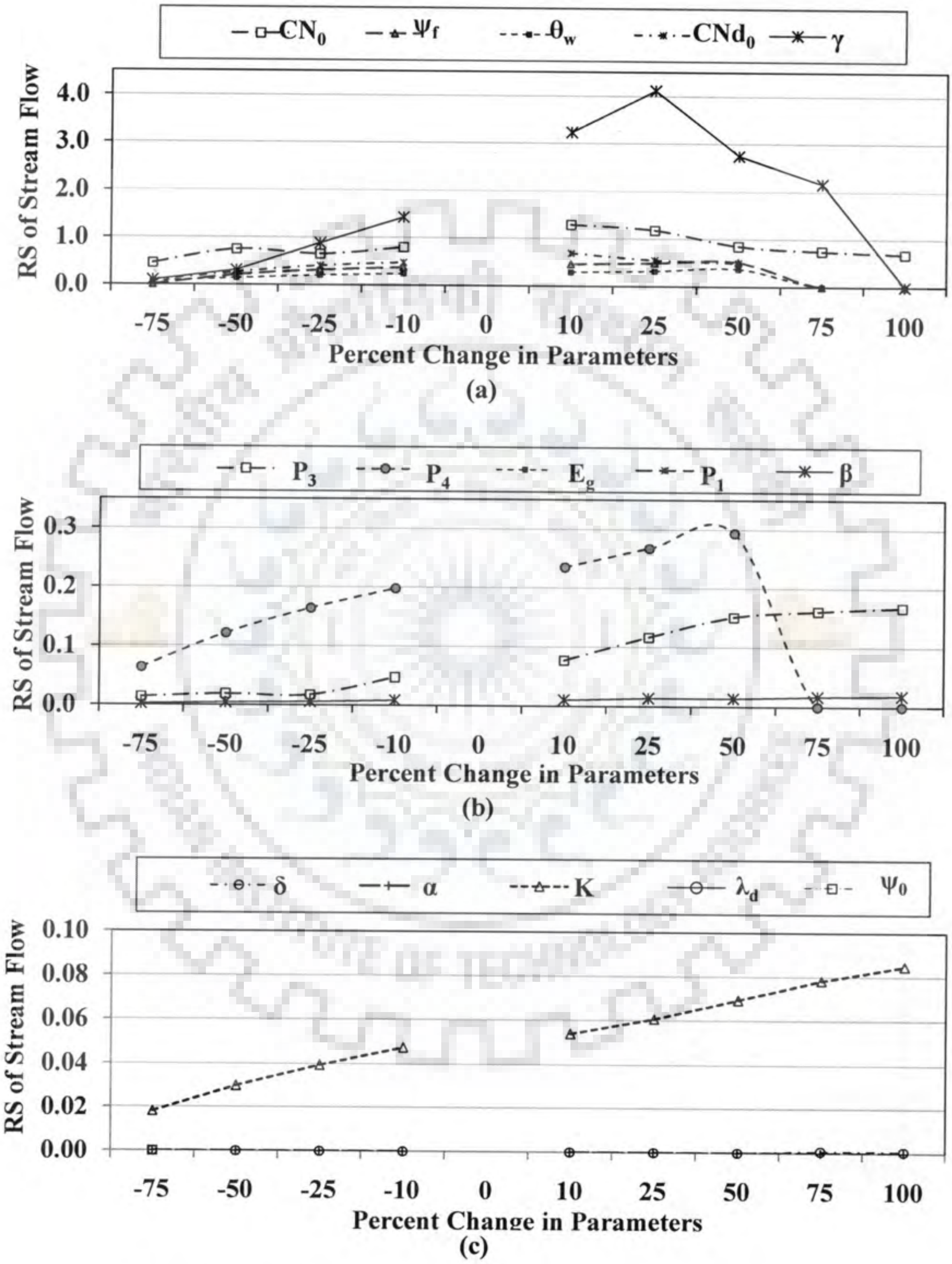
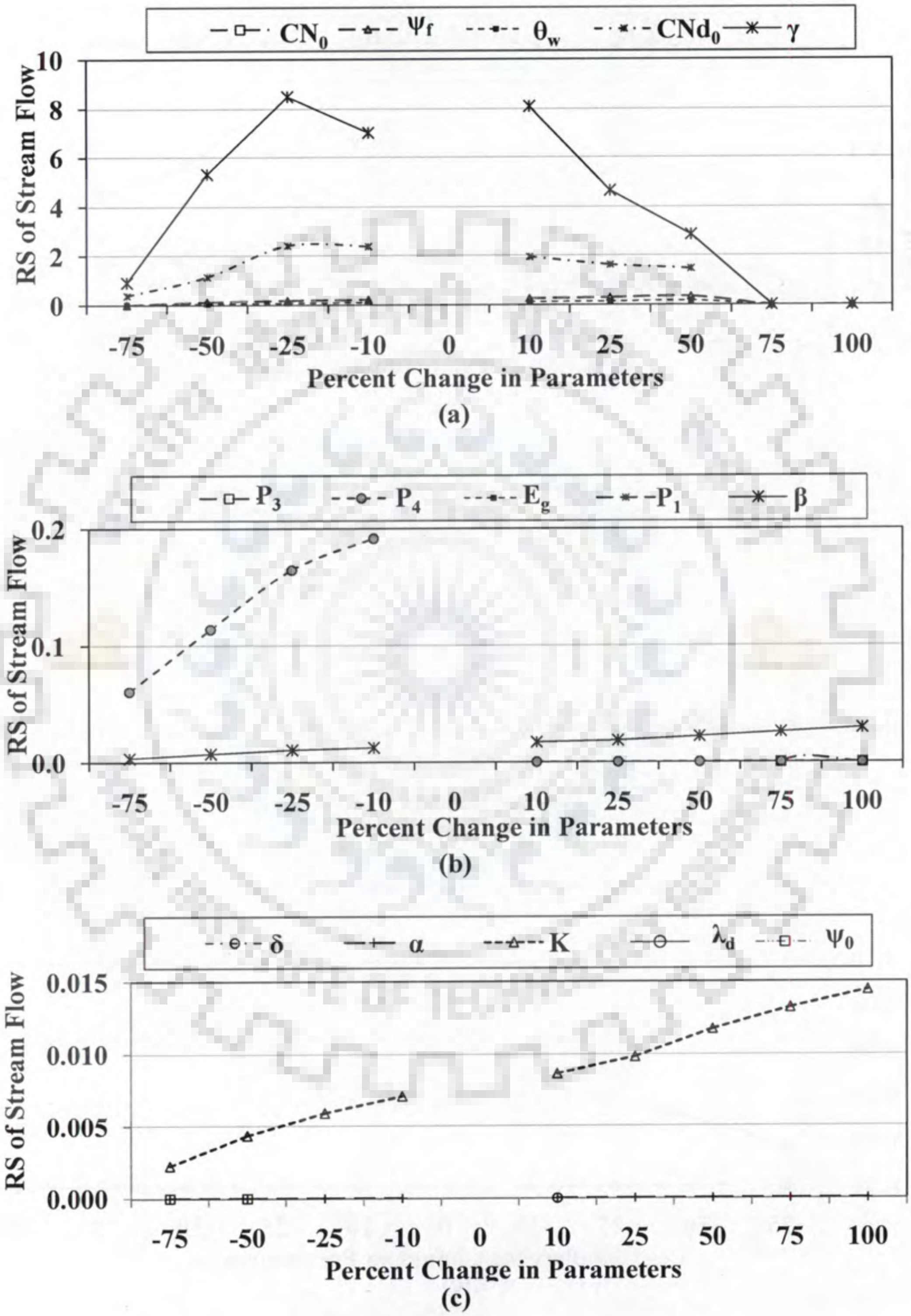


Fig. F-7 RS Plots of Stream Flow for Barchi Watershed

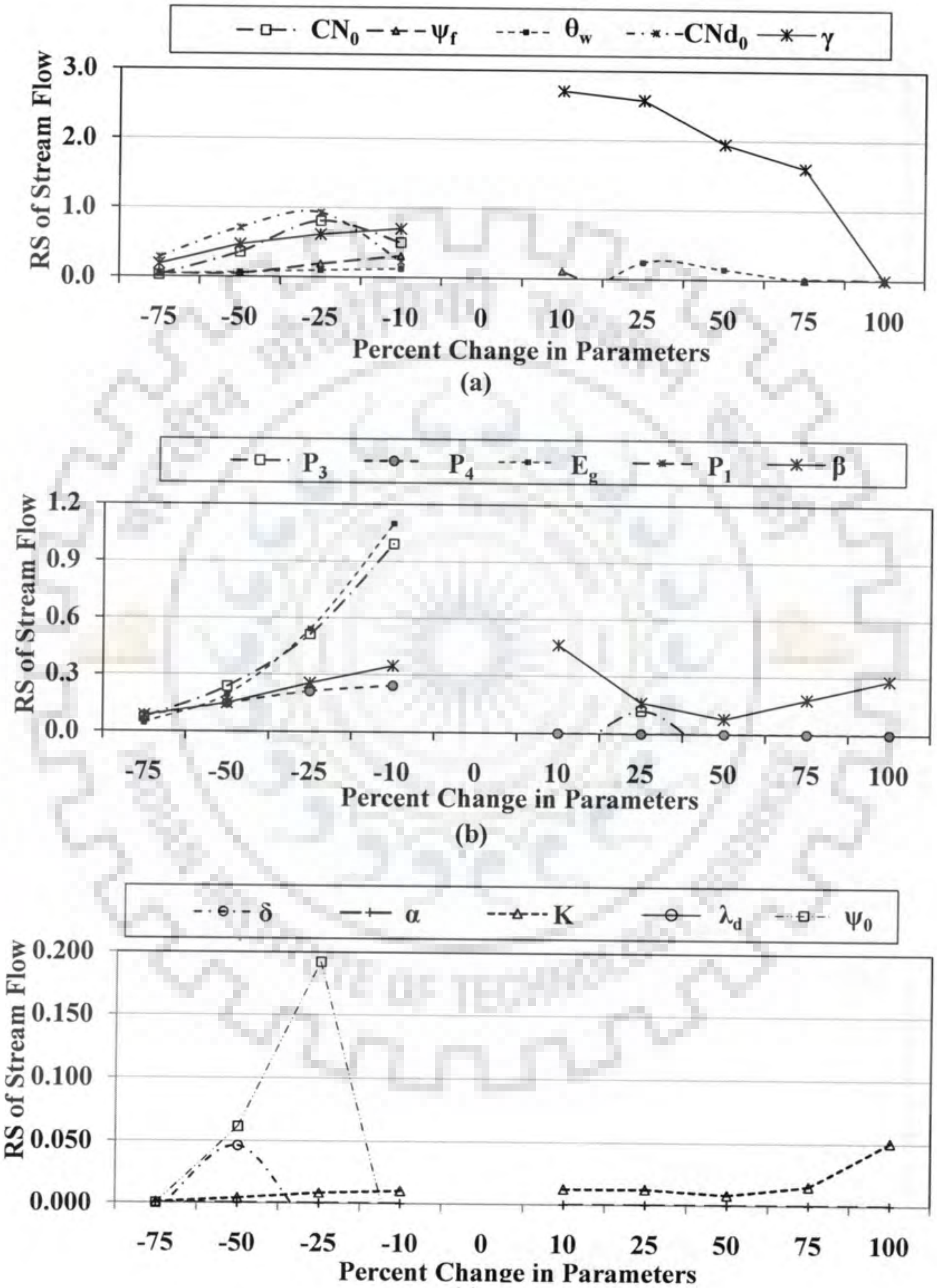


(a)

(b)

(c)

Fig F-8 RS Plots of Stream Flow for Khanapur Watershed



(a)

(b)

(c)

Fig. F-9 RS Plots of Stream Flow for Jadkal Watershed

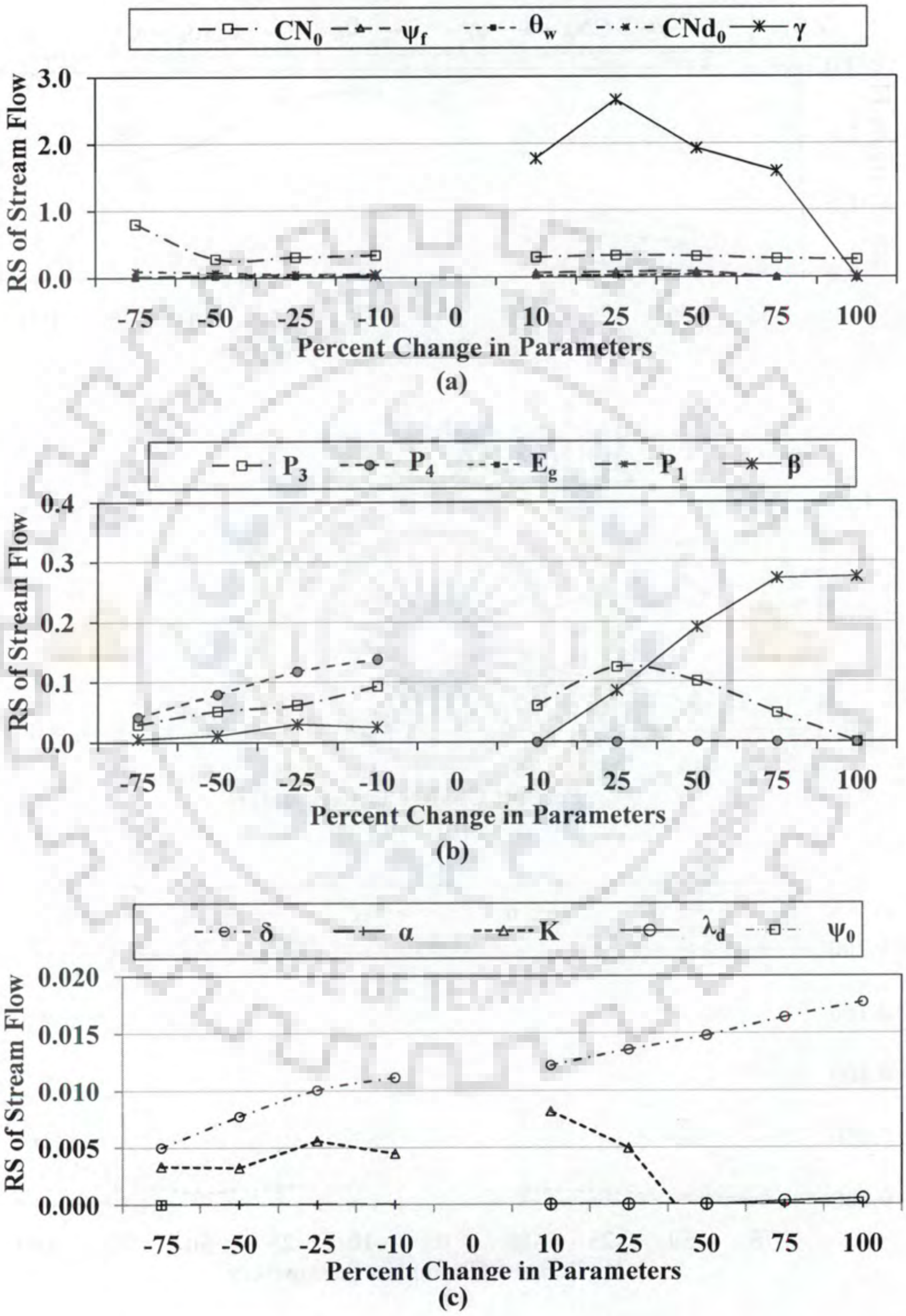


Fig. F-10 RS Plots of Stream Flow for Kokkarne Watershed

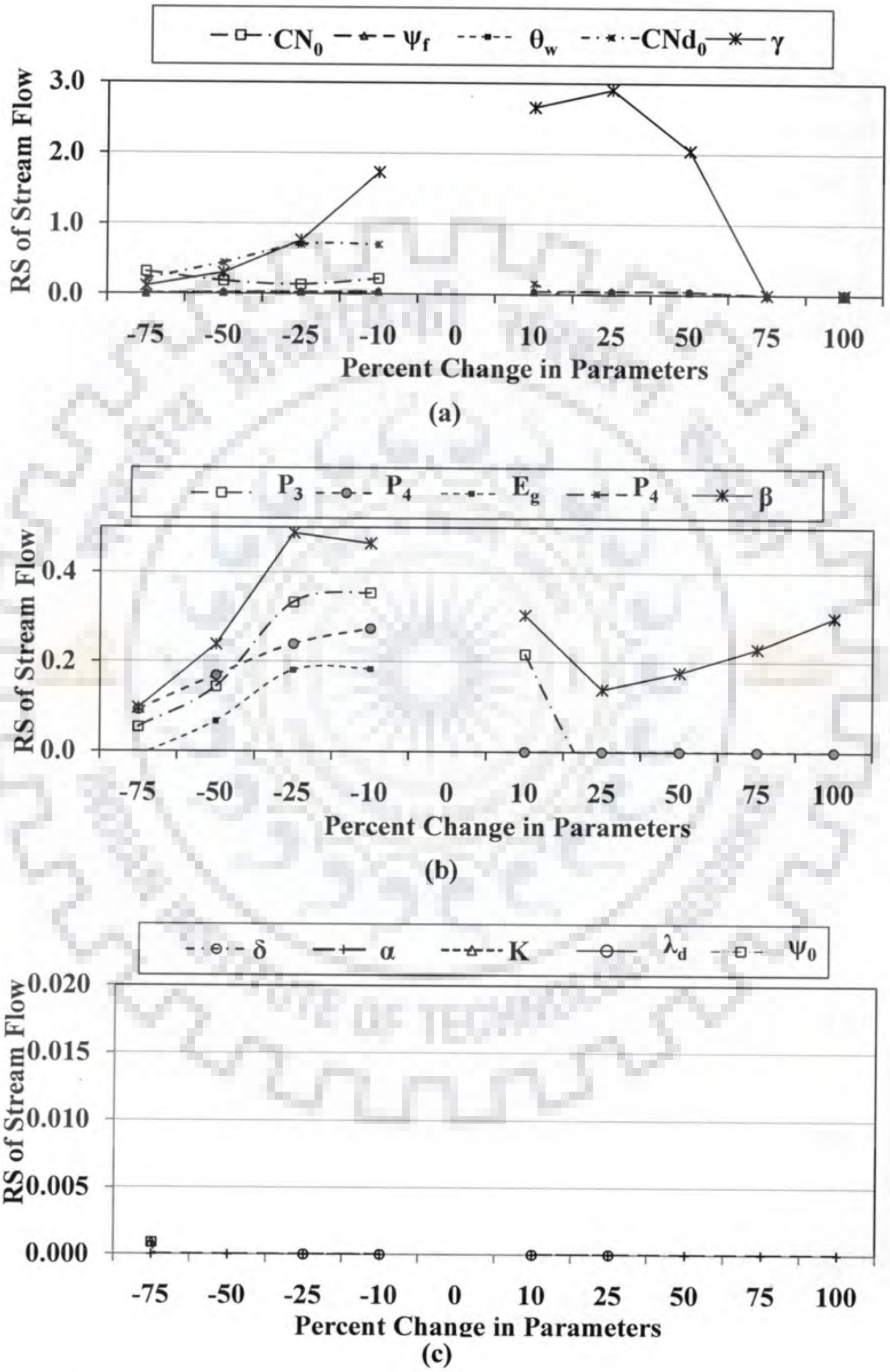
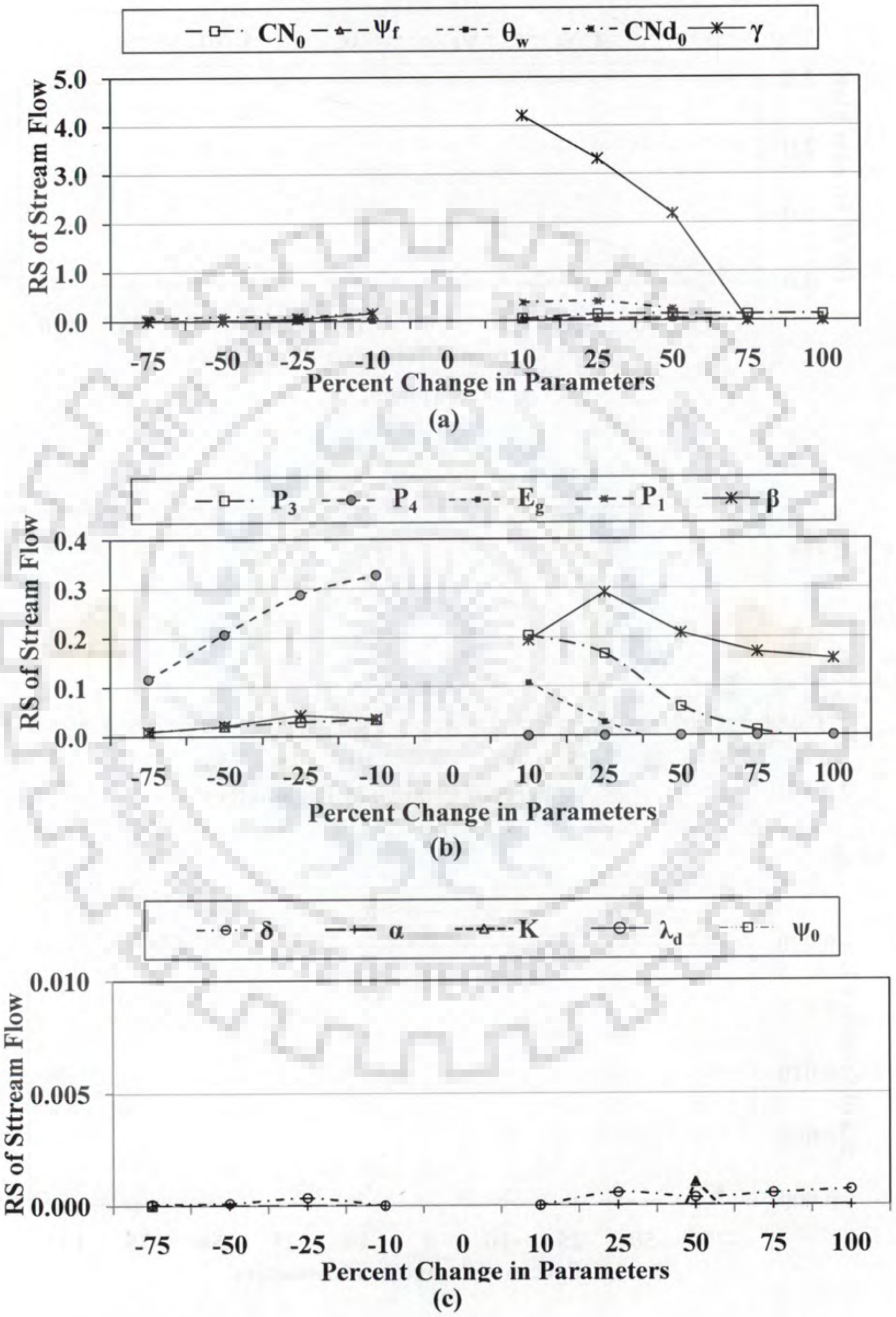


Fig. F-11 RS Plots of Stream Flow for Halkal Watershed



(a)

(b)

(c)

Fig. F-12 RS plots of Stream Flow for Dasanakatte Watershed

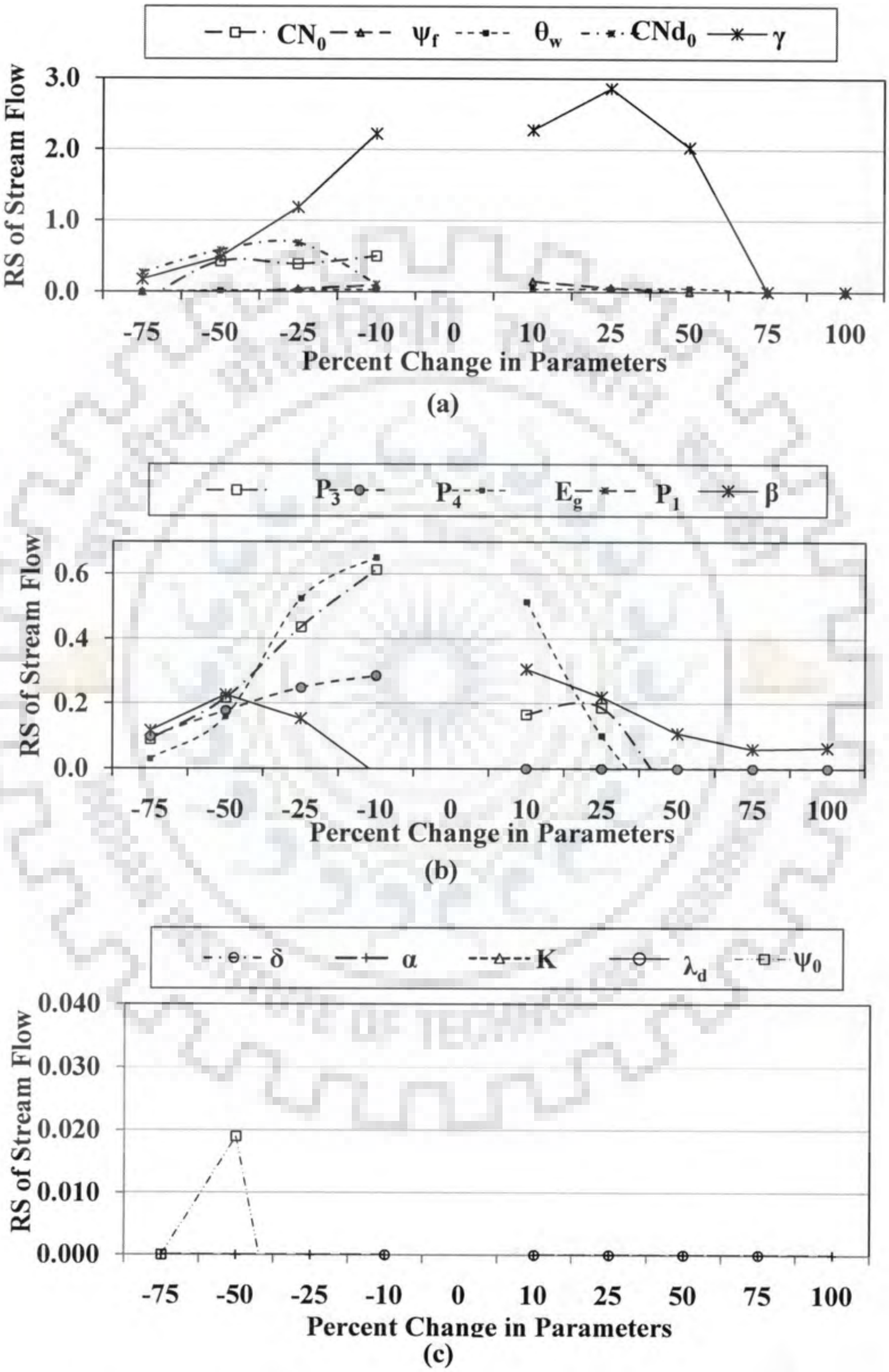


Fig. F-13 RS Plots of Stream Flow for Haladi Watershed

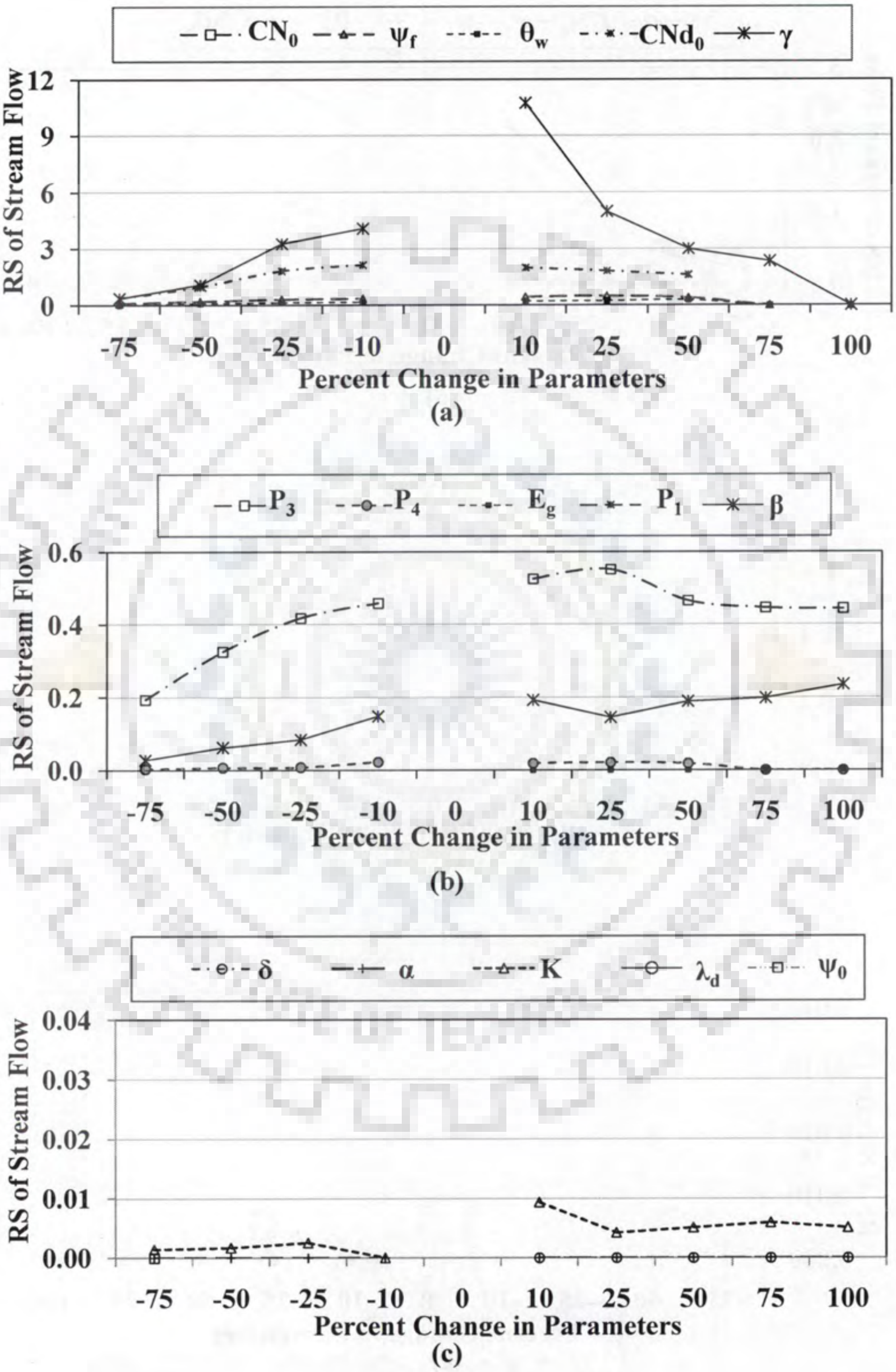
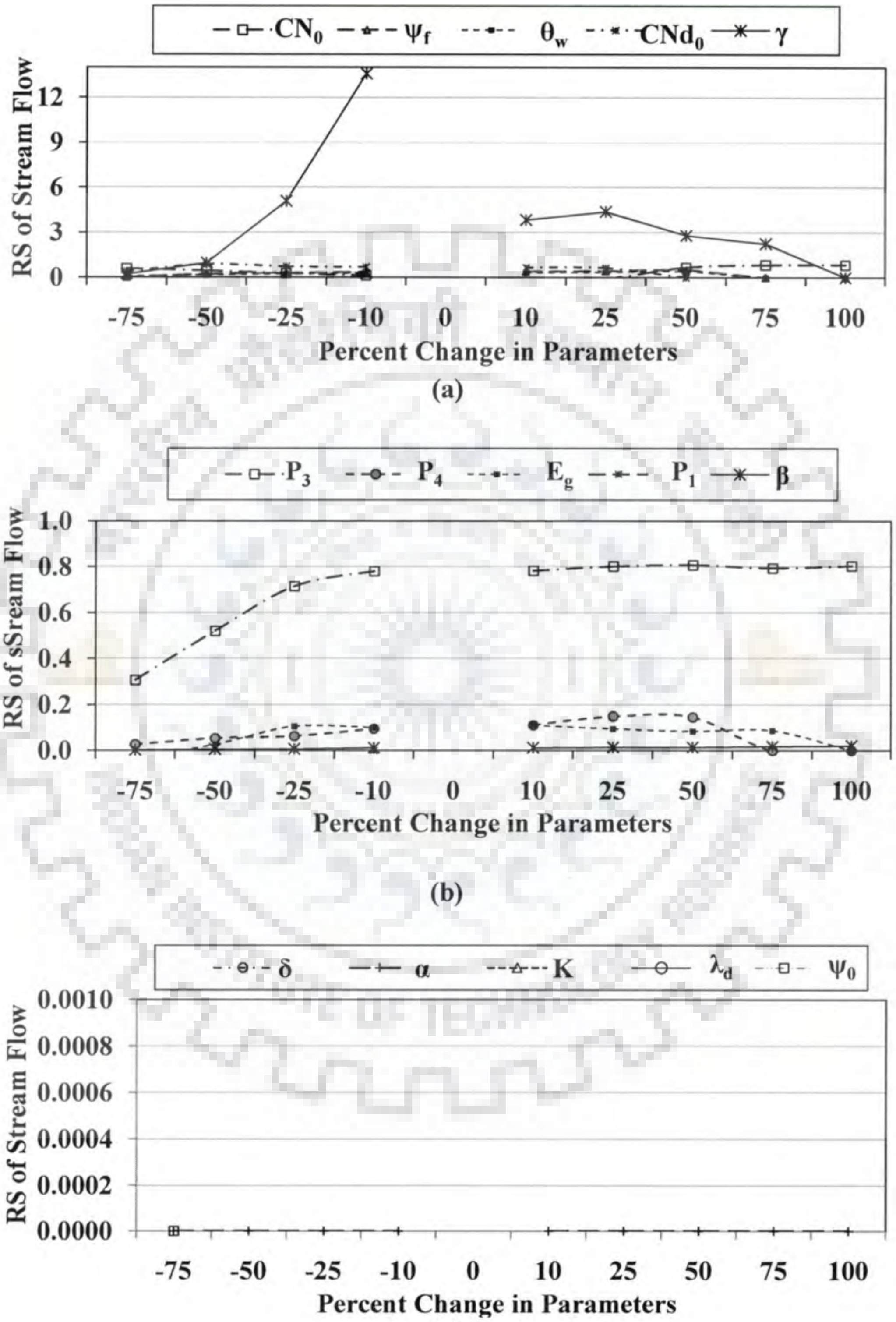


Fig. F-14 RS Plots of Stream Flow for Hirehalla Watershed



(c)

Fig. F-15 RS Plots of Stream Flow for Anthrolli Watershed

APPENDIX G

ANNUAL RAINFALL, OBSERVED RUNOFF, COMPUTED RUNOFF, AND RE (%) FOR LTHS ASMA SIMP MODEL

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Relative* Error (%)
1	Hemavathi	1975-76	2940.5	2552.5	2305.3	9.7
		1976-77	2648.1	1718.0	1481.0	13.8
		1977-78	2728.6	1896.0	1377.6	27.3
		1978-79	2889.5	2935.5	1883.2	35.8
		1979-80	3087.1	2061.8	1720.8	16.5
	Average		**2858.7**	**2232.7**	**1753.6**	**20.6**
2	Hridayanagar	1981-82	1586.6	314.4	333.5	-6.1
		1982-83	1461.5	309.3	308.1	0.4
		1983-84	1937.1	375.1	499.1	-33.0
		1984-85	1300.0	294.6	251.3	14.7
		1985-86	1457.2	254.9	236.4	7.2
		1986-87	1811.5	593.0	445.5	24.9
		1987-88	879.7	179.4	102.8	42.7
		1988-89	1375.2	560.2	246.3	56.0
		1989-90	1167.6	285.4	172.3	39.6
	Average		**1441.8**	**351.8**	**288.4**	**25.0**
3	Mohegaon	1981-82	1240.0	333.6	422.1	-26.5
		1982-83	1112.9	338.6	338.0	0.2
		1983-84	1533.1	485.7	548.6	-12.9
		1984-85	1294.9	518.0	519.8	-0.3
		1985-86	1329.1	578.5	423.2	26.9
		1986-87	1356.1	470.5	469.5	0.2
		1987-88	1125.2	377.5	309.4	18.0
		1988-89	1165.9	550.3	398.9	27.5
		1989-90	925.9	227.0	211.3	6.9
	Average		**1231.5**	**431.1**	**404.5**	**13.3**
4	Manot	1981-82	1135.5	386.8	426.5	-10.3
		1982-83	1023.9	374.8	434.9	-16.0
		1983-84	1391.1	572.8	641.6	-12.0
		1984-85	1303.4	622.5	634.5	-1.9
		1985-86	1263.6	720.0	515.7	28.4
		1986-87	1378.7	715.0	541.7	24.2
		1987-88	1347.4	775.0	592.0	23.6
		1988-89	1308.7	637.2	604.4	5.2
		1989-90	1220.0	279.5	429.5	-53.7
	Average		**1263.6**	**564.8**	**535.6**	**19.5**

Appendix G continued………

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Relative* Error (%)
5	Amachi	1985-86	1513.6	445.9	572.1	-28.3
		1986-87	1254.5	390.2	328.8	15.7
		1987-88	1360.4	304.9	328.0	-7.6
		1988-89	1800.5	458.4	612.4	-33.6
		1989-90	1722.6	494.1	484.5	1.9
		1990-91	1838.4	602.3	520.2	13.6
		1991-92	1823.3	529.9	557.0	-5.1
		1992-93	2315.7	651.1	781.6	-20.0
		1993-94	1737.1	548.2	455.3	16.9
	Average		**1707.3**	**491.7**	**515.5**	**15.9**
6	Anthrolli	1985-86	755.6	256.2	260.4	-1.6
		1986-87	709.2	147.7	227.1	-53.8
		1987-88	733.0	200.5	230.3	-14.9
		1988-89	1011.8	341.9	404.3	-18.2
		1989-90	832.5	287.0	271.7	5.3
		1990-91	1086.8	405.0	410.5	-1.4
		1991-92	1200.2	444.3	504.4	-13.5
		1992-93	1365.4	503.5	548.9	-9.0
		1993-94	1295.9	700.5	520.0	25.8
	Average		**998.9**	**365.2**	**375.3**	**16.0**
7	Attigundi	1985-86	1868.0	1274.3	1544.8	-21.2
		1986-87	2285.6	1681.0	1752.4	-4.2
		1987-88	1607.1	1131.8	971.0	14.2
		1988-89	1567.8	1086.4	1027.4	5.4
		1989-90	1457.4	985.2	769.8	21.9
		1990-91	2073.7	1309.4	1421.4	-8.6
		1991-92	1709.0	1284.0	1081.7	15.8
		1992-93	2682.2	2091.6	1802.7	13.8
		1993-94	2394.8	1793.7	1538.7	14.2
	Average		**1960.6**	**1404.2**	**1323.3**	**13.3**
8	Barchi	1989-90	998.2	225.9	330.5	-46.3
		1990-91	1602.8	615.2	452.3	26.5
		1991-92	1684.2	666.8	653.4	2.0
		1992-93	1630.4	667.8	559.2	16.3
		1993-94	1181.6	313.1	257.8	17.7
	Average		**1419.4**	**497.7**	**450.6**	**21.7**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Relative* Error (%)
9	Khanapur	1985-86	3935.0	1665.4	2257.8	-35.6
		1986-87	3175.7	1736.4	1189.5	31.5
		1987-88	3371.1	1475.2	1211.7	17.9
		1988-89	4517.6	2498.9	2568.0	-2.8
		1989-90	3832.1	1788.1	1493.7	16.5
		1990-91	4219.0	2697.4	1813.4	32.8
		1991-92	3997.3	2822.2	1987.5	29.6
		1992-93	4214.4	3375.2	1880.2	44.3
		1993-94	4560.7	3530.9	1999.4	43.4
	Average		**3980.3**	**2398.8**	**1822.4**	**28.2**
10	Hirehalla	1985-86	435.9	30.4	62.1	-104.0
		1986-87	398.4	33.4	42.2	-26.3
		1987-88	672.0	66.7	74.3	-11.4
		1988-89	712.0	89.4	84.7	5.3
		1989-90	561.9	51.7	61.7	-19.3
		1990-91	592.1	62.3	65.1	-4.6
		1991-92	515.6	78.1	62.3	20.2
		1992-93	613.6	106.0	80.2	24.4
		1993-94	849.3	92.1	118.9	-29.1
	Average		**594.5**	**67.8**	**72.4**	**27.2**
11	Sagar	1985-86	1625.7	952.4	944.2	0.9
		1986-87	1340.6	788.6	600.7	23.8
		1987-88	1417.7	791.4	501.3	36.7
		1988-89	1871.3	1191.2	1133.7	4.8
		1989-90	1797.0	976.4	898.9	7.9
		1990-91	2120.5	1471.5	1283.1	12.8
		1991-92	2040.9	1474.0	1236.5	16.1
		1992-93	2528.4	1847.5	1610.6	12.8
		1993-94	2037.4	1505.1	927.2	38.4
	Average		**1864.4**	**1222.0**	**1015.1**	**17.1**
12	Sorab	1985-86	824.8	481.9	638.2	-32.4
		1986-87	725.5	430.3	191.2	55.6
		1987-88	1004.7	556.9	376.3	32.4
		1988-89	1368.7	852.4	801.4	6.0
		1989-90	1265.3	645.6	512.4	20.6
		1990-91	1556.3	914.5	851.5	6.9
		1991-92	1605.7	1057.7	1080.1	-2.1
		1992-93	2102.9	987.8	1453.1	-47.1
		1993-94	1436.7	970.2	759.3	21.7
	Average		**1321.2**	**766.4**	**740.4**	**25.0**

Appendix G continued.........

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Relative* Error (%)
13	Dasanakatte	1985-86	4926.3	4101.0	4624.0	-12.8
		1986-87	4447.3	3937.1	3732.9	5.2
		1987-88	3534.6	3050.4	2459.4	19.4
		1988-89	4317.1	3894.7	3934.9	-1.0
		1989-90	4257.7	3901.6	3124.7	19.9
		1990-91	4992.0	4423.2	4909.1	-11.0
		1991-92	3992.4	3506.1	3264.8	6.9
		1992-93	4648.1	4407.5	3878.2	12.0
		1993-94	6542.9	6277.2	5979.6	4.7
	Average		**4628.7**	**4166.5**	**3989.7**	**10.3**
14	Haladi	1985-86	4679.8	4470.4	4819.4	-7.8
		1986-87	4615.5	4277.6	4120.6	3.7
		1987-88	3551.5	3214.7	2580.4	19.7
		1988-89	4356.2	3901.6	4156.6	-6.5
		1989-90	4417.8	3906.8	3443.9	11.8
		1990-91	5838.6	5574.5	6327.7	-13.5
		1991-92	4308.7	4058.6	2649.2	34.7
		1992-93	5242.3	4987.3	3489.7	30.0
		1993-94	5453.8	5214.2	3275.7	37.2
	Average		**4718.2**	**4400.6**	**3873.7**	**18.3**
15	Jadkal	1985-86	4552.6	4324.3	4579.0	-5.9
		1986-87	4216.4	3896.9	3828.2	1.8
		1987-88	4140.3	3877.9	3454.4	10.9
		1988-89	5469.5	5285.3	5096.5	3.6
		1989-90	4866.0	4454.0	3872.4	13.1
		1990-91	6493.1	5819.9	6474.0	-11.2
		1991-92	5310.1	4726.5	4421.2	6.5
		1992-93	6373.2	5936.4	4972.6	16.2
		1993-94	5462.8	5015.0	3730.4	25.6
	Average		**5209.3**	**4815.1**	**4492.1**	**10.5**
16	Kokkarne	1985-86	4937.7	3932.4	4207.2	-7.0
		1986-87	4555.9	3521.7	3404.6	3.3
		1987-88	3752.2	2538.8	2242.5	11.7
		1988-89	4803.9	3955.0	3771.8	4.6
		1989-90	5203.8	4119.9	3652.7	11.3
		1990-91	5608.5	4742.0	4602.6	2.9
		1991-92	4821.9	3998.1	3607.7	9.8
		1992-93	5492.0	4271.4	3910.9	8.4
		1993-94	6378.5	5016.1	4428.8	11.7
	Average		**5061.6**	**4010.6**	**3758.8**	**7.9**

Sr. No.	Name of Watershed	Year	Rainfall (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Relative* Error (%)
17	Halkal	1985-86	4552.6	4013.2	4154.1	-3.5
		1986-87	4216.4	3603.2	3329.9	7.6
		1987-88	4140.3	3466.1	2746.6	20.8
		1988-89	5469.5	4729.8	4093.1	13.5
		1989-90	4866.0	4048.8	3179.6	21.5
		1990-91	6493.1	5909.8	5315.9	10.0
		1991-92	5310.1	4778.4	4038.2	15.5
		1992-93	6648.1	6270.6	4908.4	21.7
		1993-94	5462.8	5031.9	3612.5	28.2
	Average		**5239.9**	**4650.2**	**3930.9**	**15.8**

*** Average Relative Error (%) is absolute value**
(Average RE = $\sum_{i=1}^{n}|RE(\%)|\,/n$, n=no. of years)

APPENDIX H

MULTI-LINEAR REGRESSION ANALYSIS

Stepwise backward elimination procedure via P-Value of F-Test
(P-to-Enter=0.150 and P-to Remove=0.150) No. of samples N: 17

H-I Regression statistics for CN_0

Multiple R: 0.62
Squared multiple R: **0.39**
Adjusted squared multiple R: 0.30
Standard error of estimate: 8.853

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	31.991	3.595	0.000	-	8.899	0.000
P	- 0.317	0.113	-4.296	0.019	-2.819	0.014
Lb	0.702	0.241	4.445	0.019	2.197	0.011

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	686.960	2	343.480	4.383	0.033
Residual	1097.187	14	78.370		

H-II Regression statistics for α

Multiple R: 0.72
Squared multiple R: **0.52**
Adjusted squared multiple R: 0.45
Standard error of estimate: 0.120

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.640	0.095	0.000	-	6.707	0.000
Rc	-0.424	0.143	-0.554	0.984	-2.971	0.010
H	0.000	0.000	0.398	0.984	2.131	0.051

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.220	2	0.110	7.597	0.006
Residual	0.202	14	0.014		

H-III Regression statistics for β

Multiple R: 0.870
Squared multiple R: **0.76**
Adjusted squared multiple R: 0.72
Standard error of estimate: 0.06

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.022	0.028	0.000	-	0.809	0.432
Lm	-0.001	0.000	-0.358	1.000	-2.715	0.017
H	0.000	0.000	0.786	1.000	5.955	0.000

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.166	2	0.083	21.704	0.000
Residual	0.054	14	0.004		

H-IV Regression statistics for γ

Multiple R: 0.556
Squared multiple R: **0.31**
Adjusted squared multiple R: 0.26
Standard error of estimate: 0.12

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.751	0.083	0.000	-	9.062	0.000
Rc	-0.370	0.143	-0.556	1.000	-2.592	0.020

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.099	1	0.099	6.719	0.020
Residual	0.220	15	0.015		

H-V Regression statistics for δ

Multiple R: 0.49
Squared multiple R: **0.24**
Adjusted squared multiple R: 0.14
Standard error of estimate: 2.79

Effect	**Coefficient**	**Std. Error**	**Std. Coef.**	**Tolerance**	**t**	**p(2 Tail)**
CONSTANT	-2.748	2.255	0.000	-	-1.219	0.243
Lb	0.023	0.013	0.505	0.644	1.743	0.103
Rf	10.377	5.170	0.582	0.644	2.007	0.064

Analysis of Variance

Source	**Sum-of-Squares**	**df**	**Mean-Square**	**F-ratio**	**p**
Regression	35.049	2	17.524	2.245	0.143
Residual	109.270	14	7.805		

H-VI Regression statistics for K

Multiple R: 0.64
Squared multiple R: **0.40**
Adjusted squared multiple R: 0.20
Standard error of estimate: 6.62

Effect	**Coefficient**	**Std. Error**	**Std. Coef.**	**Tolerance**	**t**	**p(2 Tail)**
CONSTANT	1.272	4.200	0.000	-	0.303	0.766
H	-0.011	0.005	-0.605	0.780	-2.469	0.027
V	0.147	0.068	0.528	0.780	2.157	0.049

Analysis of Variance

Source	**Sum-of-Squares**	**df**	**Mean-Square**	**F-ratio**	**p**
Regression	303.438	2	151.719	3.686	0.052
Residual	576.190	14	41.156		

H-VII Regression statistics for P_1

Multiple R: 0.49
Squared multiple R: **0.24**
Adjusted squared multiple R: 00
Standard error of estimate: 0.03

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.024	0.074	0.000	-	0.326	0.750
P	0.001	0.001	6.430	0.002	1.006	0.336
Lb	-0.002	0.004	-5.739	0.001	-0.570	0.580
Lm	-0.0002	0.001	-0.606	0.004	-0.143	0.889
Rc	0.169	0.203	1.521	0.021	0.834	0.422
Re	-0.182	0.284	-1.210	0.019	-0.639	0.536

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.002	5	0.000	0.704	0.632
Residual	0.007	11	0.001		

H-VIII Regression statistics for P_3

Multiple R: 0.75
Squared multiple R: **0.56**
Adjusted squared multiple R: 0.45
Standard error of estimate: 0.14

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.450	0.060	0.000	-	7.485	0.000
A	0.000	0.000	2.349	0.066	3.273	0.006
P	0.005	0.002	3.516	0.019	2.606	0.022
Lb	-0.017	0.004	-5.868	0.014	-3.721	0.003

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.324	3	0.108	5.449	0.012
Residual	0.258	13	0.020		

H-IX Regression statistics for P_4

Multiple R: 0.86
Squared multiple R: **0.74**
Adjusted squared multiple R: 0.61
Standard error of estimate: 0.23

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	1.383	0.470	0.000	-	2.942	0.013
A	-0.000	0.000	-1.102	0.059	-1.726	0.112
Lb	-0.018	0.009	- 3.294	0.008	-1.909	0.083
Lm	0.017	0.007	3.706	0.009	2.291	0.043
Re	-1.125	0.600	-0.485	0.361	-1.875	0.088
H	0.000	0.000	0.327	0.855	1.948	0.077

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	1.564	5	0.313	6.086	0.006
Residual	0.565	11	0.051		

H-X Regression statistics for θ_w

Multiple R: 0.92
Squared multiple R: **0.85**
Adjusted squared multiple R: 0.75
Standard error of estimate: 38.07

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	-133.414	100.430	0.000	-	-1.328	0.214
Lb	10.968	2.468	9.552	0.003	4.444	0.001
Lm	-8.248	2.003	- 8.459	0.004	-4.118	0.002
Rf	275.567	108.622	0.604	0.271	2.537	0.030
Rc	-481.685	112.919	-1.331	0.158	-4.266	0.002
Re	319.221	184.192	0.654	0.108	1.733	0.114
V	2.709	0.552	0.939	0.421	4.911	0.001

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	79826.415	6	13304.402	9.178	0.001
Residual	14496.531	10	1449.653		

H-XI Regression statistics for ψ_f

Multiple R: 0.73
Squared multiple R: **0.54**
Adjusted squared multiple R: 0.43
Standard error of estimate: 67.55

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	180.578	132.072	0.000	-	1.367	0.195
Lm	0.835	0.341	0.733	0.396	2.450	0.029
Rc	-330.330	137.819	-0.782	0.334	-2.397	0.032
Re	444.463	239.904	0.779	0.200	1.853	0.087

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	69313.400	3	23104.467	5.064	0.015
Residual	59311.870	13	4562.452		

H-XII Regression statistics for ψ_0

Multiple R: 0.95
Squared multiple R: **0.91**
Adjusted squared multiple R: 0.83
Standard error of estimate: 42.84

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	-207.560	136.252	0.000	-	-1.523	0.162
A	0.257	0.034	4.074	0.035	7.454	0.000
P	-15.689	2.224	-21.548	0.001	-7.055	0.000
Lb	48.909	7.192	31.400	0.000	6.800	0.000
Lm	-16.998	2.644	-12.851	0.003	-6.430	0.000
Rf	-320.068	117.533	-0.517	0.293	-2.723	0.023
Rc	-3144.857	449.956	-6.406	0.013	-6.989	0.000
Re	4051.434	600.510	6.116	0.013	6.747	0.000

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	157050.568	7	22435.795	12.227	0.001
Residual	16514.373	9	1834.930		

H-XIII Regression statistics for E_g

Multiple R: 0.80
Squared multiple R: **0.65**
Adjusted squared multiple R: 0.59
Standard error of estimate: 0.13

Effect	**Coefficient**	**Std. Error**	**Std. Coef.**	**Tolerance**	**t**	**p(2 Tail)**
CONSTANT	0.242	0.100	0.000	-	2.415	0.030
Rc	0.601	0.150	0.644	0.984	4.012	0.001
H	-0.000	0.000	-0.406	0.984	-2.528	0.024

Analysis of Variance

Source	**Sum-of-Squares**	**df**	**Mean-Square**	**F-ratio**	**p**
Regression	0.404	2	0.202	12.710	0.001
Residual	0.223	14	0.016		

H-XIV Regression statistics for CNd_0

Multiple R: 0.72
Squared multiple R: **0.52**
Adjusted squared multiple R: 0.46
Standard error of estimate: 12.58

Effect	**Coefficient**	**Std. Error**	**Std. Coef.**	**Tolerance**	**t**	**p(2 Tail)**
CONSTANT	36.786	3.965	0.000	-	9.277	0.000
Lb	1.510	0.454	5.927	0.011	3.327	0.005
Lm	-1.193	0.385	-5.514	0.011	-3.095	0.008

Analysis of Variance

Source	**Sum-of-Squares**	**df**	**Mean-Square**	**F-ratio**	**p**
Regression	2427.482	2	1213.741	7.666	0.006
Residual	2216.632	14	158.331		

H-XV Regression statistics for λ_d

Multiple R: 0.42
Squared multiple R: **0.17**
Adjusted squared multiple R: 0.12
Standard error of estimate: 0.14

Effect	Coefficient	Std. Error	Std. Coef.	Tolerance	t	p(2 Tail)
CONSTANT	0.056	0.044	0.000	-	1.284	0.219
Lm	0.001	0.000	0.415	1.000	1.768	0.097

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	p
Regression	0.062	1	0.062	3.126	0.097
Residual	0.295	15	0.020		

PUBLICATIONS FROM THE THESIS

International Journals

1. **Durbude, D. G.,** Jain, M. K.,and Mishra, S. K. (2010). "Long term hydrologic simulation using SCS-CN based improved soil moisture accounting procedure." **J. Hydrological Processes** (Published online): DOI:10.1002/hyp.7789.

2. Jain, M. K.,**Durbude, D. G.,** and Mishra, S. K. (2010). "SCS-CN Based Modified Long Term Hydrologic Simulation Model For Daily Stream Flow Simulation." **J. Hydrologic Engineering (ASCE)** (Communicated).

International Conferences

1. **Durbude, Dilip G.** and M. K. Jain (2009). "An investigation of soil moisture accounting in long term hydrologic simulation models based on SCS-CN concept. " Published in the proceedings of **International Conference** on "Food Security and Environmental Sustainability (**FSES 2009**)" during 17-19 December, 2009 organized by Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, India (**WRWM-Durbude-49**).