MODELLING RUNOFF USING MODIFIED SCS-CN METHOD FOR MIDDLE SOUTH SAURASHTRA REGION (GUJARAT-INDIA)

A Thesis submitted to Gujarat Technological University

for the Award of

Doctor of Philosophy

in

Civil Engineering

by

Gundalia Manoj Jayantilal

Enrollment No.: 119997106004

under supervision of

Prof. Dr. M. B. Dholakia

Professor, L.D.College of Engineering, Ahmedabad

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

December, 2016

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ABSTRACT

The runoff generation process is highly complex, nonlinear, dynamic in nature, and affected by many interrelated physical factors. Further, the temporal and spatial variability of these factors causes more uncertainty in the parameterization of the model. Therefore, modelling the runoff becomes more challenging task. However, with present technological capabilities, computing techniques and software tools, it is possible to identify, assess and understand the response of the dominant processes rather accurately. Accurate runoff estimation is prerequisite for effective management and development of water resources. Many methods are being used to estimate runoff in literature; however, the SCS-CN method still remains the most popular, fruitful and frequently used method. The major reasons for this popularity may be attributed to ease of use, less number of input parameters, robustness of model results, and acceptability among both researcher and practitioner community.

Runoff curve number (*CN*) is a key factor of the SCS-CN method and it is a function of land use/land cover (LULC), soil type, and antecedent soil moisture. The attractive feature of the SCS-CN method is that it integrates the complexity of runoff generation into single parameter, i. e. *CN*. However, lumped conceptual approach and simplicity of a single parameter introduces great uncertainty to estimate runoff in practical applications. The *CN* is usually selected from available standard tables in the National Engineering Handbook, Section-4 (NEH-4) as well available curves; but, this procedure is very tedious, laborious, and time consuming. It was further observed that large errors can be expected in surface runoff estimation where, the validity of the hand book tables for the *CN* was not verified. The SCS-CN method does not adequately model all of the important physical processes of runoff generation viz. impact of land use changes, accumulation of moisture, morphometric parameters, and long term evapotranspiration loss. Thus, the SCS-CN method modified by incorporating these processes into *CN* determination would be much more useful to larger research and practitioner community for better runoff estimation.

The SCS-CN method is the most suitable method for quick and accurate runoff estimation in the region such as the Middle South Saurashtra region in India where, hydrologic gauging stations are not widely available. This research work describes how to improve the

performance of the SCS-CN method by modifying *CN* for selected watersheds of the study region.

In this study, alternate LULC and soil type shape files were first obtained and compiled by using Remote Sensing (RS) and Geographic Information System (GIS) techniques. Hydrologic Soil Group (HSG) maps then developed by interpreting formative elements of soil taxonomy. Composite *CNs* are determined by integrating alternate LULC maps and HSG maps for the test watersheds. Three independent methods are developed by modifying *CN* to enhance performance of the SCS-CN method. In the first method, cumulative rainfall-runoff ordered data were applied to modify asymptotic *CN* using frequency matching technique. Morphometric parameters of watershed were incorporated in computation of weighted *CN* in the second method. While in the third method, evapotranspiration was introduced to modify *CN*. Finally, all the three proposed methods are tested and validated on the dataset of Ozat, Uben, and Shetrunji watersheds of the study region at daily time scale.

The results of this research show that the combination of RS and GIS techniques and the SCS-CN method makes the runoff estimate more accurate, efficient and fast. The RS and GIS techniques become more effective tool to detect the changes occurred in LULC and to compute the composite *CN* at sub watershed scale. The statistical criterions show that the proposed methods improved the runoff prediction accuracy of the SCS-CN method and produce results significantly better than the existing methods for the study region. It can be stated that this research work affords alternative options to the users and provides better representation of the runoff prediction. Therefore, it is recommended to adopt these developed methods for field applications in Saurashtra region and in other similar hydro-meteorological regions.

Dedicated

to

my parents (Shantaben and Jayantilal),

my wife (Harshvina),

my children (Anjali and Dev),

and

my elder brother Pradipbhai and his family

(Ramabhabhi, Khushbu and Rohan)

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Gundalia Manoj J. Date: 2nd December, 2016

Table of Content

List of Abbreviations

AFM:	Asymptotic Fit Method
AGNPS:	Agricultural Non-Point Source Model
AIC:	Akaike Information Criterion
AIC_c:	Corrected Akaike's Information Criterion
AMC:	Antecedent Moisture Condition
APEX:	Agricultural Policy/Environmental Extender
ASCE:	American Society of Civil Engineers Evapotranspiration
BISAG:	Bhaskaracharya Institute for Space Application and Geo-informatics
CN:	Curve Number
DEM	Digital Elevation Model
EPA:	Environmental Protection Agency
EPIC:	Erosion-Productivity Impact Calculator
ERDAS:	Earth Resources Data Analysis System
ET:	Evapotranspiration
ETM:	Enhanced Thematic Mapper
FAO:	Food and Agricultural Organization
GDS:	Gauge Discharge Site
GIS:	Geographic Information System
GLEAMS:	Groundwater Loading Effects of Agricultural Management Systems
HEC:	Hydrologic Engineering Centre
HMS:	Hydrological Modelling System
HSG:	Hydrologic Soil Group
ICAR:	Indian Council of Agricultural Research
ICDCW:	Istanbul-Catalca Damlica Creek Watershed
IHACRES:	Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Stream flow data
ILWIS:	Integrated Land and Water Information System
IR:	Infiltration Rate
IRS-LISS:	Indian Remote Sensing satellite with Linear Imaging Self Scanning Sensors

IUSS:	International Union of Soil Sciences
LER:	Logarithm of Evidence Ratio
LULC:	Land Use/Land Cover
MAE:	Mean Absolute Error
MBE:	Mean Bias Error
MNTTS:	Minimum Temperature Time Series
MOM:	Method of Moments
MOML:	Method of Maximum Likelihood
MXTTS:	Maximum Temperature Time Series
NBSS & LUP:	National Bureau of Soil Survey and Land Use Planning
NEH:	National Engineering Handbook
NLEAP:	Nitrate Leaching and Economic Analysis Package
NRCS:	Natural Resources Conservation Service Curve Number
PCDs	Physical Catchment Descriptors
PET:	Potential Evapotranspiration
RMSE:	Root Mean Square Error
RS:	Remote Sensing
SCS-CN:	Soil Conservation Service Curve Number
SE:	Standard Error
SMI:	Soil-Moisture Index
SWAT:	Soil and Water Assessment Tool
SWDC:	State Water Data Centre
SWMM:	Storm Water Management Model
USDA:	United States. Department of Agriculture
USLE:	Universal Soil Loss Equation

List of Symbols

a	Calibration constant
C_d	Denominator constant for reference type and calculation time step
C_n	Numerator constant for reference type and calculation time step
CN_∞	Calibration parameter of AFM
CN_{asy}	Modified asymptotic curve number
CN_{aw}	Area-weighted *CN*
CN_I	Curve number for AMC I
CN_{II}	Curve number for AMC II
CN_{III}	Curve number for AMC III
CN_{mor}	Modified *CN* by incorporating morphometric parameters
CN_{temp}	Modified *CN* by incorporating Evapotranspiration
DD	Drainage density
DF	Degrees of freedom
d_r	Willmott's index
e_a	Mean actual vapour pressure at 1.5 to 2.5m height
e^{oTmax}	Saturation vapour pressure at daily maximum temperature
e_s	Mean saturation vapour pressure at 1.5 to 2.5m height
ET_o	Reference evapotranspiration
ET_o-*PM*	Short or tall reference crop evapotranspiration
F	Cumulative infiltration after runoff begins
f	Temperature modulation
G	Soil heat flux density at the soil surface
I_a	Initial abstraction before runoff
K	Number of fit by the regression plus one
k	Calibration parameter of AFM
L	Length of main stream
l	Soil moisture index threshold
L_{ca}	Length to the centroid of area
M_t	Soil moisture index at any time t

$\O$	Soil moisture index
P	Precipitation
Q	Direct runoff
Q_c	Computed runoff
Q_{obs}	Obsrved runoff
r_k	Observed rainfall
$\mathrm{R_n}$	Net radiation at the crop surface
$\mathrm{R_s}$	Solar radiation
S	Potential maximum retention
S_{abs}	Absolute potential maximum retention
Sl	Slope
S_{max}	Maximum value of the retention parameter
SS	Sum-of-squares
T	Mean daily or hourly air temperature at 1.5 to 2.5m height
T_k	Observed temperature
$\mathrm{T_{max}}$	Maximum temperature
T_r	Reference temperature
$\mathrm{u_2}$	Mean daily or hourly wind speed at 2m height
β	Moisture depletion coefficient
γ	Psychrometric constant
Δ	Slope of the vapour pressure-temperature curve
λ	Initial abstraction (ratio) coefficient
ρ	Non-linear response terms
τ_k	Drying rate
τ_w	Reference drying rate at reference temperature

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CHAPTER 1

Introduction

1.1 Background and Significance of Study

Water is valuable asset of the earth and has been recognized as the supreme natural resource and a cardinal component in the socio-economic development of any country. Though there is plenty of water (97%) available in the universe, only 3% of the water in the universe is fresh water. Further, it is not uniformly distributed spatially and temporally with required quantity and quality. Only 5% of the fresh waters of the world water are readily available for beneficial use. Water crises are increasing at drastic rate in almost all parts of the world. This is mainly due to growth of population and higher consumption of water due to expansion and development in agriculture and industry. Owing to increase in unrestrained demand and limitation of water availability over space and time, water resources of the world are under heavy stress. According to National Water Policy, 2012, India has more than 18% of the world's population, 4% of world's renewable water resources, and 2.4% of world's land area. Hence, Indian water resources are faced comparatively heavy stress. Water resources are crucial renewable resources that are the basis for survival and betterment of a society. In such situation, proper utilization, planning and management of water resources is highly needed to minimize the gap between the supply and demand. Poor management and lack of knowledge about existing water resources and the climatic conditions create imbalance in supply and demand of water.

Large parts of the world are covered by semi-arid and arid regions. These regions normally face periodic draughts and water crisis problem due to limited water resources. Furthermore, erratic and inadequate rainfall, flash floods, soil erosion by high rainfall intensity and high velocity of surface runoff are also very frequent. Modelling technique or reliable runoff estimation plays crucial role in mitigation of flood, sustainable development and management of water resources in these regions. Two major interrelated underpinning problems are revealed in hydrological modelling in such region are: (1) the idealistic model assumptions and over simplification of the variability (2) the paucity of sufficient data. Therefore, there is a need of research to address these problems by developing models which are not too simple to ignore the important processes and not very much data requirements so far.

1.2 Problem Definition

Watershed development projects for agriculture and allied sectors production necessitate high investment costs. Feasibility of these projects is often determined based on results of hydrologic modelling, analysis and assessment. Poor hydrologic analysis for estimating runoff may result into over designed or under designed hydrologic infrastructure. This may result into loss of billions of dollars annually in water harvesting and sometime leads to failures of hydraulic structures such as dams or weirs. Hydrologic models are used for accurate hydrological assessment (Mazi et al., 2004); however, most hydrologic models have been primary developed for humid agro-climatic regions (Wheater, 2005). Further, these models are reliable for the region and over the period for which they were developed. Greater care to be taken when hydrologic models developed for humid agro-climatic regions are applied and adopted to semi-arid regions of India.

For effective planning, management and development of water resources in a watershed, the study of rainfall and runoff relationship is one of the important aspects. Literatures reviews indicate that the Natural Resources Conservation Service Curve Number (NRCS-CN) (formerly called as Soil Conservation Service Curve Number (SCS-CN)) method developed by the U. S. Department of Agriculture (USDA) is widely used and accepted method for runoff estimation at watershed scale. In the SCS-CN method effects of several important hydrological processes integrated in to single parameter curve number (*CN*) (Garen and Daniel, 2005). The primary weakness of the SCS-CN method is that it overlooks the effect and temporal distribution of rainfall intensity, impact of morphometric parameters of the watershed, effect of accumulation of soil moisture, and other dynamic processes like evapotranspiration. *CN* has not been thoroughly determined accurately (Ponce and Hawkins, 1996; McCutcheon et al., 2006) and empirical evidence suggests that with the current conventional SCS-CN method, hydrologic infrastructure is being over designed by billions of dollars annually (Schneider and McCuen, 2005).

The Middle South Saurashtra region of Gujarat (India) is semi-arid region and has been faced several water resources related problems. The some of the important problems can be summaries as;

1. Erratic rainfall pattern and inadequate rainfall amount resulting into periodic drought years.
2. Soils are of volcanic origin, generally derived from basaltic rock known as "Deccan trap". These soils have limited groundwater recharge capacity. Therefore, ground water resources are very limited or nil.
3. Soils have limited infiltration resulting into threats of flash floods, limited capacity of aquifer recharge and natural aquifer water retention.
4. Large parts of the region have already become water stressed.
5. Access to water for drinking, sanitation and hygiene is an even more serious problem.
6. Wide temporal and spatial variation in availability of water in the region as well in upper and lower parts of the watershed.
7. Inadequate sanitation and sewage treatment facilities in the watershed resulting into polluting the scarce surface water sources.
8. If current population and water consumption trends be continuing in future, it further increases water scarcity in the region

Poor hydrologic analysis due to inappropriate modelling of the distinctive features of the watershed and insufficient data are the main constraints for efficient watershed development in such region. Therefore, there is a need of research which satisfactorily resolves the above problems.

1.3 Problem Statement

The rivers of the study region are short in length, get floods instantaneously, recede quickly and dry up in fair season. Duration of most floods hydrograph lasts only 3 to 4 hours. The region harms by threats of floods, natural water retention, water scarcity and water availability. The hydrology of the study region is adversely affected due to rapid land use change caused by conversion of forest to agricultural land. People are continuously encroached in the forested areas and waste lands, cleared them for agricultural production, and expanding it in the built up areas. In most parts of the watershed, deforestation, land fragmentation, and rapid increase in human settlements produce negative impacts on water resources. The continuous over exploitation of the available water resources in the region has resulted into the situation wherein the reduction in the stream flows, drying of small streams and depletion of water levels in the wells is observed. Therefore, available water resources not adequately satisfy the water demand and the region faces water shortage during summer. Furthermore, the basaltic nature of hydrogeology (Deccan trap) of the region limits groundwater recharge. Ground water table has been declined due to decrease in ground water recharge as observed by the drying of wells within the region. Lack of major storage dam in the region further increases stress on ground water storage. Many villages of the region face drinking water problem in summer till today. Majority municipal towns depend entirely on ground water resources. Due to shortage of surface water, continuous excessive extraction of ground water is taken place; consequently, very popular green belt of erstwhile Kathiawar and Sorath is gradually changed into desert place. In addition, lack of continuous hydro-meteorological data, complex associations at spatial and temporal scale among the characteristics of rainfall, topography, antecedent moisture, long term losses, and soils, suggest that modelling of runoff generation in such region can be extremely challenging task, even at relatively small watershed scale.

1.4 Objectives of the Research

The specific issues aforementioned pragmatically led to the research objectives of the present study. It is possible to reduce structural inconsistencies of the SCS-CN method by incorporating impact of cumulative data, morphometric parameters and evapotranspiration. The prime aim of this research is to develop efficient, convenient and simple methods by modifying *CN* for better runoff prediction in the study region. The modification involved three different methods to determine *CNs* for the study region. It should be efficient in terms of consistent useable results, convenient in terms of accessibility to public domain. It should also be simple in terms of minimum input data requirement and easy application.

The following research objectives are explored in this study:

1. To develop Hydrologic Soil Group (HSG) maps for the watersheds of the study region based on soil order, infiltration rate, soil depth, and soil characteristics of the watersheds.

2. To detect the extent of Land Use/Land Cover (LULC) change occurred in the study region and examines its impact on *CN*.
3. To develop Model:
   - Based on cumulative rainfall-runoff ordered data for determination of the modified asymptotic *CN*.
   - Incorporating morphometric parameters of the watershed in weighted *CN*.
   - Integrating evapotranspiration (*ET*) loss in to *CN* determination for long-term hydrological simulation.
4. To test, evaluate and compare the performance of the proposed models with existing models for Ozat, Uben and Shetrunji watersheds of the study region.
5. To provide recommendations for continued academic research which addresses areas requiring refinement for further modelling efforts.

1.5 Scope of the Research Work

1. This research was aimed to modify existing SCS-CN method to make it more suitable and efficient for the Middle South Saurashtra region. The need for better runoff prediction in such semi-arid region has persisted for decades now. The developed methods are comparatively more physically based method that emphasizes the impact of antecedent moisture, watershed morphometric parameters and long term loss.
2. Majority watersheds in India have no past rainfall-runoff records (Sarangi et al., 2005). Mishra et al. (2003) suggested that the SCS-CN method becomes more appropriate in accurate estimation of surface runoff in such situation.
3. The scope of research is significant to identify the problems of modelling the runoff in semi-arid region and find out solutions to improve the performance of widely used SCS-CN method.
4. Developed models are run at daily time scale, hydrologic analysis at smaller time scale is out of scope of this study.
5. This research study depended upon the secondary rainfall-runoff data and hence limitations of secondary data are indirectly incorporated in modelling process.
6. HSG maps for different watersheds of the study region are developed by considering soil map, LULC map, and formative elements of soil taxonomy.

7. LULC may not be remained constant for a long period. Further, *CN* calculation is difficult for unclassified LULC. Therefore, effect of dynamic change in major categories of LULC on *CN* is studied.
8. *ET* is calculated by the proposed model which developed based on the most dominant meteorological variable (maximum temperature). The direct field *ET* data is not available in the study region. Therefore, the results of proposed model are evaluated and compared with *ET* calculated by standard Penman Monteith method.

1.6 Research Approaches

In the present study, different approaches have been applied to accomplish the above objectives. Research approaches for each one of the objectives are described as:

Objective 1: To develop HSG maps for the watersheds of the study region based on soil order, infiltration rate, soil depth, and soil characteristics of the watersheds.

This objective is achieved by identifying soil order, soil depth, infiltration rate, and soil characteristics of the study region from soil map and interpreting formative elements of soil taxonomy. The research reveals that HSG B, C, and D explicitly assigned to the soil orders Entisols, Inceptisols and Vertisols respectively by considering its characteristics for the study region. HSG map for each watershed is developed based on soil order, soil depth, infiltration rate, and soil characteristics of the watershed.

Objective 2: To detect the extent of LULC change occurred in the study region and examines its impact on *CN*.

This objective is accomplished by comparing LULC changes of the years 1994-95, 2005-06 and 2009-10. Resultant LULC and overlay maps generated in ArcGIS indicated a significant shift from Forest and Wastelands to Agriculture land. These LULC transformations slightly increase *CN* value of the watersheds.

Objective 3: To develop Model:

- Based on cumulative rainfall-runoff ordered data for determination of the modified asymptotic *CN*.
- Incorporating morphometric parameters of the watershed in weighted *CN*.

- Integrating evapotranspiration (*ET*) loss in to *CN* determination for long-term hydrological simulation.

To achieve this objective, the 'frequency matching' based modified asymptotic *CN* **(**CN_{asy}**)** method has been developed by applying different degree of cumulative days ordered data to three selected watersheds of the study region. The results show that, the proposed CN_{asy} method is judged to be more consistent at 14, 29 and 19 days cumulative daily data set for Ozat, Uben and Shetrunji watersheds respectively.

Four major morphometric parameters slope (*Sl*), total length of main stream (*L*), length to the centroid of area (L_{ca}) and drainage density (*DD*) were computed for each sub watershed. Weighted *CN* was determined from the *CN* and morphometric parameters (*Sl*, *L*, L_{ca} and *DD*) of each sub watershed. The proposed modified CN_{mor} method is appeared to be the more appropriate than Huang model (accounted only slope) and conventional SCS-CN method for runoff prediction when tested on the selected watersheds.

Based on the dependence analysis, the maximum temperature was found to be the most significant factor influencing reference evapotranspiration (ET_o) in the Middle South Saurashtra region. A sub model based on the most dominant meteorological variable is developed to estimate ET_o for the study region. CN_{temp} method is formulated by incorporating the ET_o and tested on selected watersheds. The results indicate that the attempted CN_{temp} method is found statically better than the existing Kannan model and conventional SCS-CN method.

Objective 4: To test, evaluate and compare the performance of the proposed models with existing models for Ozat, Uben and Shetrunji watersheds of the study region.

The performances of the proposed models are tested, evaluated and compared with the existing models to the selected watersheds by using three statistical criterion refined Willmott's index (d_r) (Willmott et al., 2012) (Dimensionless statistic), mean absolute error (MAE) (Error index statistic) and mean bias error (MBE). Performances of proposed models were compared with existing models. F-test and Akaike's Information Criterion (AIC) (Akaike, 1973; Hurvich and Tsai, 1989) are used to judge the best model for sample testing. Sample months from validation period are selected based on maximum precipitation.

Objective 5: To provide recommendations for continued academic research which addresses areas requiring refinement for further modelling efforts.

The proposed SCS-CN method with modified *CNs* was primarily developed from readily available information and passed through a calibration and validation procedure. This included uncertainty assessment and evaluation of model limitations. This work provides a foundation for subsequent investigation that will focus on the modification of *CN* by incorporating the most dominant physical variables to improve performance of the SCS-*CN* model. The present research work opens the scope for wide varieties of problems created in the field of modeling runoff using SCS-CN method. Some of the future scope and recommendations are also suggested for further study in the region.

1.7 Thesis Organization

The present thesis contains six chapters to address the objectives of the research work. In the first chapter, the research background and significance of the study is briefly described. The importance and necessity of runoff estimation especially for the Middle South Saurashtra region is also discussed. It is revealed that the widely adopted and used SCS-CN method with modified *CN* is more appropriate and recommended to apply for runoff prediction in the study region. Objectives and scope of the work are stated. Problem of the study is clearly defined and the need for modified models is emphasized.

The second chapter reviews the past and current literatures and it covers exhaustively the research work done on modification of *CN*. It is revealed that the research work done is meager in the direction of the effect of accumulation of moisture, morphometric parameters of the watershed and long term loss evapotranspiration in *CN* determination. The chapter concludes with a discussion of the shortcomings of the previous approaches. It also highlights the research gaps in the previous studies.

The third chapter gives comprehensive description of the study region and collection of various spatial and non-spatial data. It presents the detailed description of location, topography, LULC, soil characteristics, geology, and hydrometeorology of the study region. It also describes procedure to identify soil type based on soil taxonomy. It highlights geo-morphologic and hydrologic characteristics of the Ozat, Uben and Shetrunji watersheds of the Middle South Saurashtra region and data collection. It also describes various thematic maps to be used in the present study.

Chapter 4 elaborates the model selection criteria and discusses about methodologies to modify *CN* in the Middle South Saurashtra region (Gujarat-India). It presents procedure in detail to determine composite *CN* from RS and GIS techniques. The three independent methods developed by integrating the effect of cumulative rainfall-runoff ordered data, morphometric parameters of the watershed and evapotranspiration loss in *CN* determination procedure to enhance the performance of the SCS-CN method are also described in this chapter.

In the fifth chapter, the general concept and assumptions behind the proposed methodologies are described. It presents the extensive results of the application of proposed methodologies on the test watersheds of the study region. The results obtained are presented in form of tables as well as graphs for better understanding.

Chapter 6 consists of summaries and the conclusions drawn from the present study along with limitations, recommendations and future research scope.

1.8 Closure

Water is the basic need for the survival of human being, and hence, it is considered as a liquid gold in the regions face sever water crisis. Inattentiveness use of water, poor water resources management, growth of populations, and water pollution has at present led to serious drinking water problems. The most water resources in the arid and semi-arid regions have come under heavy stress and this has adversely affected the quality of people's life. Therefore, efficient conservation and management of water resources is an inescapable necessity in such regions. Hydrologic analysis and accurate estimation of runoff are often needed for stakeholders and policy makers in makiking appropriate policies for development and management of water resources in the watershed. Universally well accepted SCS-CN method is more reliable for runoff estimation. However, modification in conventional SCS-CN method towards better runoff estimate is very indispensible. Hence, it is proposed to modify *CN* to enhance performance of the SCS-CN method. The scope and objectives of the study are elaborated in this chapter. The next chapter discusses literatures review about the SCS-CN method in detail.

CHAPTER 2

Literature Review

2.1 General

Estimation of runoff from a watershed is an important aspect and plays vital role in flood prediction and mitigation, water quality management, hydropower production and many other water resources applications. Numerous methods have been used to determine watershed runoff but most of them are costly, time consuming and difficult to apply because of lack of adequate data. Simple methods for predicting runoff from watersheds are mainly imperative and often feasible in hydrologic engineering, hydrological modelling and in many hydrologic applications (Abon et al., 2011; Steenhuis et al., 1995; Van Dijk, 2010). The SCS-CN method based on single parameter *CN* is extensively used to estimate the runoff. Its performance can be improved by modifying *CN*. There are many methods in practice to determine *CN* for a watershed. It was felt that an exhaustive review of various *CN* estimation approaches in the SCS-CN method should be done and hence it is presented in this chapter. In the subsequent sections, all these approaches are reviewed in detail.

2.2 Methods of *CN* Determination

The widely used SCS-CN method governs by sole parameter *CN*. The *CN* relies on the watershed characteristics and treatment classes (Agricultural, Range, Forest, and more recently, Urban (SCS, 1986)), Antecedent Moisture Content (AMC), HSG (A, B, C, and D), and hydrologic surface condition (Poor, Fair, and Good) of a watershed. Hawkins (1975) pointed out that the errors occurred in *CN* may have much more serious than errors of similar magnitude in precipitation. Chen (1981) observed that smaller values of *CN* made the larger variation of initial abstraction and rainfall on runoff. Further, Bales and Betson (1981) noticed that *CN* is significantly associated with storm hydrograph model parameters. Especially, errors in runoff calculation near its threshold are severe, in low runoff and low rainfall situations. Knisel and Davis (2000) found in the runoff simulation in GLEAMS that *CN* is a sensitive parameter and noticed that small changes in high *CNs* are more sensitive than equivalent small changes in low *CNs*. Thus, it is clearly understood that the accurate estimation of *CN* plays significant role in storm runoff calculation. Contemporary literature indicates that there are many techniques available to assess, simulate and predict hydrological variables. However, the selection of appropriate techniques usually depends on the objectives of the study, availability of required input data, the quality of available models and some pre-defined assumptions. Makridakis et al. (1998) suggested that each method is different in terms of accuracy, scope, time horizon and the cost. To facilitate a satisfactory level of accuracy, the developer has to be responsive to the characteristics of different methods, and determine if a particular method is appropriate for the undertaken situation before embarking its usage in real application.

Basically the *CN* is a coefficient in range 0 to 100 that reduces the total precipitation to runoff potential, after various losses like absorption, transpiration, evaporation, surface storage, etc. Therefore, higher the *CN* value, higher the runoff potential will be. With all of the ambiguity surrounding the origin and development of the *CN* values, it is crucial to use the *CN* value that best mimics the land uses, soil types, soil moisture, and hydrologic conditions. The *CN* estimation procedure is categorized as shown in Fig. 2.1:

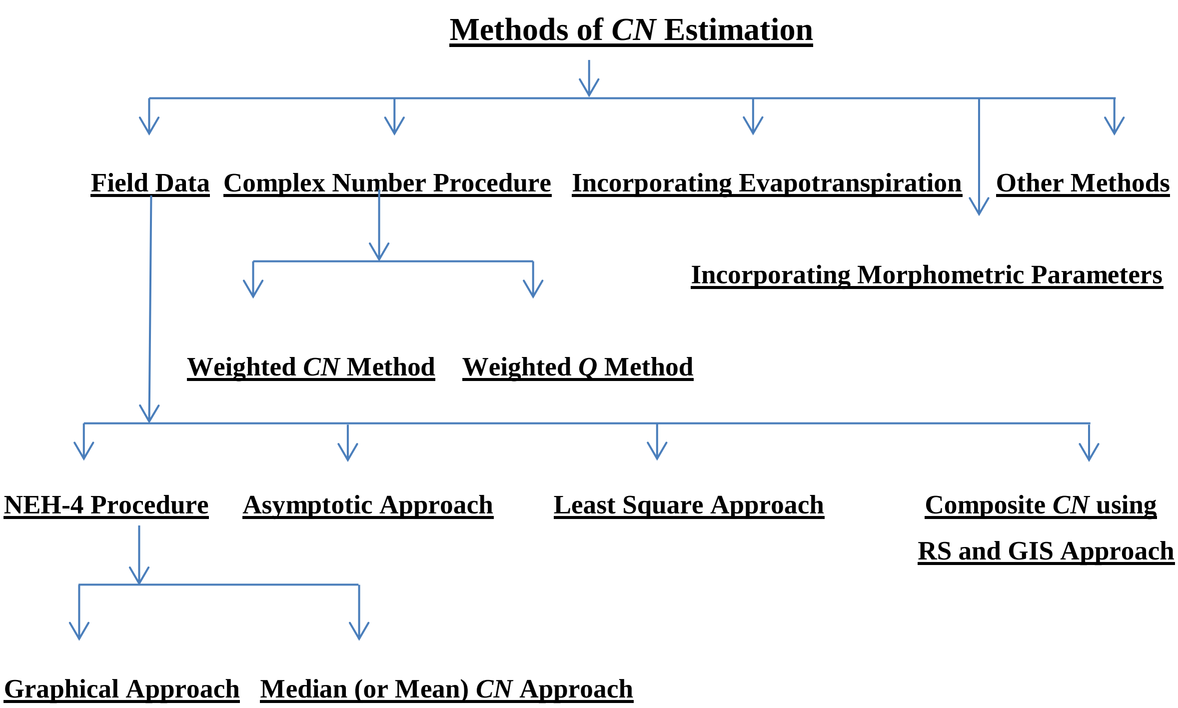


FIGURE 2.1 Classification of *CN* estimation methods

2.2.1 *CN* from Field Data

NEH-4 PROCEDURE: The *CN* is usually calculated from available standard tables in the National Engineering Handbook, Section 4 (NEH-4) as well available curves; however, this procedure is very tedious, laborious, and time consuming. This NEH-4 (SCS, 1972) procedure consists of graphical approach and median (or mean) *CN* approach. It was further observed that large errors can be expected in surface runoff estimation where, the validity of the hand book tables for *CN* was not verified.

Graphical approach: The graphical approach is a simple procedure, prescribed by NEH-4 (SCS, 1972), in which the dataset (annual precipitation *P*: annual flood *Q* data) is superimposed on the NEH-4 *P*: *Q*: *CN* plot, and the *CN* is selected by visual interpretation. But it consists of the following drawbacks:

1. It uses only one piece of data (the annual flood event) from each year of measurement, which is an inefficient and expensive way to use data.
2. It does not assure freedom from the *P*: *CN* bias. Many annual datasets contain the *P* influence, including the NEH-4 graphical example.
3. In dry years, some small watersheds may not have flow.
4. Many applications of the *CN* method go well beyond only annual event circumstances.

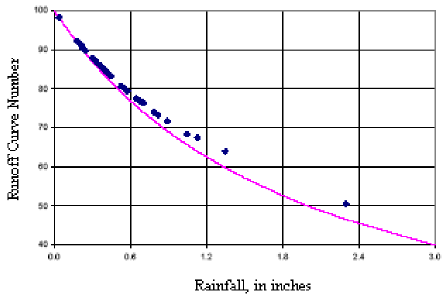
Due to these drawbacks, this graphical approach is generally not practiced and also it became obsolete. Instead of that, a simple average (mean) or median *CN* from a number of storms is practiced.

Median approach: The *CN* is determined for each *P*–*Q* pair by using the observed rainfall–runoff data. From these arrays of *CNs*, either 'median' or 'mean' *CN* is selected as a representative *CN* for a watershed. Here, the occurrence of low *P*–high *CN* bias is judiciously considered. This is a common method adopted elsewhere, for example, Rallison and Cronshey (1979), Hawkins et al. (1985), Hjelmfelt (1991), Hawkins et al. (2002), Mishra et al. (2004a), Schneider and McCuen (2005), Mishra et al. (2005a) and Mishra et al. (2005b) considered the 'median' *CN* of large storms. In addition to that, the NEH-4 (SCS, 1985) example divides the *P*–*Q* plot into two equal numbers of *P*–*Q* points for deriving the median *CN* corresponding to average antecedent moisture condition (AMC II). However, either median or mean *CN* of large storms is appropriate, if the bias in dataset is removed (Hawkins, 2005). The median is more appropriate for small samples. It reduces the effect of outliers (Schneider and McCuen, 2005) and is useful in operational setting (Hjelmfelt, 1991). This approach can be applied to both 'ordered' and 'natural' datasets, and thus differs from asymptotic approach. Since the asymptotic method considers the 'ordered' dataset and, in turn, shifts the values to another position, but within the conditional distribution function of *Q* for the measured *P* (Schneider and McCuen, 2005), its accuracy in the estimated *CN* is affected. In a comparative study among asymptotic method, median *CN* method, and least square method, Simanton et al. (1996) found them to yield similar results, and sensed the existence of *CN*–drainage area relationship. Traditionally, these 'median' or 'mean' *CN* value is represented as CN_{II}, describes the 'average condition' of the watershed in terms of wetness, and is considered as representative *CN* for the watershed.

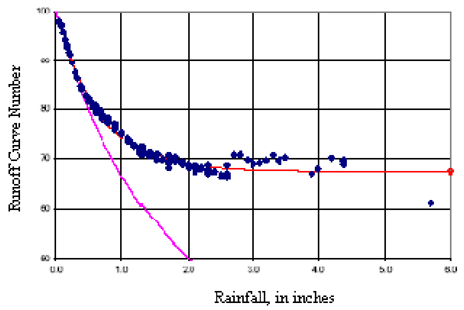
ASYMPTOTIC APPROACH: This 'frequency matching' based approach was first pointed out by Hjelmfelt (1980) in the SCS-CN model. In this approach the return period for the runoff is assumed to be the return period of the rainfall. The 'Natural' data retain the actual *P*–*Q* dataset. The field data analyse under the same assumption by rank ordering the rainfalls and runoff separately, and reconvening them as rank-ordered pairs. This is called "ordered" data. In order data, *P* and *Q* data are arranged in descending order, in which a *Q*-value corresponding to a particular *P* may not necessarily represent the actual runoff due to this rainfall. Therefore, this approach preserves the return-period matching between rainfall and runoff. This procedure has become a much useful technique in rainfall-runoff analysis.

Sneller (1985) shown that *CN* is function of *P* and identified three types of watershed behaviour, namely, complacent, standard, and violent. The study found 80% of 70 watersheds investigated to have a standard response. This research provides guidance on how to judge the response of watershed from these behaviours.

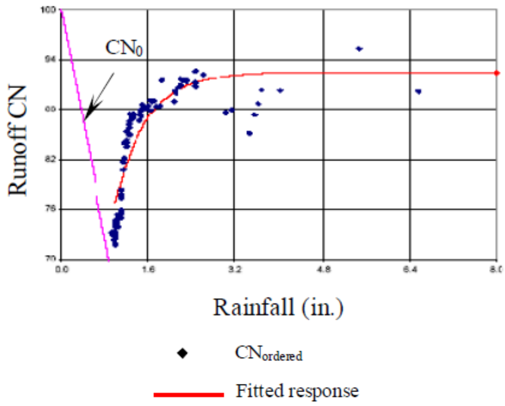
Hawkins (1993) found a secondary relationship between the *CN* and the *P* depth from ordered *P*–*Q* dataset. This secondary *P*-*CN* relationship exhibits three types behaviour, namely, complacent, standard, and violent, as shown in Fig. 2.2. The standard and violent responses lead to a constant *CN* with increasing rainfall depth, but the complacent response does not lead to a stable *CN*. The standard response is the most frequent scenario in which *CNs* decline progressively with increasing storm size, approaching an asymptotic *CN* value with increasingly larger storms. The violent response occurs when the *CNs* has an apparently constant value except for very low rainfall depths. In less common cases (complacent behaviour), the observed *CNs* declines steadily with increasing rainfall but have no appreciable tendency to approach a stable value. This study found that 70% watersheds have a standard response and 10% watersheds have a violent response out of 37 watersheds. This research gives hydrological definition of the watershed and some measures of asymptotic attainment of the fitting equations.



Complacent Behaviour



Standard Behaviour



Violent Behaviour

FIGURE 2.2 Watershed responses due to a secondary relationship in ordered *P*–*Q* dataset (Hawkins, 1993).

Rietz and Hawkins (2000) also used this approach in *CN* estimation for different land use on each watershed at three scales - local, regional and national.

The asymptotic approach is questionable and debatable as it was valid only in frequency matching sense, and therefore, applied particularly to return-period cases (Hawkins, 2005). Further, some of the statistical uneasiness exists in the procedure such as: (1) built-in bias in all *P*: *Q* fitting insofar as $0 \le Q \le P$. That is, all points must fit into the octant below the 1:1 line and above Q=0. Mere random generation of $Q \le P$ for given *P* will lead to a series of points displaying an unnaturally high coefficient of determination, R^2. This is exacerbated with the *CN* situation where, all points must fit in the reality space of $CN_o \leq CN$ (*P*, *Q*) ≤ 100, and also due to the *CN* which is already a function of *P*; (2) sampled watersheds are assumed to be truly valid samples of what they are taken to represent; (3) data points used are end-of-storm total *P* and *Q*, and the array of many of these does not necessarily define the relationship with time for an individual event. That is, *Q* and *P* are assumed to be *Q* (t) and *P* (t) respectively. The study stated advantages of this approach, such as (1) it is a more efficient use of data resources; (2) it negates the absolute need for rainfall data directly on-site; (3) it avoids *CN* biasing with high *CNs* for low *P*; (4) from experience, the results seem more consistent with external factors such as seasonal issues and adjacent watershed findings; (5) *CN* solutions with it are less sensitive to occasional outlier *P* and *Q* values, and give more consistent results; (6) results are similar to those done with natural data; (7) it is trendy.

Istanbulluoglu et al. (2006) examined the effect of 5-day antecedent precipitation index of the SCS-CN method on the precipitation-runoff relationship using long-term measured rainfall data from Istanbul-Catalca Damlica Creek Watershed (ICDCW) located in a semi-arid region. In this investigation, any statistically significant difference is not found between the calculated runoff values under with and without 5-day antecedent conditions. The study examined that calculated runoff values larger up to 7 folds than the observed runoff. This clearly questioned the reliability of the SCS-CN method, either using with or without 5- day antecedent moisture conditions (AMC, I, II and III). Therefore, the SCS-CN method was criticised in terms of over-sizing hydraulic structures and increasing the cost. The research concluded that the 5-day antecedent moisture condition has an effect on monthly runoff depth but no effect has been found on yearly runoff.

Banasik et al. (2010) used more than sixty rainfall-runoff events, collected during 29 years (1980-2008) in a lowland and agricultural watershed (Smaller area A=23.4 km^2) in the Center of Poland, to determine *CN* and to check change tendency. The *CN* has been estimated by three means: (i) based on LULC and soil types (USDA, 2003; ASCE, 2009) (ii) based on rainfall-runoff records of largest storms (Hawkins at al., 1985) and (iii) based on “asymptotic approach” with the use of all rainfall-runoff events (Hawkins, 1993). This research concluded that a representative *CN* value can be obtained based on the procedure described in USDA-SCS Handbook for estimating runoff from high rainfall depths. This has been confirmed by applying "asymptotic approach" for estimating the watershed *CN* from the rainfall-runoff data. This work also noticed that *CN*, estimated from the recorded events with rainfall depth higher than initial abstraction, is also approaching the theoretical *CN*. The study observed that in a watershed showing standard response, *CN* declines with increasing storm size (ranging from 59.8 to 97.1). This study also demonstrated the variability of *CN* during a year. Analyses showed that empirical *CN* computed for events of $P \geq 20$ mm is very close to *CN* estimated from LULC and soil types for the watershed.

Mishra et al. (2013) derived the design *CN*-values for Banjar, Manot, Burhner, and Shakkar catchments of Narmada River. The study employed 10 years daily rainfall–runoff data, frequency-based design *CNs* of different rain durations and for 2, 5, 10, 25, 50, 100, and 200 years return periods were derived for normal, dry, and wet weather conditions, representing 50%, 10%, and 90% probability of exceedance, respectively. The design runoff values derived from design storm and design *CN*-values were found quite close to the conventionally derived design runoff for a given rain duration. It was observed that for a given duration, as the wetness level (wet through dry) decreases, the *CN* value decreases, and for a given AMC, as the duration increases, the *CN* value decreases, and vice versa. Further, for a given wetness condition and duration the *CN* value increases as the return period increases. They concluded that the study will be very helpful for hydrologists and engineers engaged in flood forecasting, looking for suitable sites for hydro-electric plant, etc. and also for soil conservationists.

Mishra and Kansal (2014) suggested a simple approach for derivation of the design *CN* for different durations, AMCs, and return periods. In this study design *CNs* were derived by employing the long-term daily rainfall-runoff data of three hydro-meteorologically different watersheds, viz. Ramganga watershed in Uttarakhand (India), Maithon watershed in Jharkhand (India), and Rapti watershed in Mid-Western Region (Nepal) and tested their validity using the design runoff computed from observed data conventionally. The study revealed that for a given duration, as AMC level (AMC III through AMC I) decreases *CN* decreases and, for a given AMC, as duration increases, *CN* decreases, and vice versa. It was noticed that for a given AMC and return period, *CN* decreases as rain duration increases, and vice versa, furthermore, for a given AMC and duration, *CN* increases as return period increases. Further the study observed that for a given duration and return period, *CN* increases as AMC level increases from AMC I to AMC III. The results were found reasonable for return periods up to 10-year, 50-year, and 50-year for Maithan, Ramganga, and Rapti watersheds, respectively.

Kowalik and Walega (2015) described the *P-CN* relationships by means of different asymptotic functions. The standard function described by Hawkins, kinetics equation and complementary error function peak were applied in the watersheds located in Gaj in the eastern part of the Wieliczka Foothills, and in the municipality of Andrychów, in the eastern part of the Little Beskids. The study described a strong correlation between *CN* and *P*. The study observed a typical pattern of *CN* stabilization during abundant precipitation in three of the analysed watersheds. A kinetics equation based model was described the *P-CN* relationships most effectively in this research. They specified that *CN* in the investigated watersheds was similar to the empirical *CN* obtained by using NEH-4 standard tables. This study concluded that proposed model provides the utmost stability of *CN* at 90% sampled event rainfall.

LEAST SQUARE APPROACH: This approach, as outlined by Simanton et al. (1996), depends on curve-fitting technique. Initial abstraction (I_a) (or λS) and potential maximum retention *S* (or *CN*) are determined by adopting iterative least squares procedure fitting of the *P*, *Q* data to the basic *CN* (Equation 2.1).

$$Q_C = \frac{(P - I_a)^2}{P - I_a + S} \tag{2.1}$$

To avoid *CN* low rainfall–high *CN* bias and uncertainty, only events with P>25.4 mm are considered in calculation of *CN*. A least squares objective function can be used to find the optimised values of parameter I_a and *CN* by minimizing the sum of the square of differences between observed runoff (Q_{obs}) and computed runoff (Q_c). The sum of the square of differences is selected for minimization and the aim is to make the objective function E_{min} minimum (Equation 2.2).

$$E_{min} = \text{Min} \sum_{i=1}^{n} |Q_{obs} - Q_c|^2 \tag{2.2}$$

If this is the case, then the optimised *CN* (or *S*) value should be very similar to the asymptotic values (especially for the ordered data), insofar as they both use the same data, and both are taken to be free of the rainfall depth influence. This suggests that little is gained by least squares fitting, except for the natural data case. Therefore, least squares *CNs* may be an unnecessary refinement.

COMPOSITE *CN* USING RS AND GIS APPROACH: The advances in geo-spatial techniques such as Remote Sensing (RS), satellite data digital image processing and Geographic Information Systems (GIS) have increased its potential applications and proved its capability in determination of different land use types and vegetation cover. These techniques result in a less time-consuming, more accurate and less expensive methodology to monitor soil conservation practices and predict runoff. Especially, remote sensing techniques offer a good means of monitoring the adoption of these conservation practices (Logan et al., 1982; Trolier and Philipson, 1986; Welch et al., 1984). Many researchers (Melesse, 2002; Xu, 2006; Gupta and Panigrahy, 2008; Pradhan, 2010; Fan et al., 2013) used RS and GIS tools to estimate *CN* and concluded that these techniques are versatile and popular for quick, reliable and relatively easy estimation of composite *CN* for watershed. Therefore, to get more precise and consistent estimation of *CN*, it is necessity to develop credible GIS based method of determining composite *CN*.

Halley et al. (2002) developed an ArcView GIS extension for estimating *CNs* based on land use and HSG maps. The most difficult phase here is to acquire data, and input that into GIS. GIS is advantageous, if the study area is large, runoff is modelled repetitively, and alternative land use/land cover scenarios are explored. They suggested that in developing countries such as India, these latest techniques need to be explored extensively in hydrological modelling applications.

Patil et al. (2008) developed an interface in GIS by the in-built macro-programming language Visual Basic for Applications (VBA) of the ArcGIS tool for surface runoff estimation using *CN* techniques (ISRE-CN). In this study CN_I was modified based on the concept of zero I_a, i.e. immediate ponding for calculating the runoff depth Q froma given rainfall depth P. CN_{II} was improved by modifying the I_a by linking a non-dimensional parameter λ with the S. CN_{III} was amended by dividing the cumulative infiltration F parameter into basic and dynamic components during the rainfall–runoff processes. The study emphasized both the prediction of surface runoff from ungauged watersheds as well as application of the advanced ArcGISs tool to predict the surface runoff. The results indicated that the surface runoff predictions by NRCS-CN are very sensitive to the AMC of watershed systems; this imposes further modification of the *CN*-based methods to incorporate more realistic parameters to account for AMC prevailing in the watershed during and before the rainfall event. The developed inference then validated using the dataset for the periods from 1993 to 2001 of Bhana watershed in the Upper Damodar Valley, Jharkhand, India. In this study, comparison was made between the observed runoff depths and predicted runoff values of the NRCS-CN methods and its three modifications using statistical significance tests for different rainfall events. The research concluded that modified CN_I perfromed the best, followed by the modified CN_{III} method, while the modified CN_{II} method failed to predict accurate runoff from the study watsershed. Further, the modified CN_{II} method performed the worst under all AMC.

Kumar et al. (2010) applied and analysed the SCS-CN method in a semi-arid Miditerranean watershed in Hydrabad (India). They obtained a detailed land cover and soil survey using RS and GIS techniques and found that the watershed has coarse soils with high hydraulic conductivities, whereas a smaller part is covered with medium textured soils and impervious surfaces. Their analysis indicated that the SCS-CN method not given satisfactorily results to pre direct runoff for the storm events studied. They were taken hypothesis that rainfall-runoff correlation could be attributed to the existence of an impermeable part in a very permeable watershed. They were examined hypothesis by developing a numerical simulation water flow model for each of the three 15 soil types of the watershed. The validation of hypothesis indicated that for most of the events, the linear runoff formula affords superior results than the conventional SCS-CN method.

Geena and Ballukraya (2011) estimated runoff using the SCS method and GIS for Red hills watershed (situated near Chennai, India). The HSG and soil maps have been used to demarcate land use class and soil combinations of the watershed in the study area. From HSG and soil map, different *CN* values were assigned and the weighted value of *CN* for the whole watershed was worked out. The retention capacity *S* was calculated based on this *CN* value. They found good correlation between rainfall and concluded that a minimum of about 66 mm rainfall in a month is required to generate runoff in the area.

Ebrahimian et al. (2012) used NRSC-CN method to estimate runoff in mountainous watershed (semi-arid Kardeh watershed Mashhad, Khorasan Razavi Province, Iran). They prepared HSG, land use and slope maps by using GIS tools. *CN* values map then made by integrating HSG and LULC maps. The calculated *CN* values were used to estimate runoff depth for selected storm events in the watershed. Based on the results obtained they concluded that the combined GIS and *CN* method can be used in semi-arid mountainous watersheds with about 55% accuracy only for management and conservation purposes.

Patel et al. (2012) prepared thematic maps viz. drainage map, LULC and Hydro-geomorphological map of the sub watershed of 16940 ha comprising of 23 micro watersheds (ranging from 366.62 to 1332.51 ha) falling in Bhesan and Visavadar talukas of Junagadh district in Gujarat (India) using the RS images and GIS software for the study purpose. RS images dated 05/01/2005 and 19/10/2005; soil maps and reports prepared by National Bureau of Soil Survey and Land use Planning (NBSS & LUP) were used and computed runoff by using the SCS-CN method to assess impact of alternative land use and management practices. The study found the percentage area under single crop and double crop as 71.81 and 18.02% respectively. It has also been argued that major part (84.83 %) of the sub watershed covered by the moderate to poor groundwater prospects. The existing single crop pattern in soil having shallow (40.75%) and moderately (36.02%) buried pediplain were recommended to cover under agro-horticulture and double cropping respectively. This research observed that the annual mean runoff yield for the entire watershed decreased by 11.76 % of the values at pre-conservation.

Nayak et al. (2012) used the SCS-CN method for the Uri river watershed in Lower Narmada basin (Central India) to investigate the effects of land-use change on surface runoff. They interpreted satellite imageries of two different periods, i.e. year 2001 and 2007 in ILWIS GIS platform for preparation of LULC maps and analysed spatial distribution and changes of LULC. The weighted average *CN* for both the year calculated on the basis of respective LULC and HSG in the catchment area. The direct surface runoff volume computed by the SCS-CN method have been compared with the observed runoff calculated from recorded hydrograph at gauging site for the selected rainfall events. It was shown from the results that the agricultural area has been replaced drastically with forest area and as a result surface runoff volume increased 20-40 % in year 2007 in comparison to those in year 2001 for the similar rainfall events.

Fan et al. (2013) demonstrated a simulation model based on the SCS-CN method to analyze the rainfall-runoff relationship in Guangzhou, a rapid growing metropolitan area in southern China. They presented that successful SCS-CN modelling depends on key variable *CN*. They noticed that because of the complexity of LULC in urban environments, *CN* calculated from look-up table of TR-55 cannot be applied to all surface types. Therefore, they developed an innovative method using RS variables to compute composite *CN* for contented use of the SCS-CN method. The developed method encompassed the impact of the percentages of vegetation, soil, and impervious surface in the urban areas. The results indicated that the RS based improved SCS-CN method computed more accurate composite *CN*. They suggested that proposed method convenient and easy to use in runoff estimation and becomes useful tool for storm management for the local governments.

Gajbhiye et al. (2013) examined seasonal and monthly effects on the *CN* for four watersheds of Narmada basin. They determined *CNs* using observed rainfall and runoff data for the Pre-Monsoon and Post-Monsoon seasons. The *CNs* were grouped to their respective seasons for statistical analysis. Variability of annual and seasonal *CNs* were analysed in all the watersheds. The results indicated that monthly *CN* exhibits a homogeneous pattern of variation in all the studied watersheds in the basin. The monthly *CN* has peak (during July) and valley (during August). However, at Shakkar watershed the peak is during August instead of July. The maximum monthly *CN* is recorded during the month of September with the average value of 97.96 in Mohgaon watershed and the minimum *CN* is recorded during the month of September with the average value of 17.88 in Bamhani watershed. Pre-monsoon contributes the major portion of the *CN* with the average value range 25.70-27.76% for all watersheds. However, Post-monsoon *CN* is almost negligible in Bamhani watershed (3.46 %). The average maximum and minimum *CN* is obtained 97.43 and 95.74 for Manot and Bamhani watershed respectively. Higher values of *CN* were obtained for cultivated lands than Forest land. However, they have not studied the effect of these *CNs* on runoff prediction.

Thakuriah and Saikia (2014) successfully demonstrated an integrating RS and GIS based methodology for estimation of runoff in Buriganga watershed of Assam (India). They demonstrated that RS and GIS techniques much useful in preparation of HSG, LULC and slope maps. The study exhibited that hydrological modelling in GIS with the aid of RS technology is a powerful tool for system investigation of runoff generation in geo-hydrologic environment. The *CN* values from NRCS Standard Tables were allotted to intersected HSGs and LULC maps and then to estimate runoff depth for selected storm events in the micro watershed. The study concluded that the rainfall, slope, vegetation cover, soil condition are considered to be important factors in surface runoff. It was also observed that recharge is relatively low on the northern part due to the presence of dissected hilly hard rock terrain with moderate to high degree of slope than the southern part of Buriganga basin having high surface runoff covered by exposed or bare surface to crop land in gentle slope. The suitability of recharge in the northern part is poor due to the impermeable lithology.

Sharma et al. (2014) used RS and GIS technique to generate information regarding factors affecting soil erosion and to identify the most vulnerable area for erosion in Kanhiya nala watershed of Gusuru River which is a tributary of Tons river basin (Madhya Pradesh, India). Topology, vegetation, soil and morphology related indices were estimated separately for each nine sub watersheds and the integrated effect of all the parameter was evaluated to find different areas vulnerable to soil erosion. This study showed that relative vulnerability to soil erosion for a watershed can be assessed more conveniently with RS and GIS techniques.

Vaishali and Regulwar (2015) estimated the runoff by using the SCS–CN method and GIS technique in Dawarwadi Watershed, Aurangabad (India) with an area of 380.25 Sq.Km. The most prominent land use classes were cultivated land, water bodies, and residential area while B, C and D were three HSGs. 26 years (1986 to 2013) rainfall data were used to calculate runoff. The study observed that the average annual runoff depth of watershed is 488.4mm and total runoff volume is 4828.58Mm^3.

Viji et al. (2015) presented GIS based *CN* method for Kundahpalam micro watershed with an area of 14.37 Sq. Km, lies in the Nilgiris District of Tamil Nadu (India). Composite *CN* vales were estimated for AMC (Antecedent Moisture Condition) I, AMC II and AMC III for the entire watershed and were about 48, 68 and 83 respectively. They estimated average annual runoff depth 72.5 mm for the average annual rainfall of 173.5 mm using the SCS-CN method. The study exhibited that GIS based SCS-CN method makes the runoff estimation more accurate and fast. Due to the hilly terrain of the watershed (1560 to 2410 above mean sea level), 89% of rainfall would be converted into runoff while remaining 11% rainfall was infiltrated into the ground. The study stipulated that spatial distribution of *CN* value varies from 46.25, 86.75, and 100 correspondences to dense forest, built-up land and water. Due to the high infiltration capacity of the dense forest, the runoff was low and in the hard surface of the built up land the runoff was high. In the water body, 100% of rainfall is converted into runoff. In horticulture plantation, agricultural land and degraded forest the infiltration is very less, and surface runoff will be more and join to the stream at the base that may cause top-soil loss. The estimated runoff showed that the watershed had a very good surface runoff potential. Hence, the surface water can be recharged into the ground by constructing suitable artificial ground water recharge structures.

Gajbhiye (2015) argued that the synoptic concept of satellite image is fairly easy for identification of the broad physical features of the watershed. The study verified reliability of RS and GIS technique in determination of *CN* in Kanhaiya nala watershed located in Satna district of Madhya Pradesh (India). Land cover information were obtained from Landsat Enhanced Thematic Mapper (ETM) satellite image and generated Soil map, Land Use map and slope map in GIS Environment. The ETM satellite image was used as input in ERDAS 9.1 software. Soil map, elevation map, rainfall map and land cover map were created using Arc GIS 9.3 software. *CN* was assigned for different land cover and soil types. The study recommended the proposed methodology in estimating the runoff for places which do not have runoff record and to make management plans for usage and development of watershed.

2.2.2 Complex Number Procedure

This method uses the available standard *CN* table (hydrologic soil–cover complex number) of NEH-4 (SCS, 1993) to estimate the *CN* of a watershed based on its land use type and hydrological soil group type. This is used mostly for the ungauged watersheds. According to SCS, there are four hydrologic soil groups: A, B, C, and D. (1) ‘A’ Soils having high infiltration rates, even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission; (2) ‘B’ Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission; (3) ‘C’ Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission; and (4) ‘D’ Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission. Some wet soils are classified as dual hydrological soil groups (A/D, B/D and C/D) that could be adequately drained. The first letter applies to the drained and the second to the un-drained condition. Especially, the soils are assigned to these dual groups if the shallow depth to a permanent water table is the sole criteria for assigning a soil to hydrologic group D. Of late, Golding (1997) noticed several discrepancies where, the SCS has classified the soils as being A/D and B/D, which are supposed to reflect a high ground water table. Further, Golding (1997) added that urbanization of an area could change the height of the ground-water table. In addition, professionals tend to use A or B rather than D classification to economize the project.

WEIGHTED *CN* METHOD: The *CN* values of NEH-4 tables represent the average median site *CN* (the *CN* corresponding to the curve that separated half of the plotted *P*–*Q* data from the other half for the given site) values with the indicated soil, cover, and surface condition. This is denoted as CN_{II}, corresponding to AMC II (average runoff potential). Further this approach is done in two ways;

(1) Weighted *CN* approach and (2) Weighted *Q* approach. In the first one, the *CN* values of the respective hydrological–soil cover complex were multiplied to the respective per cent areal coverage of the complexes, that is (Equation 2.3),

$$CN_{aw} = \frac{\sum_{i=1}^{n}(CN_i * A_i)}{\sum_{i=1}^{n}(A_i)} \quad (2.3)$$

Where, CN_{aw}=the area-weighted *CN* for a watershed; CN_i=the *CN* for each land use–soil group complex; A_i=the area for each land use–soil group complex; and n=the number of land use–soil group complex in a watershed. Then, based on this weighted *CNs*, the runoff is estimated.

WEIGHTED *Q* METHOD: The second one primarily calculates the respective runoff (*Q*), with the corresponding *CNs* of the hydrological–soil cover complex, and finally the *Q* values on each complexes, were weighted similar to the above. It is obvious that the weighted *Q* method is superior to the weighted *CN* method, as the former is more rational than the latter for water balance reasons.

However, the weighted *CN* is easier to work with the watershed having many complexes or with a series of storms. Mishra and Singh (2003c) pointed out that the computed runoff by the earlier two approaches would significantly deviate for a wide range of *CNs* for various complexes in a watershed. In general, the weighted *CN* method is less time-consuming but tends to be less accurate when compared to the actual measured runoff depth. Therefore, again it is clear that weighted *Q* method is superior to weighted *CN* method.

Two problems arise while using this ‘hydrologic soil-cover complex number’ approach:

1. The calculation is much more sensitive to the tabulated *CN* than it is to the rainfall depths (Hawkins, 1975; Bondelid et al., 1982).
2. It is difficult to select the *CNs* accurately from the standard *CN* tables of handbook (Hawkins, 1984).

It is difficult to select the *CNs* accurately from the standard *CN* tables of handbook (Hawkins, 1984). Recently, this approach has been tried with the aid of remote sensing and GIS techniques in case of distributed modelling. Hawkins (1984) suggested that the determination of *CNs* from field data is better than hydrologic soil–cover complex number method, as later one leads to variable, inconsistent, or invalid results.

2.2.3 Incorporating Morphometric Parameters

Very few attempts have been made to incorporate morphometric parameters of watershed in the SCS-CN method, though these have strong influence on runoff generation. The geomorphological parameters reflect watershed based causative factor affecting runoff. RS data provides real time and accurate information related to distinct geological formation, it coupled with GIS topographical data analysis procedures currently become more effective tool to understand and manage the natural resources. Morphometric parameters describe the morphological and climatic characteristics of a watershed govern a hydrological response to a considerable extent. The morphological characteristic may be employed in synthesizing hydrological response in ungauged watershed. Therefore, morphometric parameter cannot be ignored in accurate prediction of runoff. Hence, linking of the morphologic parameters with the *CN* can lead to simple and useful procedure to estimate reliable runoff volume.

Sharpley and Williams (1990) presented (Equation 2.4) having three parameters, which adjusts the CNII values for the slope. The equation has three empirical parameters: a, b, and c, which have the values of 0.33, 2, and 13.86 respectively.

$$CN_{II\alpha} = a(CN_{III} - CN_{II})(1 - be^{-c\alpha}) + CN_{II} \qquad (2.4)$$

Where, $CN_{II\alpha}$ is the adjusted value of CN_{II} for a given slope; CN_{II} and CN_{III} are *CN* for soil moisture condition II (average) and III (wet), respectively; and α (mm^{-1}) is the slope of watershed.

Haung et al. (2006) conducted an 11-year experiment, consisting of seven pasture plots and two alfalfa plots, with slopes ranging from 14 to 140% to develop an equation incorporating a slope parameter into the *CN* method to predict surface runoff from steep slopes in the Loess Plateau of China. *CN* values determine by standard NEH-4 table presumably correspond to slope <5%, for higher slope, *CN* values are to be adjusted. In this study, a slope factor was incorporated into the *CN* method with the objectives to evaluate existing approaches and to develop an equation incorporating a slope factor into the *CN* method for application in the steep slope areas. Two experimental sites, consisting of 7 pasture plots and 2 alfalfa plots with slopes ranging from 14 to 140% and having 11 years of rainfall and runoff measurements were selected. The results indicated that the standard *CN* method underestimated large runoff events and overestimated small events. The developed model improved runoff prediction for steep slopes, but large runoff events were still underestimated and small ones over predicted. Based on relationships between slope and the observed and theoretical *CN* values, an equation was developed that better predicted runoff depths with an R^2 of 0.822 and a linear regression slope of 0.807. The study concluded that the developed slope-adjusted *CN* equation appears to be the most appropriate for runoff prediction in the steep areas of the Loess Plateau of China, but it needs to be validated and possibly improved for other sites.

Pal et al. (2012) used the topographical map and Landsat ETM Plus satellite image for morphometric analysis of six morphometric parameters viz. absolute relief, relative relief, dissection index, average slope, drainage density and ruggedness index, for better hydrologic analysis in a watershed. These parameters were obtained from monthly and annual rainfall data, soil data, topographic map, satellite image using RS and GIS techniques (with use of Normalized Difference Vegetation Index) respectively. LULC, hydrologic soil characteristics, rainfall, and *CN* were used for surface runoff assessment using the SCS-CN method. This experimental study was carried out on Watut watershed (A=5410.74 Sq. Km) under Morobe province of Papua New Guinea. The average drainage density of the Watut watershed is computed 0.5 Km/ Km^2 with the average slope measuring about 31%. The result indicated that an average of 68.23% of total rainfall flowing out as surface runoff in the study watershed. The study highlighted that the integrated approach of SCS and USLE model with RS and GIS technologies have great potential for modelling of different hydrological parameters and producing risk maps in any watershed region.

Chaudhary et al. (2013) experimentally verified the effect of watershed (i.e. field plot of 22mx5m) slope on rainfall-generated runoff and resulting *CN* for a given soil (Hydrologic Soil Group C) and land use of sugarcane. The study found that the plot of 5% slope yielded the largest runoff compared to those due to the plots of 3% and 1% grades, for the same rainfall, soil, and land use. These experiments revealed that derived *CN* values are fairly close to those from NEH-4 *CN*-values which support the applicability of NEH-4 *CN* values to Indian watersheds. The results indicated that *CN* increases with slope and with AMC from I to III.

Shrestha et al. (2013) investigated the effect of slope on *CN* through experimental plots of maize crop (each of 22m x 5m) established on three different slopes of 1%, 3%, and 5%. They were used measured rainfall and runoff data to derived *CN*. Double ring infiltrometer test indicated HSG C category soil type in their study. These soils have a low rate of water transmission (1.27-3.81 mm/hr). The results showed positive correlations between *CN* and slope and *CN* and antecedent soil moisture content.

Jha et al. (2014) conducted a study on an agricultural (fallow land) experimental watershed (size: 22mx5m) located in village Toda Kalyanpur near Roorkee in District Haridwar, Uttarakhand state in India to evaluate the effect of slope, soil type, and antecedent moisture content (AMC) on the runoff *CN* for the selected three grades of 5%, 3% and 1% with Hydrologic Soil Groups (HSG) A, B, and A, respectively. The CN_{II} values for the plots of grades 5%, 3% and 1% were computed 81.46, 85.62 & 82.14 respectively. The study shows that the soil affects the *CN* more prominently than that of slope. Further, the plot of grade 3% resulted the highest runoff and *CN* rather than others although coefficient of determination between rainfall and runoff was highest for grade 5% (R^2=0.933). The study concluded that soil type influenced more on both runoff and *CN* than the slope of the watershed.

Gajbhiye (2015) carried out morphometric analysis by employing RS and GIS for Shakkar River catchment (Area 2220 Sq. Km.). The study area exhibited dendritic drainage pattern with the drainage density varies from 2.84 to 3.67 km/km^2, the bifurcation ratio varies from 3.49 to 5.52 and the elongation ratios vary from 0.47 to 1.00. The disparity in bifurcation ratio among the sub watersheds is attributed to the difference in topography and geometric development. The area is observed highly permeable and structurally controlled. The study revealed that out of 8 sub watersheds, sub watershed 3 shows lower value of drainage density and stream frequency, sub watershed 6 shows low value compactness constant and sub watershed 7 shows lower value of circulatory ratio and form factor, the relief aspect lower in the sub watershed 2, and the values of average slope vary from 9.27 to 88.50%. The analysis described that the study area produces high surface runoff values and low infiltration rates. The study demonstrated that morphometric analysis using GIS technique is more reliable and accurate as compared to time consuming, tiresome and error prone conventional methods.

2.2.4 Incorporating Evapotranspiration

Out of many physical processes like Interception, surface storage, infiltration, evaporation and evapotranspiration, infiltration is considered to be the most important hydrologic abstraction for hydrological analysis of rainfall-runoff relationship. Out of these processes, interception and surface storage are of secondary importance whereas evaporation and evapotranspiration are important for long-term and short-term seasonal or annual yield evaluations. The *CN* method is an infiltration loss based method; hence, it does not account for long term losses like evaporation and evapotranspiration. Therefore, its application was restricted in the field of surface runoff modelling (Boughton, 1989). However, the method has been used with suitable soil moisture accounting procedure (Huber et al., 1976; Williams and LaSeur, 1976; Knisel, 1980; Sharpley and Williams, 1990; Arnold, et al. 1993; Williams et al., 2000). *CN* varies from event to event, therefore, a comprehensive soil moisture accounting procedure combined with the *CN* procedure is needed to predict realistic runoff value from rainfall. Oover a period of several years, few soil moisture accounting procedures have been developed and incorporated into hydrologic modelling tools (Sharpley and Williams, 1990; Arnold et al., 1993; Williams et al., 2000). One such soil moisture accounting procedure was developed by Williams et al. (2000) for the use of the *CN* method for continuous hydrologic modelling in the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993) and Agricultural Policy/Environmental Extender (APEX).

Williams and LaSeur (1976) developed a continuous simulation model for computation of runoff using the retention parameter (S) and the soil moisture (M). They accounted antecedent moisture which depleted continuously between storms by *ET* and deep storage. He was the first to incorporate this concept in the *CN* determination. In this study, antecedent moisture was assumed to vary with the lake evaporation to eliminate sudden quantum jumps in the *CN* values between different AMC levels. However, arbitrary assumed value 508 mm for absolute potential maximum retention and loss of one year's rainfall–runoff information were the major constraints of this method (Mishra and Singh, 2004). Furthermore, assumed soil moisture decay with lake evaporation was not correct. The developed model can be simulated monthly and annual runoff. Since monthly lake evaporation was taken in to account, the daily average evaporation was used in the model calibration and validation. The study revealed that the model is more efficient at larger time scale than shorter time scale.

Hawkins (1978b) proposed a continuous soil-moisture accounting model in which the S-value was also varied with *ET*, a significant feature of the model, as it plays a significant role in long-term hydrologic simulation. The proposed model was based on a (I_a + S) scheme, whereas I_a is separate from S.

Hawkins (1978) modified the SCS-CN method by linking *ET* and *CN* for use in continuous hydrologic simulation model. Volumetric concept has been used by him for accounting site moisture. Sudden quantum jumps were eliminated in the *CN* values between different AMC levels. The study fails to distinguish between the dynamic infiltration and the static infiltration and also couples the interim drainage with *ET* which was quite contradictory because the fact that the water drained down to water table may not be available for evapotranspiration.

Kannan et al. (2008) developed a simple one-parameter continuous soil moisture accounting methodology using the expression of Williams et al. (2000) for continuous hydrologic simulation. This procedure was embedded into two widely used models, i.e. APEX and SWAT. The developed methodology, its performance and the sensitivity of the parameter depletion coefficient were tested in four United States watersheds in different water resources regions of the USA using the SWAT model. The retention parameter at present time step can be estimated and an initial estimate of *S* can be obtained based on the existing value of CN_{II} (*CN* for AMC II). They used monthly potential evapotranspiration (*PET*) in their equation. However, the use of *PET* is strongly discouraged due to ambiguities in their definitions. The study analysed behavior of different *ET* methods, viz. Penman-Monteith and Hargreaves in combination with two *CN* methods (with existing and newly developed soil moisture accounting procedures). Four possible combinations from these methods were tested within SWAT model. Combination of new *CN* method with

Penman-Monteith performed better than the existing *CN* method. However, the proposed model found more suitable for shallow soil conditions. The limitation of this model is that it does not take into account the effects of the amount of rainfall on a given day.

Jajarmizadeh et al. (2012) studied the impact of new accounting *CN* method (Plant *ET* method) using SWAT model on stream flow. The runoff volume were simulated by SWAT model incorporating plant *ET* method for Roodan watershed located in southern part of Iran. The study used 21 years (1988 to 2008) meteorological data in SUFI-2 algorithm for calibration and uncertainty analysis of daily stream flow. *CN* value was calculated as a function of plant *ET*. Nash-Sutcliffe and coefficient of determination of 0.66 and 0.68 for calibration as well 0.51 and 0.55 for validation were indicated that Plant *ET* method could give satisfactory results in arid and semi-arid region under condition of 30% low storage soil and 215 mm annual precipitation.

Williams et al. (2012) modified the SCS-CN method by incorporating the direct-link soil-moisture approach and the revised soil-moisture index (SMI) method for runoff estimation. The study compared the results of both these approach at different sites with varying soils in a large watershed (the Bosque Watershed) for demonstration purposes. The NRCS uses the *CN* method for designing and evaluating the hydraulic structures. A single event of a certain probability of occurrence is commonly taken into account in structural design. They noticed that during the years 1950 to 1980, many floodwater-retarding watershed projects were planned and constructed. These projects were evaluated by using the *CN* equation in a continuous mode. Approximately a daily rainfall-runoff record of approximately 30 years was used in this evaluation process. In order to assign an appropriate *CN* values for different AMC, the five-day antecedent rainfall was used. The daily runoff was estimated with the appropriate CN_{I} (dry condition), CN_{II} (average condition), or CN_{III} (wet condition). The research have perceived that *CN* can be linked directly to soil water content and *PET* to derive a soil moisture index in continuous hydrologic simulation models. Numerous methods with different degrees of success were tried and used in evolution of the continuous *CN* method over a period of many years. The evolution of the continuous *CN* method and its recent developments were described in this study. The test results were presented on the basis of the direct-link soil-moisture approach and the revised soil-moisture index method. The study concluded that the modified soil-moisture index method is robust and produce realistic results over a wide range of soil properties.

Mishra et al. (2014) derived a relationship between the *CN* and mean *PET* based on most frequently accessible long-term daily rainfall-runoff data. Eight different agro-climatic river watersheds of India have been selected for this study and mean *PET* was derived from meteorological variables using standard Penman-Monteith method. *CN* values were computed from the long-term daily rainfall-runoff data and mean *PET*. The results showed that high R^2 values (0.99 for Hemawati and Mohegoan; 0.98 for Haridanagar, Kalu, and Seonath; 0.96 for Manot, Ghodahadho, and Ramganga) strongly support the adaptability of the derived relationship. This relationship is also highlighted *PET* determination from the available published *CN* values. The study suggested that the derived relationship may be quite useful in field applications.

2.2.5 Other Methods

The SCS-CN method being much sensitive to *CN* estimation for accurate runoff estimation, therefore, some researchers tried entirely different approaches to estimate *CN*. For example, Bonta (1997) evaluated the derived frequency distribution approach for determining watershed *CNs* from measured data, treating *P* and *Q* data as separate frequency distributions. This method gives fewer variable estimates of *CN* for a wide range of sample sizes than do the methods of asymptotic and median-*CN* for *CN* estimation. It is advantageous in limited *P–Q* data situation, and does not require watershed response type to estimate *CN*, as needed in the asymptotic method. Mishra and Dwivedi (1998) presented an approach to determine the upper and lower bounds or enveloping *CNs*, which are useful in high and low flow studies, respectively. McCuen (2002) found the quantity (100-*CN*) to fit the gamma distribution, which he used for developing the confidence intervals for *CNs* ranging from 65 to 95, with parameter estimation by Method of Moments (MOM). Later, Bhunya et al. (2002) and Bhunya et al. (2003) provided a more reliable procedure for estimation of confidence interval by employing the Method of Maximum Likelihood (MOML), and Method of L-moment in addition to MOM as parameter estimation. These methods however require testing on a large dataset. The appropriate *CN* values for various soil and LULC conditions can be selected from standard tables, but it is preferable to estimate the *CN* value from measured rainfall-runoff data if available (Soulis and Valiantzas, 2012).

Alagha et al. (2016) argue that usually *CN* computes from the standard tables that follow United State land features classification which might not be applicable to the land features in Saudi Arabia. They were estimated *CN* values from the data of rainfall and runoff events (1984-1987) of some gauged watersheds in the western region of Saudi Arabia (Yiba watershed and its sub basins). The *CN* values were estimated in the range of 61 and 99 in their study. It follows the standard regime with an approached value of 52 and the factor of initial abstraction (λ=0.2). The study verified that some watershed morphometric characteristics give a strong relation with the average *CN* such as basin average elevation, shape factor, basin slope, basin length, and watershed area where, R^2 was 0.99, 0.81, 0.87, 0.78 and 0.56 respectively. This study suggested that the obtained relationships could be useful in determination of average *CN* for similar basins without relying on NRCS-CN tables.

2.3 Gaps and Shortcomings of Previous Approaches

The practical application of the SCS-CN model should be simple and direct. It relies on the determination of the *CN* which is widely documented in the literature for various land uses and soil types (NEH-4, 1964; Chow et al., 1988). However, in spite of its apparent simplicity, the application of the *CN* method leads to a diversity of interpretations and confusion due to ignorance about its limitations. The existing documentation of how *CN* was developed is severely limited (Hawkins, 1979; Boznay, 1989; Hjelmfelt, 1991; Pilgrim and Cordery, 1993). Difficulties in its application are mainly related to the classification of soils outside the USA into the four hydrological soil groups A, B, C and D, and the determination of the antecedent moisture condition (AMC), which is an index of basin wetness. The principal shortcomings of the previous approaches include the following:

1. Most approaches of *CN* estimation relied on standard tables of NEH-4 that follow land use and HSG of USA. These tables might not be applicable to the land features in India. Further, LULC may not be remained constant for a long period. Therefore, in the present study effect of dynamic change in major categories of LULC on *CN* is studied. HSG maps are developed for the selected watersheds of the study region based on the NBSS & LUP soil classification, formative elements of soil taxonomy, soil depth, infiltration rate, and soil characteristics. Composite CN_{II} value is then determined by integrating LULC and HSG Map.
2. The Asymptotic Fit Method (AFM) is based on ordered data and frequency matching approach, the effect of the cumulative data has been ignored in

Asymptotic *CN* approach. In this study, an attempt has been made to modify existing AFM by using cumulative data of different degree of day.

3. Limited attempts were made in previous research work to account for the morphometric parameters of watershed considered in *CN* determination. It has been noted that morphometric parameters have strong influence on runoff generation. Most approaches focus on the slope to adjust *CN*. Therefore, in the proposed methodology, morphometric parameters viz. Slope, Drainage Density and Stream Length are incorporated in *CN* calculation.
4. Few approaches focus on the Integrating *ET* loss in to *CN* determination for long-term hydrological simulation. Therefore, a need was felt to develop *CN* accounting procedure based on continuous losses like *ET* for long-term hydrological simulation.

Therefore, this study mainly focus to develop modified models by integrating the effect of cumulative rainfall-runoff ordered data, morphometric parameters of the watershed and evapotranspiration loss in *CN* determination procedure for the selected study region.

2.4 Closure

In this chapter, the review of past studies on *CN* estimation is presented. The different approaches for *CN* estimation are discussed along with their classification. Comprehensive review on current scenario of *CN* estimation is also presented, which is very useful to derive important inferences regarding the trend and potential of further research. Review of literatures shows that limited research works have been carried out on *CN* estimation by incorporating impact of cumulative rainfall-runoff data, morphometric parameters and evapotranspiration. Hence, there is a need to develop a new methodology involving these parameters in *CN* determination for better performance of the SCS-CN method. The next chapter provides description of the study region in detail.

CHAPTER 3

Study Region and Data Collection

3.1 General

This chapter concentrates on the description of the test watersheds selected in this study. Soil taxonomy is explored with its formative elements and elaborates different soil characteristics. The procedure of identifying soil type and its characteristics based on the interpretation of formative elements of the soil taxonomy is discussed. Data collection including topographic information, soil characteristic and land use pattern of the watersheds, and the hydro-meteorological data viz. rainfall, runoff, temperature, is also described in a separate section. Quality and adequacy of the hydro-meteorological data are examined for the model calibration and validation. Drainage maps, soil maps, LULC maps and HSG maps of the test watersheds of the study region are prepared and presented in this chapter.

3.2 The Study Region

The Middle South Saurashtra region of Gujarat state (India) is selected for the present study. Geographical area of the Middle South Saurashtra region covers Junagadh district (lies between 20^0 26' to 21^0 24' North latitudes and 69^0 24' to 71^0 03' East longitudes) and Amreli district (lies between 20^0 27' to 22^0 15' North latitudes and 70^0 18' to 71^0 45' East longitudes). Three major rivers viz. Ozat, Uben and Shetrunji are flowing in this region. The region features comprising a central undulating plain broken by hills and dissected by rivers. Altitude varies from 50 m in downstream areas to 1117 m at Guru Gorakshnath in the mountain Girnar. Three watersheds (Ozat, Uben and Shetrunji,) from the study region as shown in Fig. 3.1 are selected to evaluate the impact of modified SCS-CN method in runoff prediction. The soils of the region have developed from basaltic and Gaj bed milliolitic lime stone parent materials from hill slope to lower piedmont and alluvium in piedmont plain. The soils have clay loam to clayey texture, moderate to strong sub angular blocky structure and very dark grayish to brown colour.

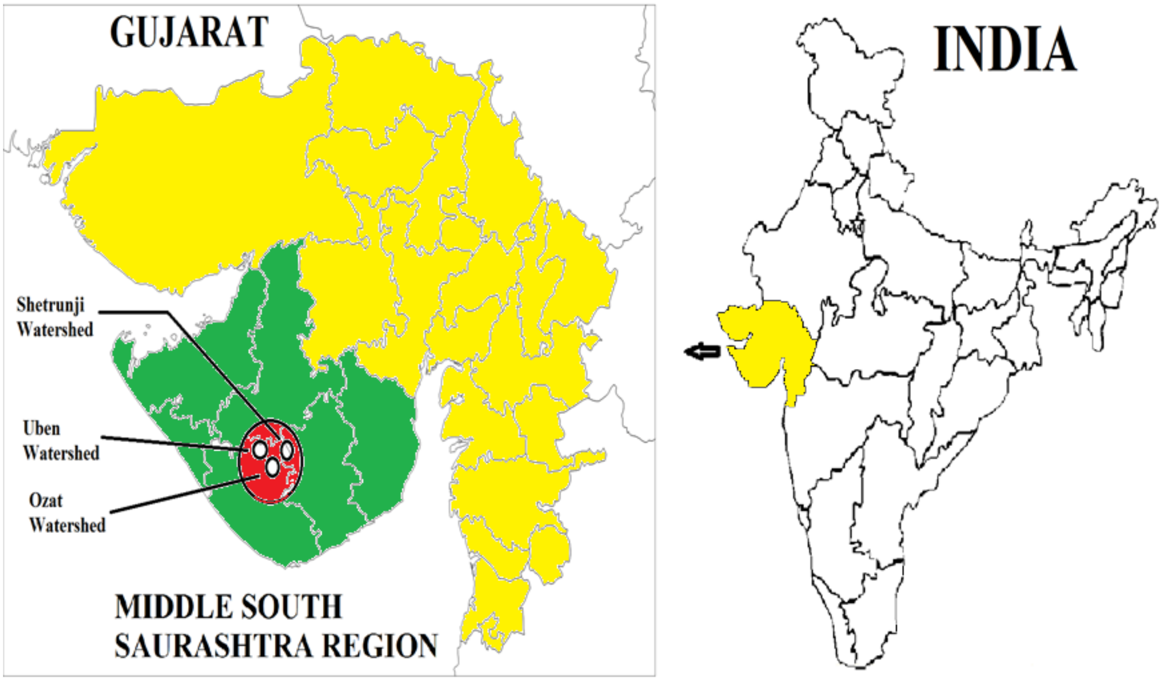


FIGURE 3.1 Index Map of the Middle South Saurashtra region of Gujarat State (India)

3.2.1 Drainage Pattern

Drainage pattern reflects physiographic condition and terrain characteristics of any region, being controlled by its physiography, climate and tectonic framework. The drainage pattern of Saurashtra peninsula is radial. The various rivers and streams flow in all directions from the central high ground. Most of the rivers and streams of the region have their origin within the territory and their watercourses are short, rain fed, and not perennial. Due to the short and rugged course and shallow beds, these rivers become dangerous in the heavy rainfall condition. Uben is tributary of Ozat River. Ozat and Shetrunji are draining into the Arabian Sea.

3.2.2 Geomorphology

Watershed geomorphology reflects the physical characteristics of the watershed. Certain physical properties of watershed significantly affect the runoff and thus they have great importance in hydrologic analyses. A first order stream is a stretch which receives flow directly from flow on the ground surface alone. Higher order streams form when two preceding order streams meet e.g. two second order streams combine to form a third order stream and so on.

Topographic data from Survey of India (SOI) toposheets of scale 1:50,000 41K (0-3-6-10-11-14-15 and 16) were obtained from Divisional Office Junagadh (Irrigation Department) Gujarat and used to identify the study region. Satellite Imageries: The Indian Remote Sensing satellite with Linear Imaging Self Scanning Sensors (IRS-LISS III) satellite data of scale 1:50000 were used to prepare LULC map of the study area. Satellite data were pre-processed in ERDAS (Earth Resources Data Analysis System) imagine for geo-referencing, mosaicking and sub setting of the imagines on the basis of area of interest. The physical and morphometric characteristics like LULC, Soil type, area of drainage basin, length of streams, slope, etc. were measured in GIS environment. The base maps of all three watersheds were digitized and analysed as per the laws of Horton (1945) and prepared by following stream ordering system of Strahler (1964). The seven major sub watersheds are identified and delineated for Ozat watersheds and six sub watersheds for Uben and Shetrunji watersheds based on the 3rd order stream. The important morphometric parameters of all the three watersheds were calculated using standard formulae and their values are presented in Appendix A-1. The drainage maps of Ozat, Uben and Shetrunji watersheds covering major sub watersheds are shown in Fig. 3.2-3.4 respectively.

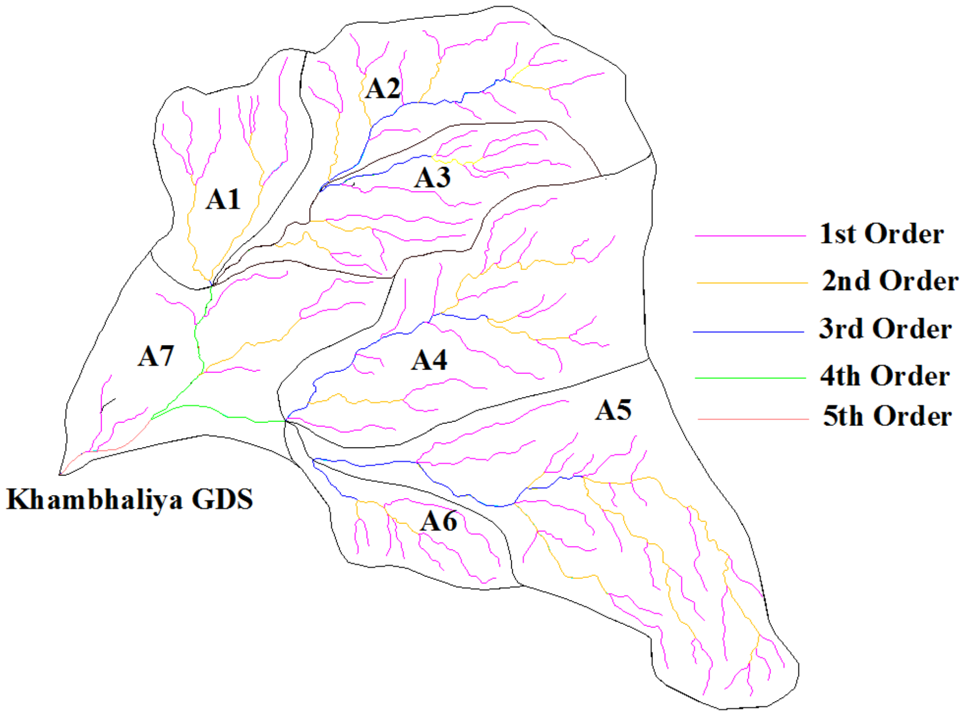


FIGURE 3.2 5th Order drainage map of Ozat watershed with seven sub watersheds

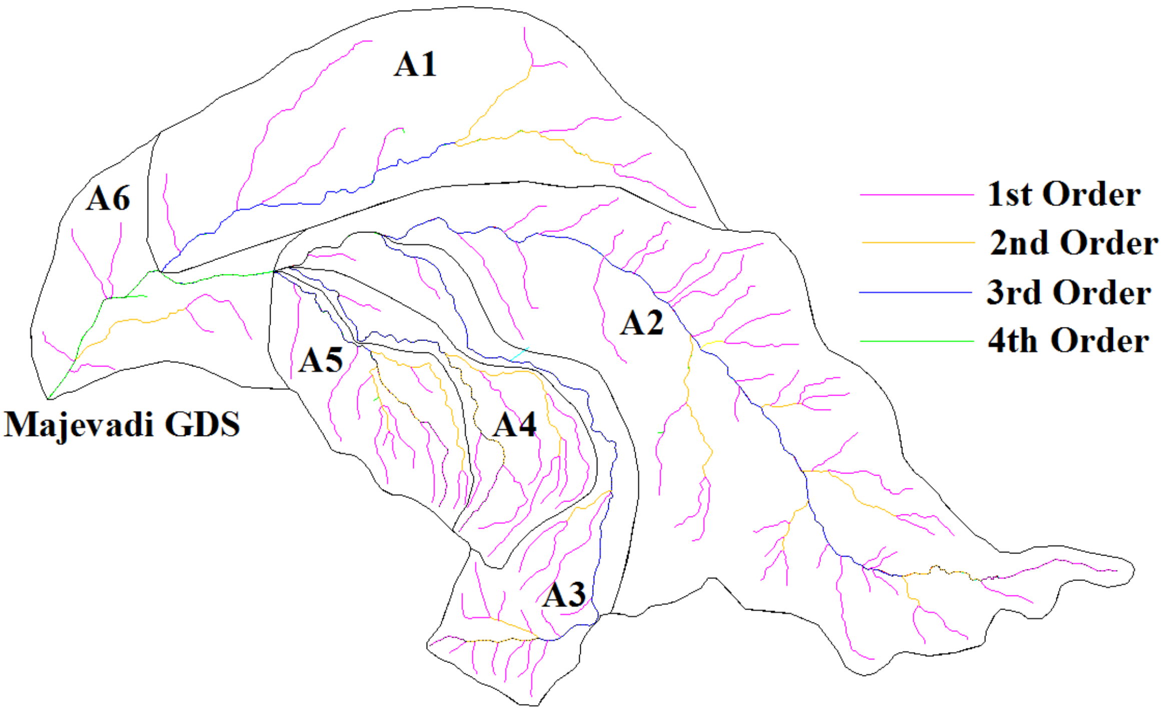


FIGURE 3.3 4th Order drainage map of Uben watershed with Six Sub watersheds

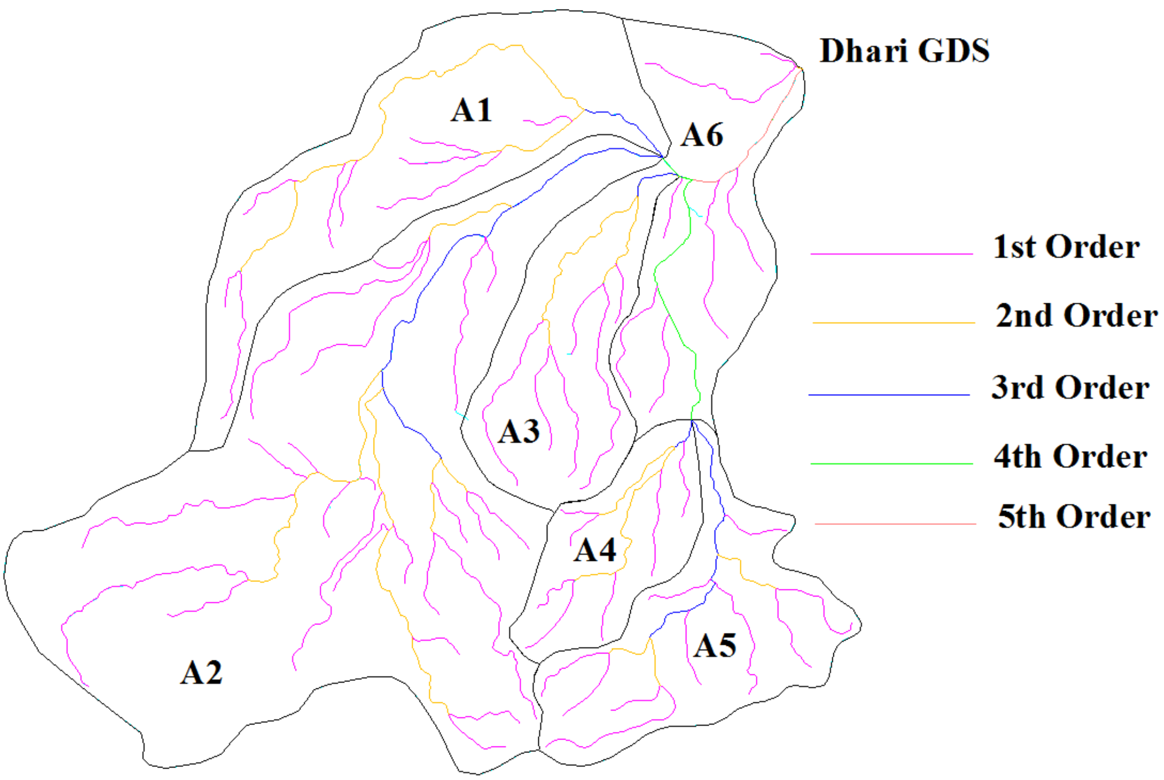


FIGURE 3.4 5th Order drainage map of Shetrunji watershed with Six Sub watersheds

3.2.3 Soil

The main problem faced in conventional soil survey and soil cartography is the accurate delineation of boundary and tedious, laborious and time consuming field observations. In such situation the RS data in conjunction with ancillary data and GIS provide the best alternative (Karale, 1992; Sehgal, 1995). RS techniques and GIS have significantly reduced field work and more precisely delineated soil boundaries than conventional methods. The soils of the Middle South Saurashtra region are unique in origin having diverse genesis, physiography, climate, vegetation, depth, colour and age. Soils as the geographical formation of the region is of volcanic origin, the soils are generally derived from basaltic rock known as Deccan trap. Most of soils in the region are having shallow (25 to 50 cm) to moderately shallow (50 to 75 cm) depth soils. Soil texture acts as a guide to many soil characteristics directly or indirectly related to plant growth. Three textural groups used are clayey (fine), Loamy (medium) and sandy (coarse). The majority of soils in the region have clayey (fine) and loamy (medium) texture. Some scattered parts have somewhat excessive drainage. Mean unsaturated hydraulic conductivity of the soil of study region is 10087.89 x 10^{-3} cm/h at 10 KP_a, 1846.19 x 10^{-3} cm/h at 30 KP_a and 2.73 x 10^{-3} cm/h at 1500 KP_a (Zalawadiya et al., 1999). Most of the soils are well drained in the region.

SOIL TAXONOMY: Soil taxonomy is developed by United States Department of Agriculture (USDA) to elaborate soil types based on its key properties. It is a basic system for making and interpreting soil surveys. It is widely used system for classifying soils. The soil classification is adopted based on the established standards of United States Department of Agriculture (USDA) to elaborate soil types by its key properties. The prime objective of soil taxonomy is to develop a hierarchical classification that reflects the relationships between different soils, and between soils and the factors responsible for their character. Soil survey provides an accurate and scientific inventory of different soils, their kind and nature, and extent of distribution so that one can make prediction about their characters and potentialities. It also provides adequate information in terms of land form, terraces, vegetation as well as characteristics of soils (viz. texture, depth, structure, stoniness, drainage, acidity, salinity and so on) which can be utilized for the planning and development of the watershed. According to Krasilnikov et al. (2009), many countries have developed soil classification systems for national use, but Soil Taxonomy (Soil Survey Staff, 1999) is used worldwide. The International Union of Soil Sciences (IUSS) officially endorsed “Soil Taxonomy” as an IUSS-approved system of soil classification. There are six categories in soil taxonomy. In order of decreasing rank and increasing number of differentiae and classes, the categories are order, sub order, great group, sub group, family, and series. The soil categories and its characteristics are presented in Appendix A-2.

INTERPRETATION OF FORMATIVE ELEMENTS OF SOIL TAXONOMY:

Soil Order: Soil orders indicate very broad and most general properties of soil. They are differentiated by the presence or absence of diagnostic horizons or features that reflect soil forming processes. There are 12 recognized soil orders in the world. The three soil orders, Entisols, Inceptisols, and Vertisols, are mapped in the study region. Brief description of the soil orders is given below:

1. Alfisols are naturally fertile soils with high base saturation and a clay enriched subsoil horizon.
2. Andisols are relatively young soils, mostly of volcanic origin, that are characterized by unique minerals with poorly organized crystalline structure.
3. Aridisols are the dry soils of deserts.
4. Entisols are young soils with little or no profile development.
5. Gelisols are very cold soils with permafrost in the subsoil.
6. Histosols are soils that formed in decaying organic material.
7. Inceptisols are youthful soils with a weak, but noticeable, degree of profile development.
8. Mollisols are very dark-colored, naturally very fertile soils of grasslands.
9. Oxisols are highly weathered tropical soils with low natural fertility.
10. Spodosols are acid soils with low fertility and accumulations of organic matter and iron and aluminium oxides in the subsoil.
11. Ultisols are soils with low base status and clay-enriched subsoil.
12. Vertisols are very clayey soils that shrink and crack when dry and expand when wet.

According to soil taxonomy, the Middle South Saurashtra region is characterized by mainly three types of soil, i.e., Entisols, Inceptisols and Vertisols Appendix A-3.

Entisols are immature soils with little evidence of soil formation and indicated by “ent”. These soils are light grey, greyish brown and reddish brown in colour and have formed under tropical semi-arid climate. They are often associated with recently deposited sediments and the depth ranges from a few cm to 1 m. By texture, they are sandy-clay, loam or clay-loam to clay. Structurally these soils are weak, mainly sub-angular, blocky and sometimes crumb-like, calcareous and alkaline in nature.

Inceptisols are designated by “ept”. They are young soils with weakly developed subsurface horizons but more developed than Entisols. These soils are occurred on steeply sloping land and are dark to light grey, reddish brown, yellowish red and dark reddish brown in colour, produced through weathering under tropical semi-arid to humid climates, calcareous in nature. They may be shallow to bedrock and vary in depth from 30-80 cm. These soils are texturally silty-loam to clay and neutral to alkaline in reaction.

Vertisols are fairly deep, heavy clay soils, and have no definite structure. Because of the montmonllonitic nature of the clay minerals they shrink and crack when dry and expand when moist. Large and deep cracks which close only after prolonged wetting are developed due to substantial shrinkage and swelling of these soils. The soils are saline and texturally sandy loam with silty clay loam. All Vertisols are dominated by clay minerals (smectites) that dramatically shrink when dry and swell when moistened. These soils tend to be very sticky and plastic when wet and very firm and hard when dry. They are commonly very dark in colour due to the deep mixing resulting from the shrink-swell cycles which churn the soil. Vertisol are indicated by “ert” and characterized by low non-capillary pore space which prevents drainage of excess water. The black cotton soil is an example of a Vertisols.

Soil Sub Order: Soil order further defines based on characteristics related to soil moisture, soil temperature and dominant chemical or textural features. Currently, sixty-four sub orders are recognized. Orthents (clay or loam), Ochrepts (mainly light coloured, brownish, more or less freely drained soils), and Usterts (ustic moisture regime - moisture is limited, but available, during portions of the growing season) sub orders are found in the selected study region.

Great Groups: There are more than 300 great groups. The great group level reflects a combination of important properties, including the presence of various diagnostic horizons, the presence of cemented layers, electrical conductivity and pH, significant carbon accumulation in the upper part of the soil, and patterns of soil saturation. The moisture and temperature regimes are causes of properties, and they also are properties of the whole soil rather than of specific horizons. Great groups represent soil temperature and soil moisture regime of particular sub order.

Sub Groups: There are more than 2,400 sub groups. Sub groups make addition to the properties of the great group. The name of a sub group comprises of the name of great group modified by adjectives. There are three kinds of sub groups.

Typic sub groups - Typic sub groups simply represent the soils that do not have the characteristics defined for the other sub groups.

Inter grades (or transitional forms to other orders, sub orders, or great groups) - To have intermediary properties between those of two or three great groups. The properties used to define the intergrades may be: Sub group belongs to one great group but that have some properties of another order, sub order, great group or other kind of soil.

Extra grades - these sub groups have some properties that are not representative of the great group but that do not indicate transitions to any other known kind of soil.

Families: In this category, the intent has been to group the soils within a sub group having similar physical and chemical properties that affect their responses to management and manipulation for use. In some cases soil properties are used in this category without regard to their significance as indicators of soil forming processes.

Series: The series is the lowest category in this system. More than 19,000 series have been recognized in the United States. The primary use of soil series in the classification system is to relate the map units represented on detailed soil maps to the taxa and to the interpretations that may follow. The function of the series is pragmatic, and differences within a family that affect the use of a soil should be considered in classifying soil series. The separation of soils at the series level of this taxonomy can be based on any property that is used as criteria at higher levels in the system.

The soil maps of Ozat, Uben and Shetrunji watersheds are prepared by using the soil map of NBSS & LUP and the satellite imageries in GIS environment at Bhaskaracharya Institute for Space Application and Geo-informatics (BISAG), Gandhinagar (Gujarat-India). The spatial distribution of soil texture in Ozat, Uben and Shetrunji watershed are shown in Fig. 3.5-3.7 respectively. The classification of the soils of Ozat, Uben and

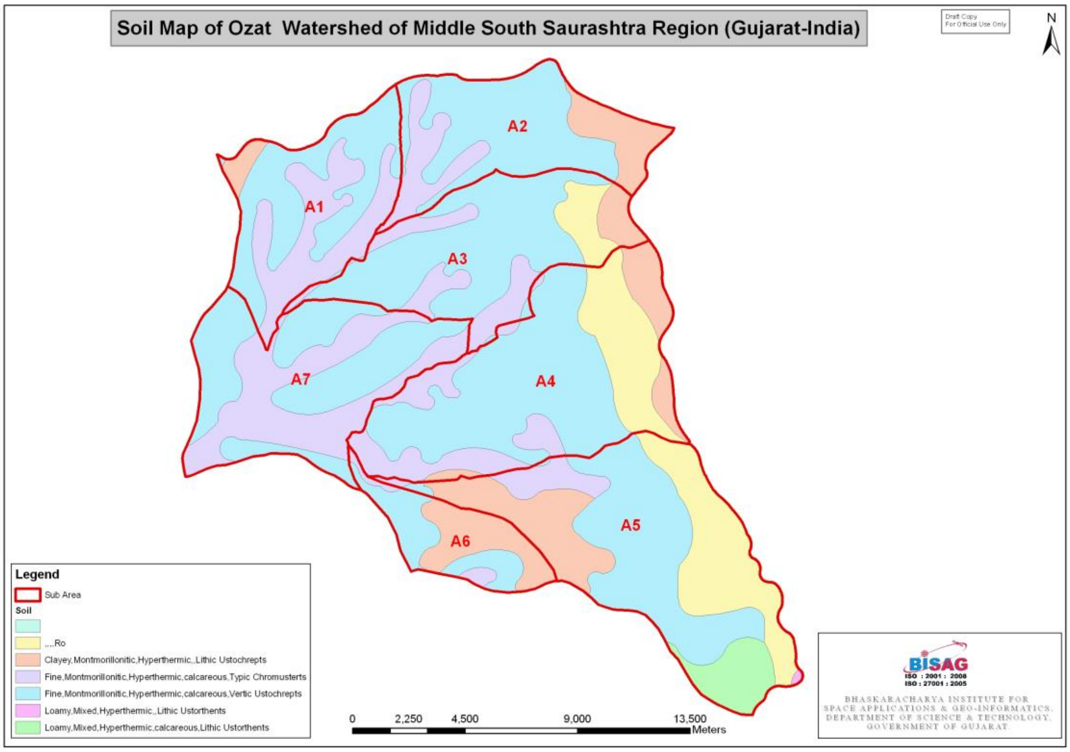


FIGURE 3.5 Soil map of Ozat watershed

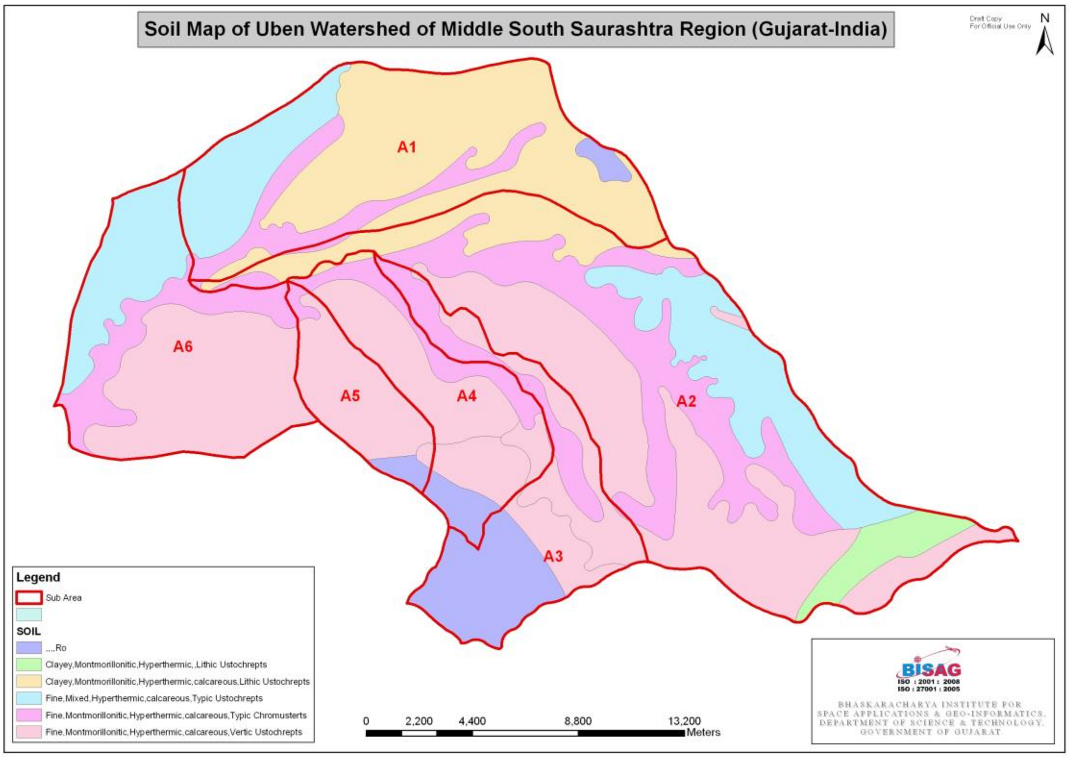


FIGURE 3.6 Soil map of Uben watershed

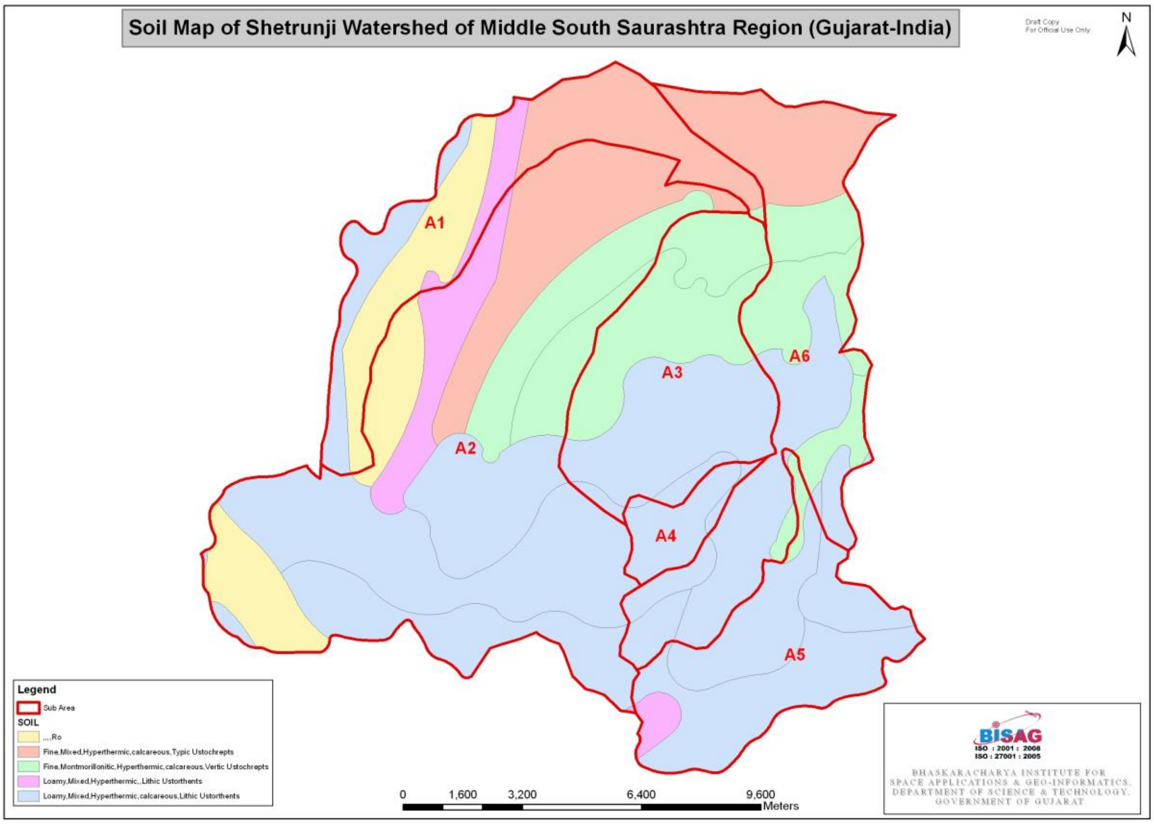


FIGURE 3.7 Soil map of Shetrunji watershed

TABLE 3.1 Soils of the Ozat, Uben and Shetrunji watersheds based on soil taxonomy

Watershed	Soil Order	Sub Order	Great Group	Sub Group
Ozat	Entisols	Orthents	Ustorthents	Lithic Ustorthents
	Inceptisols	Chrepts	Ustochrepts	Lithic Ustochrepts
	Inceptisols	Ochrepts	Ustochrepts	Vertic Ustochrepts
	Vertisols	Usterts	Chromusterts	Typic Chromusterts
Uben	Inceptisols	Ochrepts	Ustochrepts	Lithic Ustochrepts
	Inceptisols	Ochrepts	Ustochrepts	Typic Ustochrepts
	Inceptisols	Ochrepts	Ustochrepts	Vertic Ustochrepts
	Vertisols	Usterts	Chromusterts	Typic Chromusterts
Shetrunji	Entisols	Orthents	Ustorthents	Lithic Ustorthents
	Inceptisols	Ochrepts	Ustochrepts	Typic Ustochrepts
	Inceptisols	Ochrepts	Ustochrepts	Vertic Ustochrepts

Shetrunji watersheds based on soil taxonomy are presented in Table 3.1. Soil information of the study area obtained is used for making appropriate HSG and Soil Map.Interpretation of the soils of the Ozat, Uben and Shetrunji watersheds at sub group level are presented in Tables 3.2-3.6.

A group of soils belonging to other soil orders possesses the many but not all characteristics of Vertisols are named by using adjective "Vertic" as a modifier of the great group name. Soils lie outside the range of Typic sub groups in an opposite direction, truncated by hard rock and are shallow or are intermittent between rocks outcrops are, in effect, inter grades to not-soil are named "Lithic" sub groups.

TABLE 3.2 Interpretation of Soil sub group Lithic Ustorthents

No	Soil Category	Category Name	Characteristics
4	Sub group	Lithic Ustorthents	Presence of a shallow Lithic contact within 50 cm of the soil surface
3	Great group	Ustorthents	Ustic soil moisture regime. Moisture is limited, but available, during portions of the growing season
2	Sub order	Orthents	Clay or loam
1	Order	(Ent)isol	Young soils with little or no profile development

TABLE 3.3 Interpretation of Soil sub group Lithic Ustochrepts

No	Soil Category	Category Name	Characteristics
4	Sub group	Lithic Ustochrept	Identified at the boundary between soil and continuous soft bedrock
3	Great group	Ustochrepts	Redish or brownish ochrepts of semi-arid region- Considered as Alluvial Soils
2	Sub order	Ochrepts	Mainly light coloured, brownish, more or less freely drained Inceptisols
1	Order	Inc(ept)isols	Youthful soils with a weak, but noticeable, degree of profile development.

TABLE 3.4 Interpretation of Soil sub group Typic Ustochrepts			
No	**Soil Category**	**Category Name**	**Characteristics**
4	Sub group	Typic Ustochrept	Fixed on thick soils that have shallow horizon in which carbonates have accumulated. The soils are dry for extended periods in most years
3	Great group	Ustochrepts	Redish or brownish ochrepts of semi-arid region- Considered as Alluvial Soils
2	Sub order	Ochrepts	Mainly light coloured, brownish, more or less freely drained Inceptisols
1	Order	Inc(ept)isols	Youthful soils with a weak, but noticeable, degree of profile development.

TABLE 3.5 Interpretation of Soil sub group Vertic Ustochrepts			
No	**Soil Category**	**Category Name**	**Characteristics**
4	Sub group	Vertic Ustochrept	These soils are clayey and have deep wide cracks at some season in most years
3	Great group	Ustochrepts	Redish or brownish ochrepts of semi-arid region- Considered as Alluvial Soils
2	Sub order	Ochrepts	Mainly light coloured, brownish, more or less freely drained Inceptisols
1	Order	Inc(ept)isols	Youthful soils with a weak, but noticeable, degree of profile development.

TABLE 3.6 Interpretation of Soil sub group Typic Chromusterts (Chromic Dystrusterts)			
No	**Soil Category**	**Category Name**	**Characteristics**
4	Sub group	Typic Chromusterts (Chromic Dystrusterts)	Fixed on soils that are mostly on slopes on which water never stands
3	Great group	Chromusterts (Dystrusterts)	Vertisol that occurs in places with a pronounced dry season – readily recognized by their dark colors.
2	Sub order	Usterts	Ustic moisture regime
1	Order	V(ert)isols	Fertile soils - very clayey soils that shrink and crack when dry and expand when wet. Well-developed soils

3.2.4 Land Use and Land Cover

LULC information is very important in the estimation for runoff as well as the soil loss. The LULC maps were prepared by visual interpretation of satellite imageries IRS LISS data in GIS environment. These maps can also be prepared by scanning and delineating the topographic and NBSS & LUP maps with the help of AUTO CAD 2010 when the satellite images are not available. The total geographical region is divided in to six major LULC classes viz. Agriculture, Built-up, Forest, Others, Wastelands and Water Bodies. SCS runoff *CN* for different LULC and HSGs under AMC II condition for the study region is given in Table 3.7.

TABLE 3.7 Values of *CN* for different LULC and HSGs in the study region

Major Land Cover/Use Classes	Hydrologic Soil Groups			
	A	**B**	**C**	**D**
Agriculture	74	80	82	74
Built-up	69	79	84	69
Forest	40	58	61	40
Others	55	69	73	55
Wastelands	80	85	88	80
Water Bodies	74	80	82	74

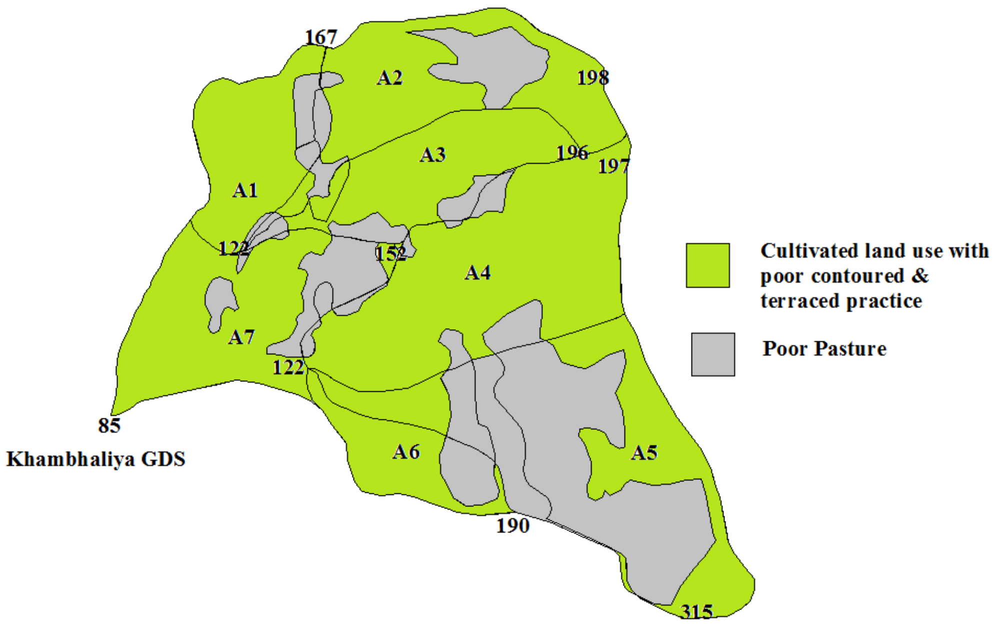


FIGURE 3.8 LULC map of Ozat watershed for the year 1994-95

To detect the change in major categories of LULC occurred in the study region, the LULC maps of Ozat and Shetrunji for the year 1994-1995, 2005-2006 and 2009-2010 and LULC maps of Uben watershed for the year 2001-2002, 2005-2006 and 2009-2010 are prepared and presented in Fig. 3.8-3.16.

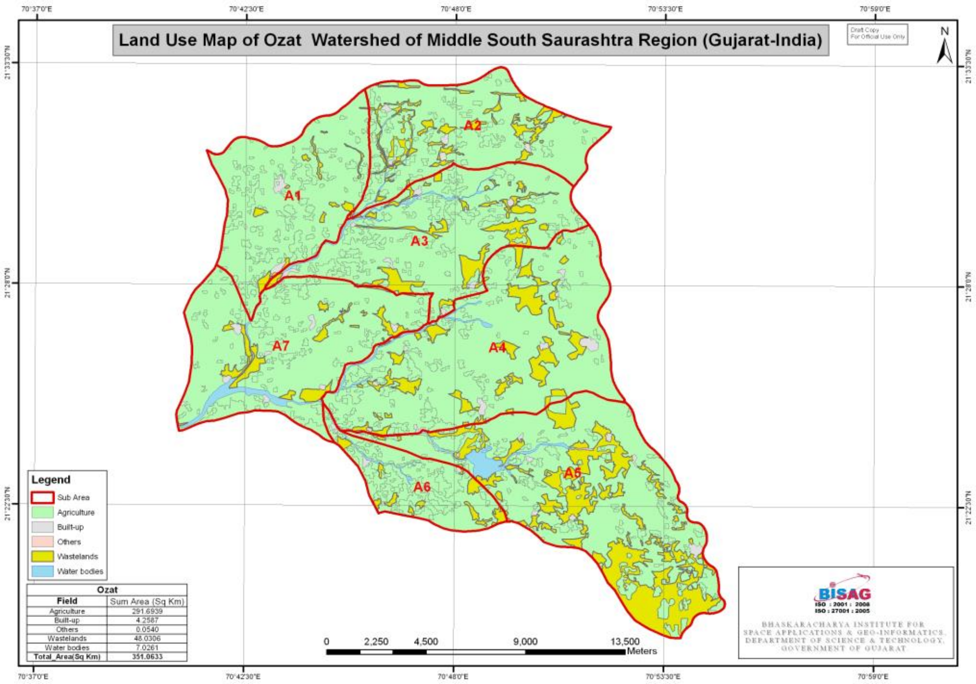


FIGURE 3.9 LULC map of Ozat watershed for the year 2005-06

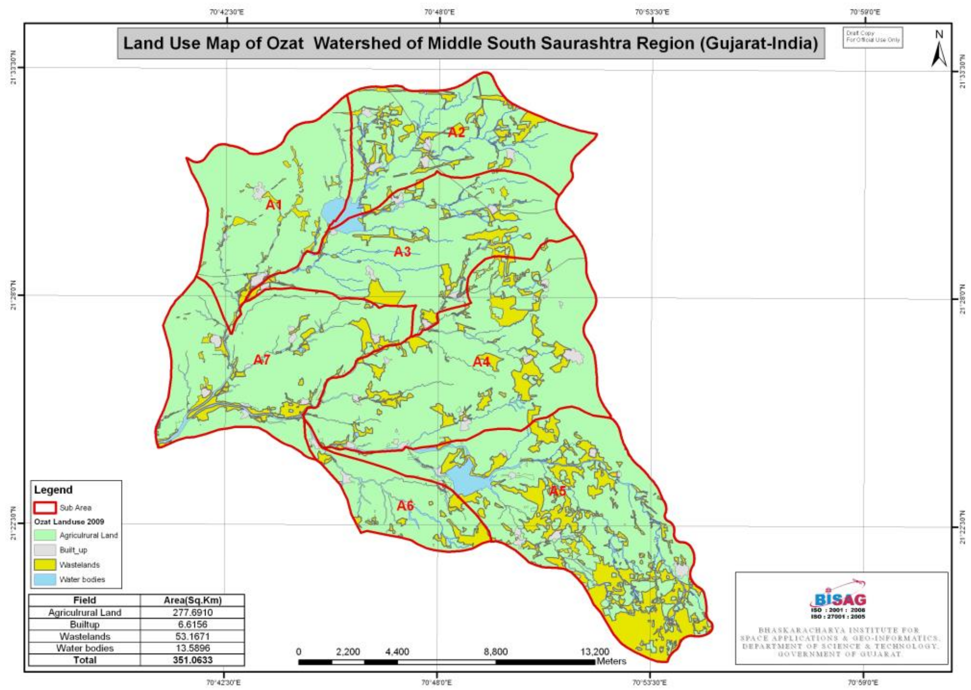


FIGURE 3.10 LULC Map of Ozat Watershed for the year 2009-10

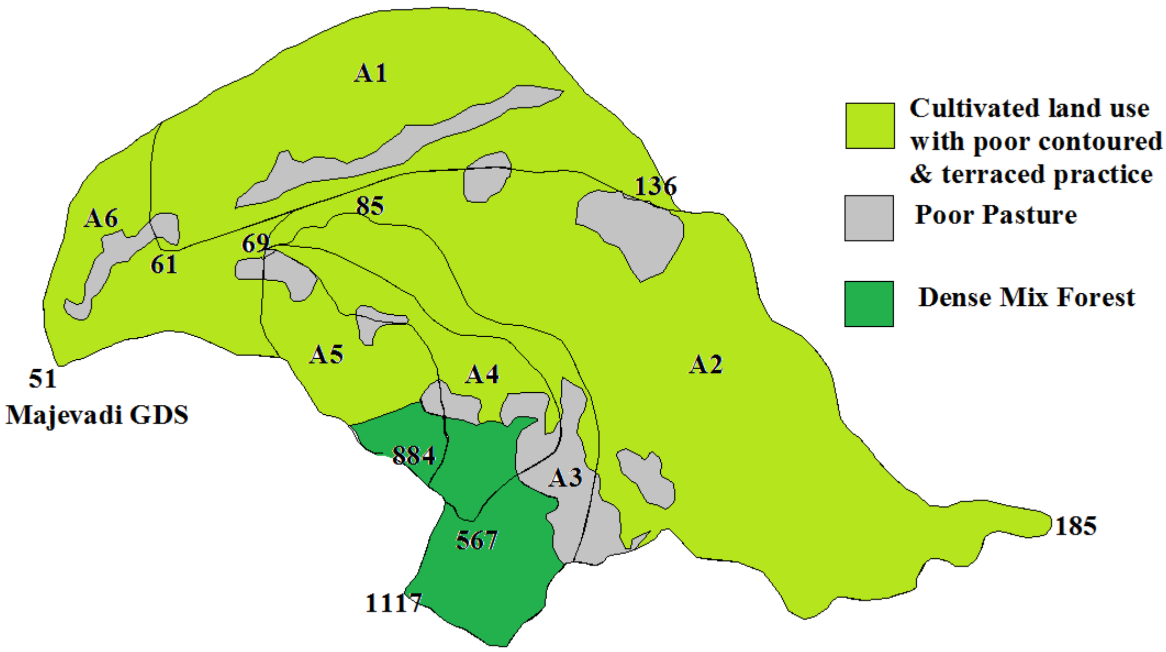


FIGURE 3.11 LULC map of Uben watershed for the year 2001-02

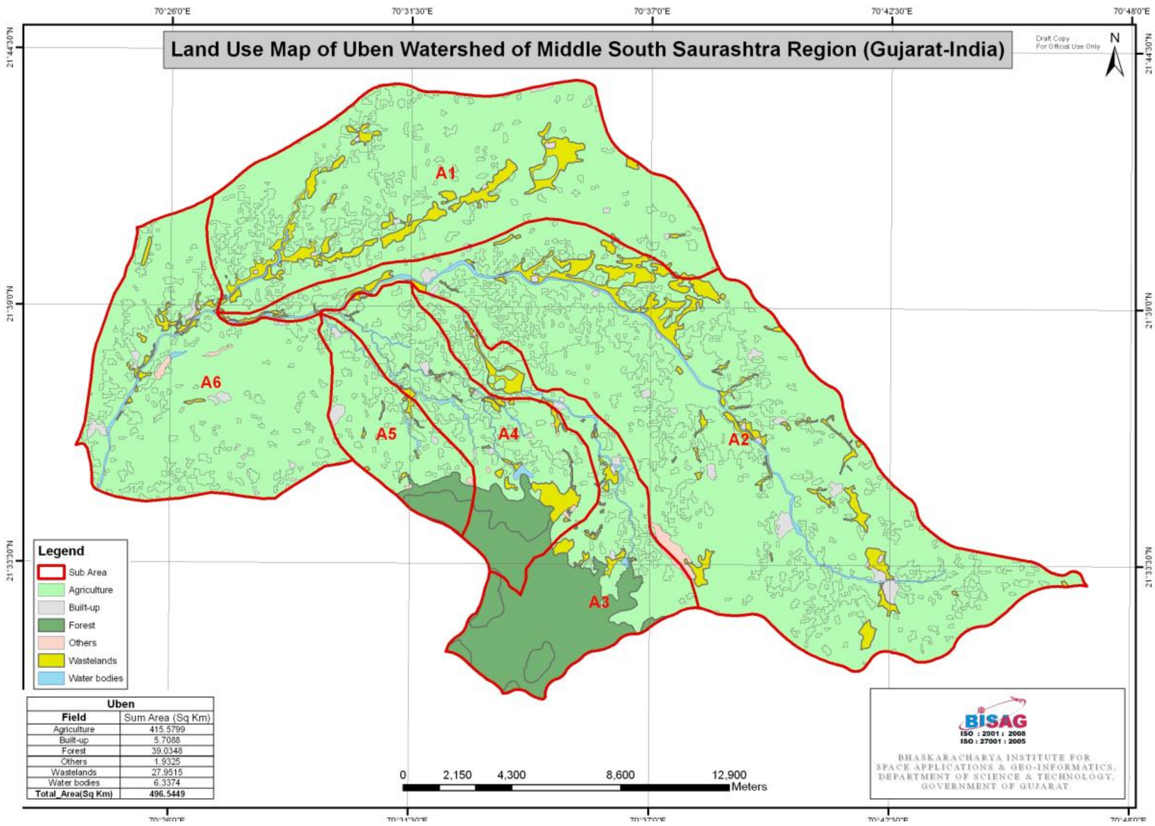


FIGURE 3.12 LULC map of Uben watershed for the year 2005-06

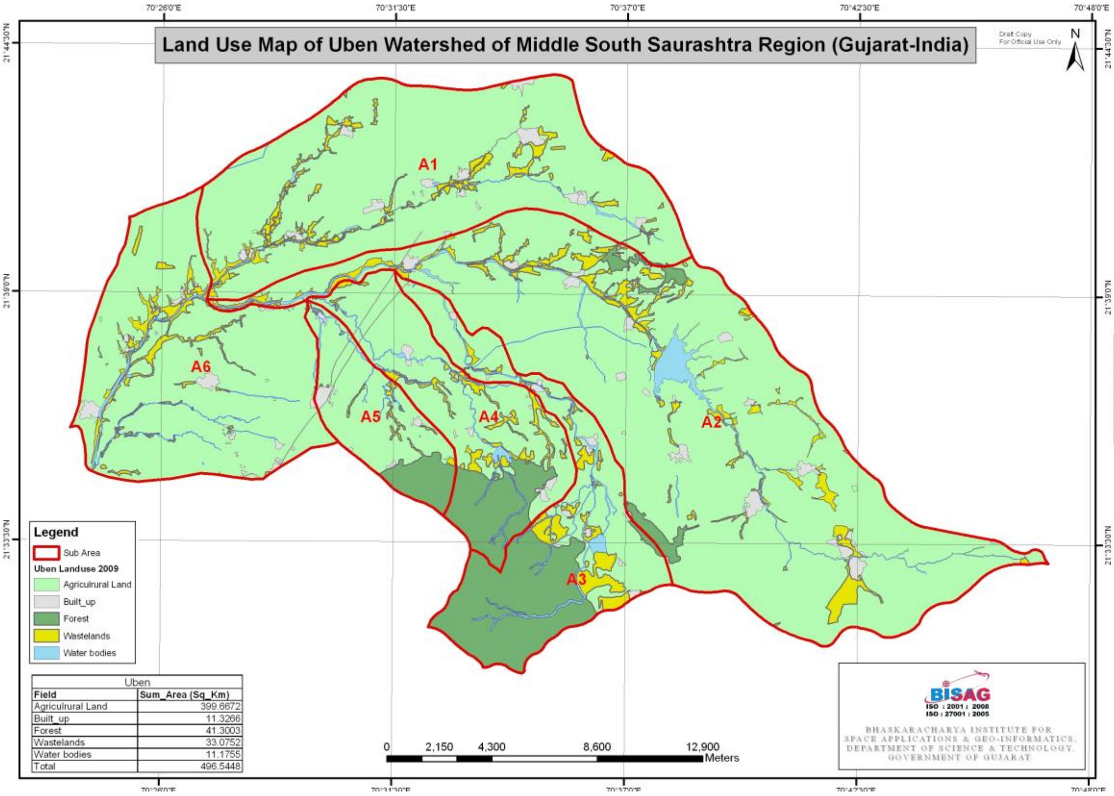


FIGURE 3.13 LULC map of Uben watershed for the year 2009-10

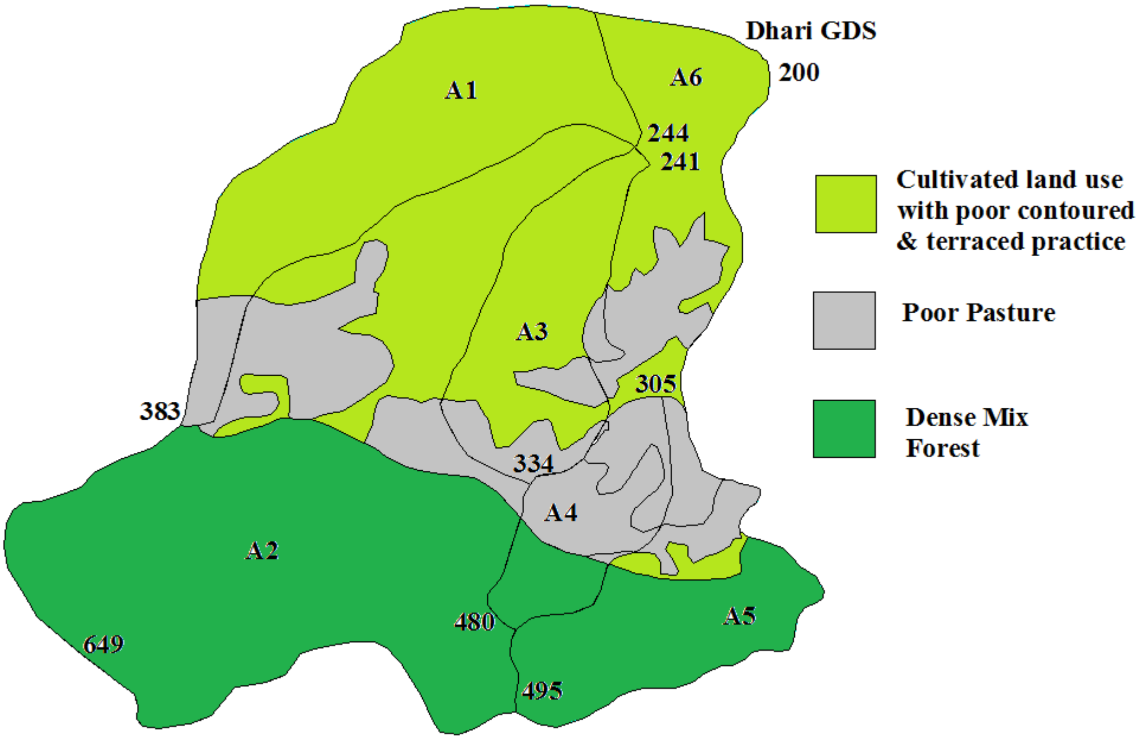


FIGURE 3.14 LULC map of Shetrunji watershed for the year 1994-95

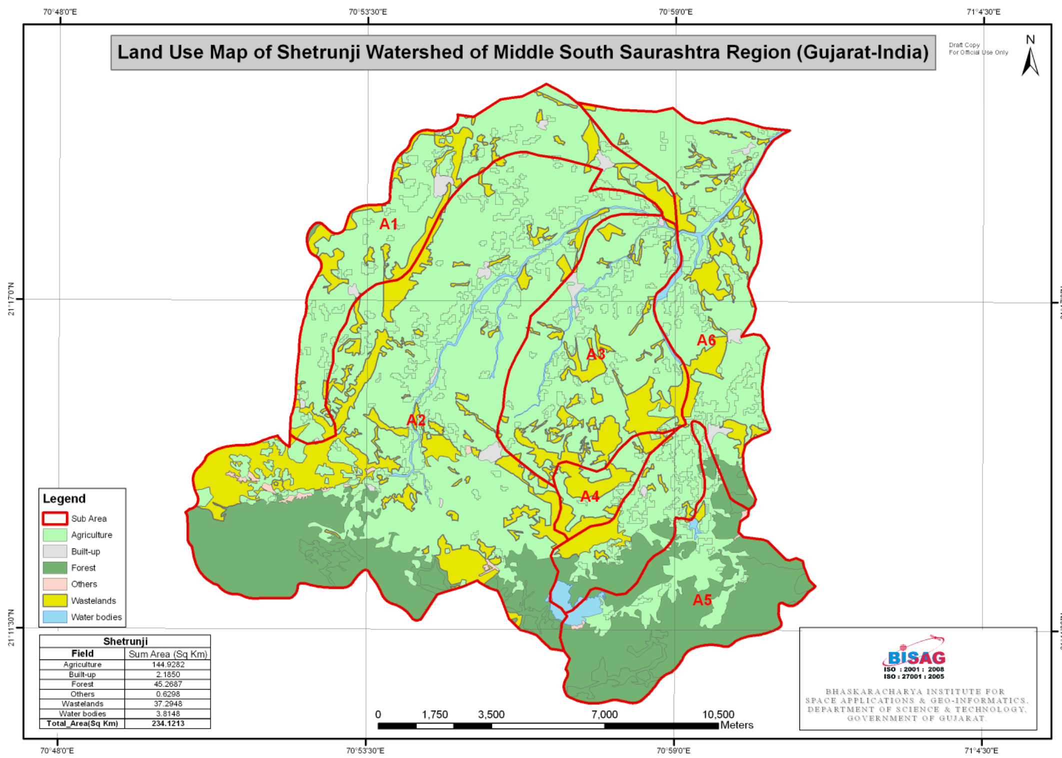


FIGURE 3.15 LULC map of Shetrunji watershed for the year 2005-06

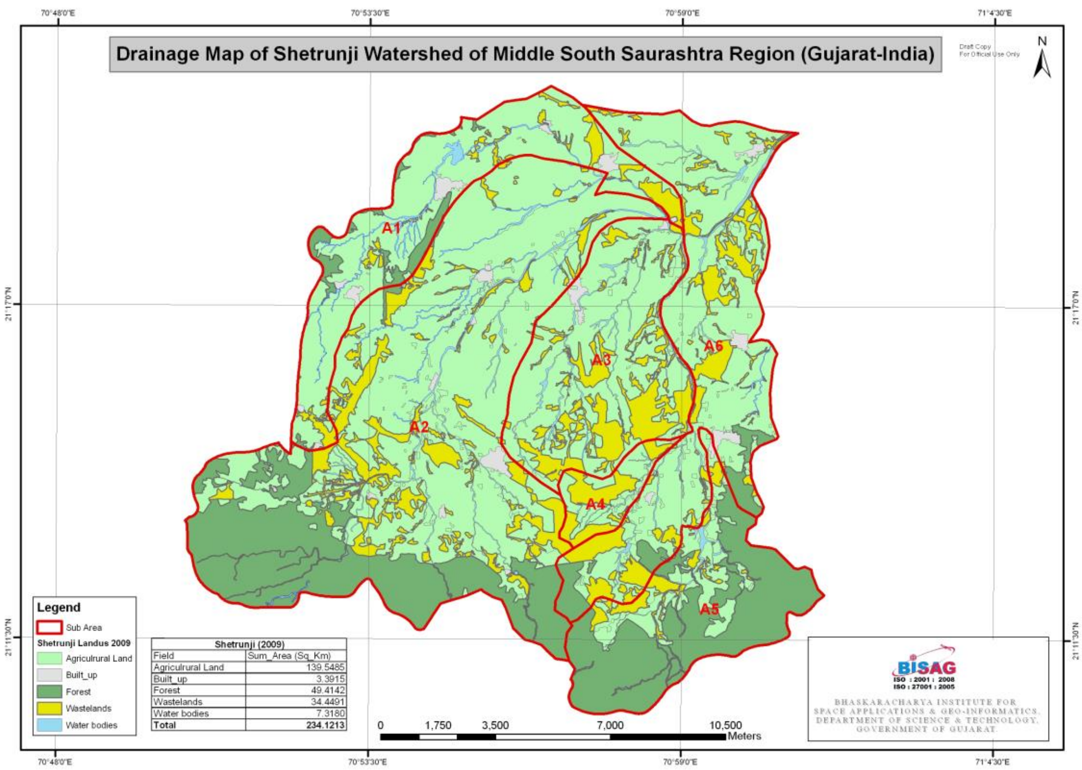


FIGURE 3.16 LULC map of Shetrunji watershed for the year 2009-10

Among the total geographical area of the region about 72% of the land area is covered by the agricultural land. The second largest area, the waste land, is covered 14% of the land area. About 12% of the land is covered by the forest.

3.2.5 Hydrologic Soil Groups (HSGs) of the Study Region

HSGs reflect the minimum rate of infiltration and the transmission rate obtained for bare soil after prolonged wetting. The infiltration rate is controlled by surface conditions and the transmission rate is controlled by the soil profile. The four HSG's A, B, C, and D, along with LULC, hydrologic conditions and management practices, are important elements used in determining runoff *CN*. The four HSGs are described as:

GROUP A: These soils have more than 90% sand or gravel, and hence, water is transmitted freely through the soil. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission (greater than 0.76 cm/hr). Soils of this group have low runoff potential and high infiltration rates when thoroughly wet.

GROUP B: Soils have moderate infiltration rate and moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded. These soils typically have between 10% and 20% clay and 50% to 90% sand and have loamy sand or sandy loam textures. These soils consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.38-0.76 cm/hr).

GROUP C: Soils in this group have moderately high runoff potential and low infiltration rates when thoroughly wet. These soils with moderately fine to fine texture which impede downward movement of water. These soils have between 20% and 40% clay and less than 50% sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. Therefore, water transmission through the soil is somewhat restricted. These soils have a low rate of water transmission (0.13-0.38 cm/hr).

GROUP D: These soils have a very slow infiltration rate and high runoff potential when thoroughly wet. Group D soils typically have greater than 40% clay, less than 50% sand, and have clayey textures; therefore, water movement through the soil is restricted or very restricted. They have a high swelling potential with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0.0-0.13 cm/hr).

The saturated hydraulic conductivity data and water table depth information should be used to place the soil into the appropriate hydrologic soil group. If these data are not available, the HSGs are determined by perceiving the properties of the soil such as texture, depth, infiltration rate. Thomas et al. (2004) provided the guideline basic infiltration rate for various soil types as presented in Table 3.8. Infiltration rate are categorized according to Thomas et al. (2004) in the study region. HSG 'D' has high runoff potential and very slow infiltration rate, therefore, the soil having extremely slow to very slow infiltration rate (IR) should be interpreted as a HSG 'D' soil. HSG 'C' assign to the soils having moderately slow IR while HSG 'B' assign to the soils having moderately rapid IR. HSG 'A' has low runoff potential and very high infiltration rate, therefore, the soil having very rapid infiltration rate (IR) should be interpreted as a HSG 'A' soil.

TABLE 3.8 Guideline basic infiltration rate for various soil types (Thomas et al., 2004)

Soil Type	Basic Infiltration Rate mm/hr	Infiltration Class
Sand	>30	Very Rapid
Sandy Loam	20 to 30	Moderately Rapid To Rapid
Loam to Silt Loam	10 to 20	Moderately Slow to Moderately Rapid
Clay Loam	3 to 10	Slow to Moderately Slow
Clay	1 to 5	Very Slow to Slow

HSGs are assigned to the soils based on soil orders; NBSS & LUP report, soil depth, soil characteristics of the watershed, and infiltration rate (IR) in this study. Table 3.9, Table 3.11, and Table 3.12 show the assigned HSGs for Ozat, Uben and Shetrunji watersheds respectively.

In this study, soil great group Ustorthents, Ustochrepts, and Chromusterts are grouped in category A, B, and C respectively. The study reveals that HSGs are explicitly assigned by soil orders as presented in Table 3.12. HSG 'B' assigned to Entisols, HSG 'C' assigned to Inceptisols and HSG 'D' assigned to Vertisols and land without soils.

TABLE 3.9 HSGs for Ozat watershed					
USDA Soil Order	**NBSS & LUP Class**	**Depth**	**IR (cm/hr)**	**Soil Characteristics**	**HSG**
Land without Soil	Rock Outcrops (Rocky Land)	-	Extremely Slow (< 0.10)	Naked Land without Soil	**D**
Inceptisols	Clayey, Montmorillonitic, Hyperthermic, Para Lithic Ustochrepts	Moderately shallow	Moderately Slow (0.50-1.0)	Moderately drained, clayey soils on very gently sloping with moderate erosion	**C**
Vertisols	Fine, Montmorillonitic, Hyperthermic, Calcareous, Typic Chromusterts	Deep	Very Slow (0.10-0.5)	calcareous, Poorly drained, fine soils on very gently sloping piedmont plain with slight erosion	**D**
Inceptisols	Fine, Montmorillonitic, Hyperthermic, Calcareous, Vertic Ustochrepts	Moderately shallow	Moderately Slow (0.50-1.0)	calcareous, Moderately drained, fine soils with moderate erosion	**C**
Entisols	Loamy, Mixed, Hyperthermic, Lithic Ustorthents	Shallow	Moderately Rapid (2.0-3.0)	well drained, loamy soils with moderate erosion	**B**
Entisols	Loamy, Mixed, Hyperthermic, Calcareous, Lithic Ustorthents	Shallow	Moderately Rapid (2.0-3.0)	calcareous, well drained, loamy soils with moderate erosion	**B**

TABLE 3.10 HSGs for Uben watershed					
USDA Soil Order	**NBSS & LUP Class**	**Depth**	**IR (cm/hr)**	**Soil Characteristics**	**HSG**
Land without Soil	Rock Outcrops (Rocky Land)	-	Extremely Slow (< 0.10)	Naked Land without Soil	**D**
Inceptisols	Clayey, Montmorillonitic, Hyperthermic, Para Lithic Ustochrepts	Moderately shallow	Moderately Slow (0.5-1.0)	Moderately drained, clayey soils on very gently sloping with moderate erosion	**C**
Inceptisols	Clayey, Montmorillonitic, Hyperthermic, Calcareous, Para Lithic Ustochrepts	Moderately shallow	Moderately Slow (0.50-1.0)	Moderately drained, calcareous, clayey soils on very gently sloping with moderate erosion	**C**
Inceptisols	Fine, Mixed, Hyperthermic, Calcareous, Typic Ustochrepts	Moderately deep	Moderately Slow (0.50-1.0)	Calcareous, Moderately drained, fine soils on gently sloping with moderate erosion	**C**
Vertisols	Fine, Montmorillonitic, Hyperthermic, Calcareous, Typic Chromusterts	Deep	Very Slow (0.10-0.50)	Calcareous, Poorly drained, fine soils on very gently sloping piedmont plain with slight erosion	**D**
Inceptisols	Fine, Montmorillonitic, Hyperthermic, Calcareous, Vertic Ustochrepts	Moderately shallow	Moderately Slow (0.50-1.0)	Calcareous, Moderately drained, fine soils with moderate erosion	**C**

TABLE 3.11 HSGs for Shetrunji watershed					
USDA Soil Order	**NBSS & LUP Class**	**Depth**	**IR (cm/hr)**	**Soil Characteristics**	**HSG**
Land without Soil	Rock Outcrops (Rocky Land)	-	Extremely Slow (< 0.10)	Naked Land without Soil	**D**
Inceptisols	Fine, Mixed, Hyperthermic, Calcareous, Typic Ustochrepts	Moderately Deep	Moderately Slow (0.50-1.0)	Moderately drained, calcareous, fine soils on very gently sloping piedmont with slight erosion	**C**
Inceptisols	Fine, Montmorillonitic, Hyperthermic, Calcareous, Vertic Ustochrepts	Moderately Shallow	Moderately Slow (0.50-1.0)	calcareous, Moderately drained, fine soils with moderate erosion	**C**
Entisols	Loamy, Mixed, Hyperthermic, Lithic Ustorthents	Shallow	Moderately Rapid (2.0-3.0)	well drained, loamy soils with moderate erosion	**B**
Entisols	Loamy, Mixed, Hyperthermic, Calcareous, Lithic Ustorthents	Shallow	Moderately Rapid (2.0-3.0)	calcareous, well drained, loamy soils with moderate erosion	**B**

TABLE 3.12 HSGs for soil orders			
Sr. No.	**Soil Orders**	**Soil Characteristics**	**Assigned HSG**
1	Entisols	Young soils with little or no profile development	B
2	Inceptisols	Youthful soils with a weak, but noticeable, degree of profile development.	C
3	Vertisols Rock Outcrops (Rocky Land)	Fertile soils - very clayey soils that shrink and crack when dry and expand when wet. Well-developed soils	D

Soil depth maps, Soil order maps and HSGs maps for the Ozat, Uben and Shetrunji watersheds are developed and presented in Fig. 3.17-3.22.

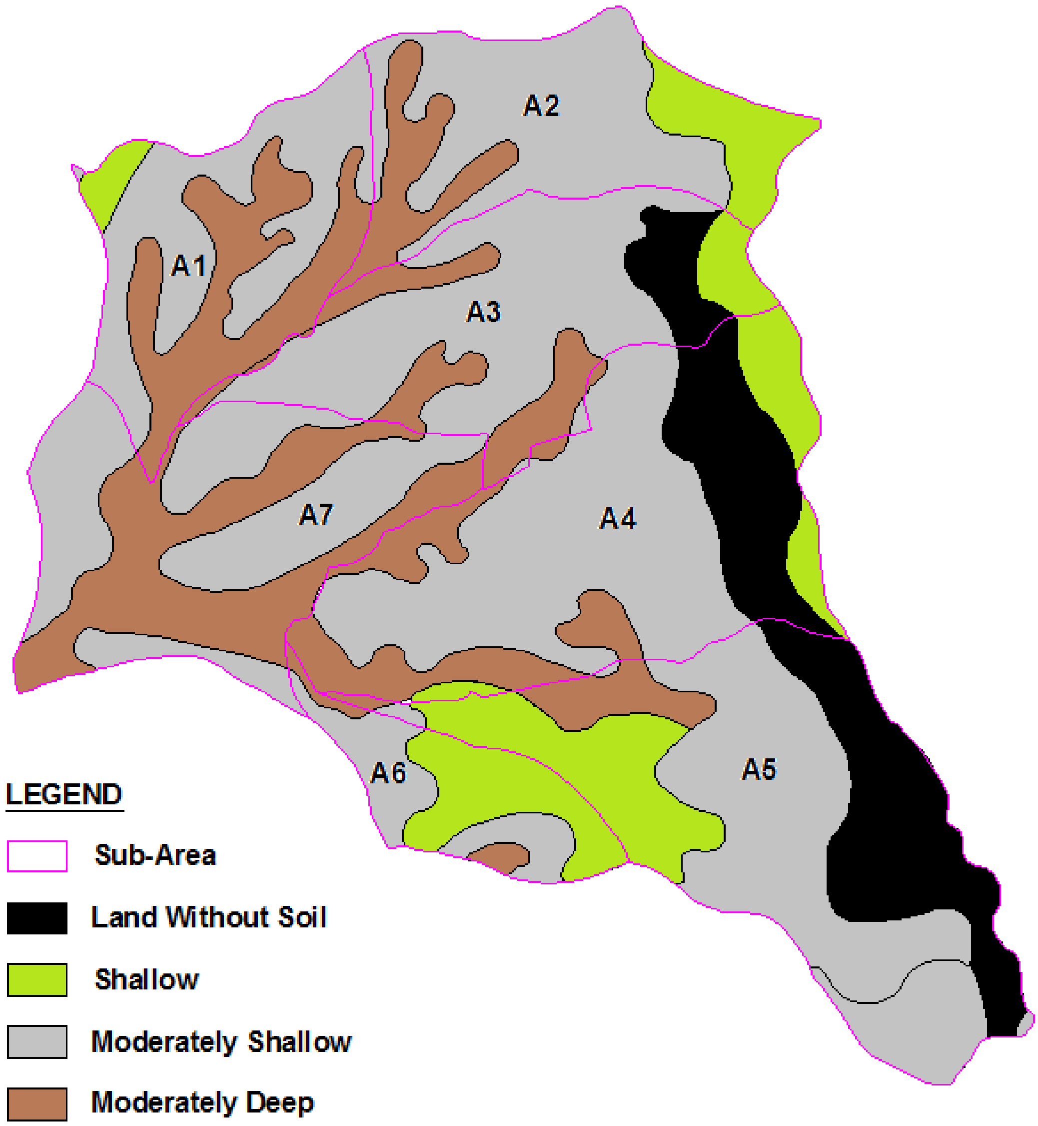


FIGURE 3.17 Soil depth map of Ozat watershed

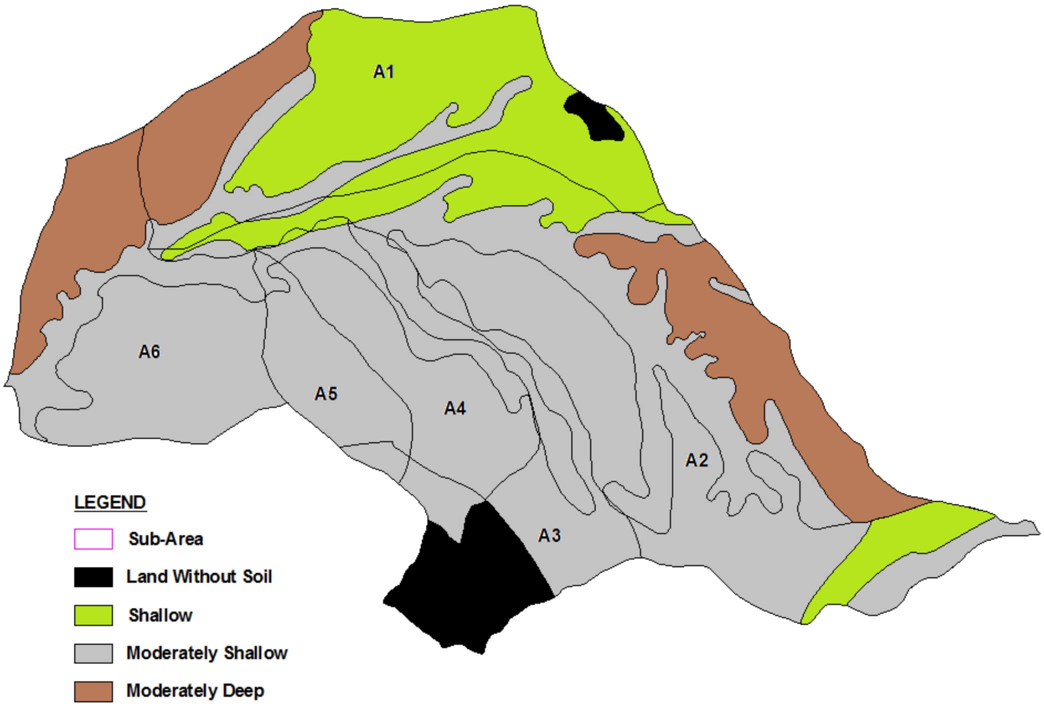


FIGURE 3.18 Soil depth map of Uben watershed

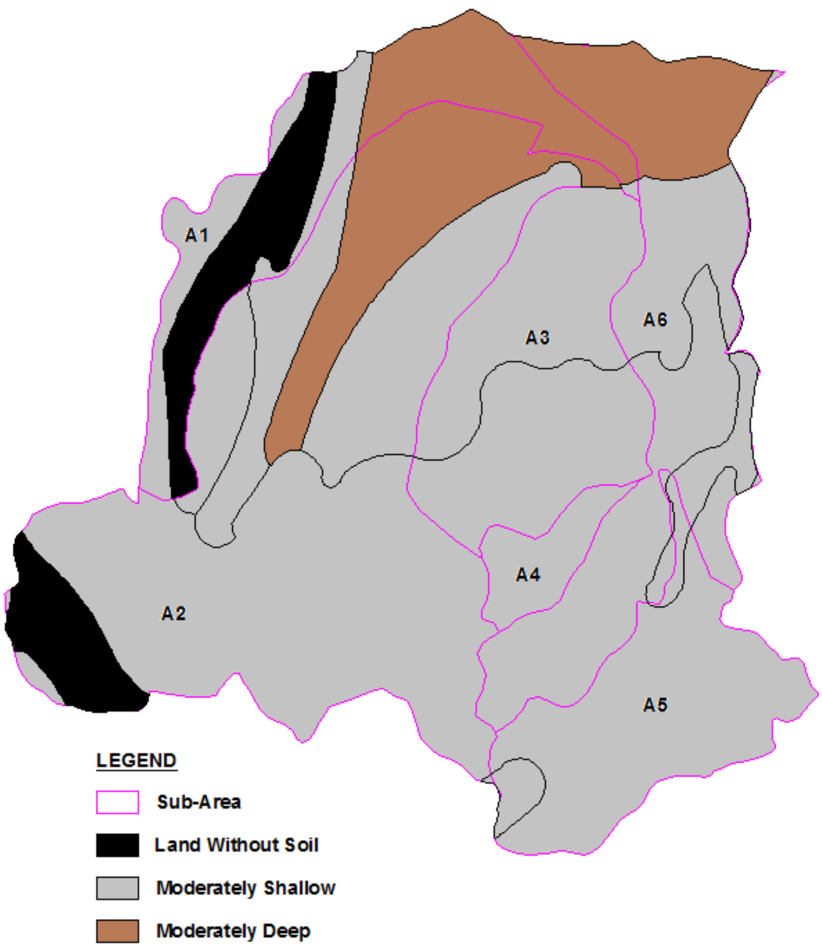


FIGURE 3.19 Soil depth map of Shetrunji watershed

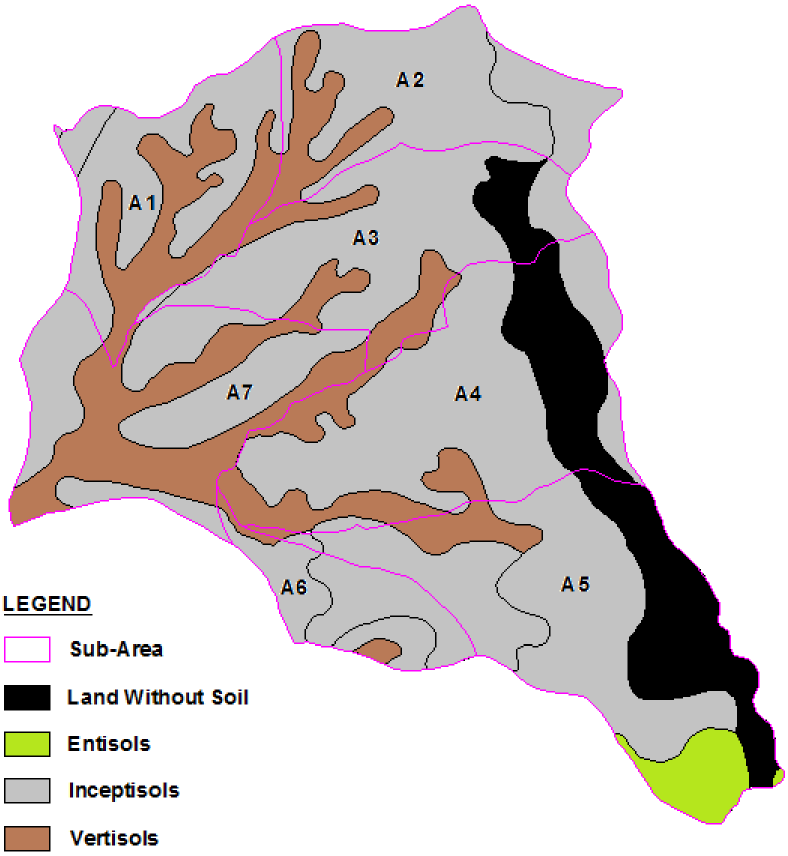


FIGURE 3.20 Soil order map of Ozat watershed

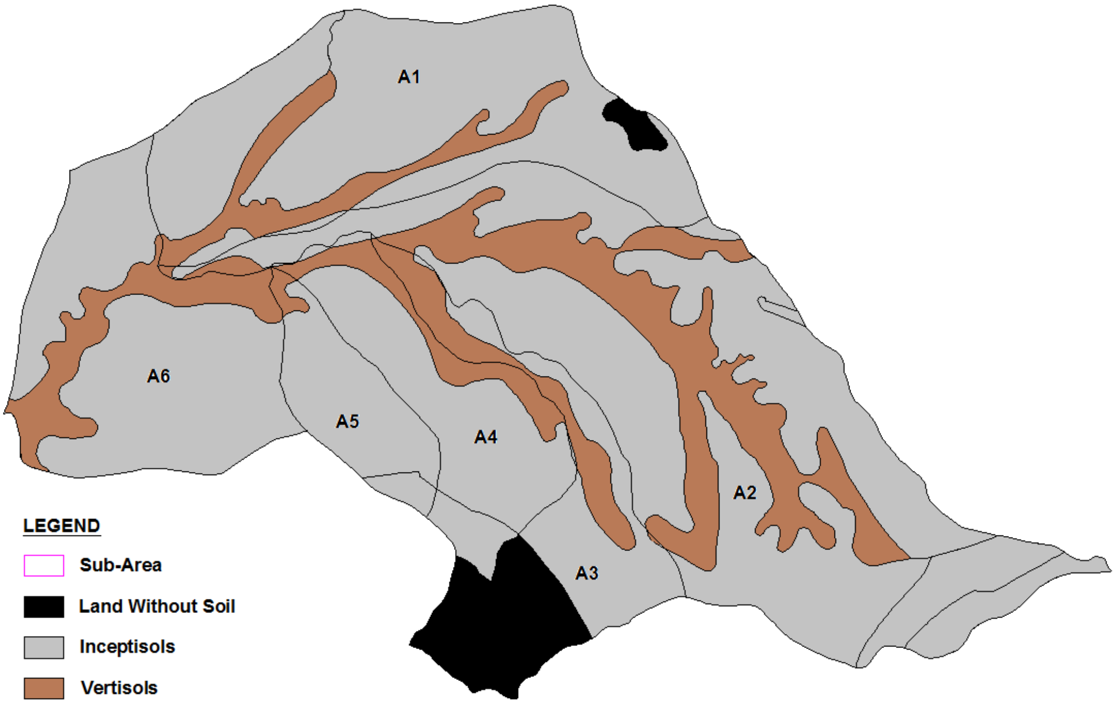


FIGURE 3.21 Soil order map of Uben watershed

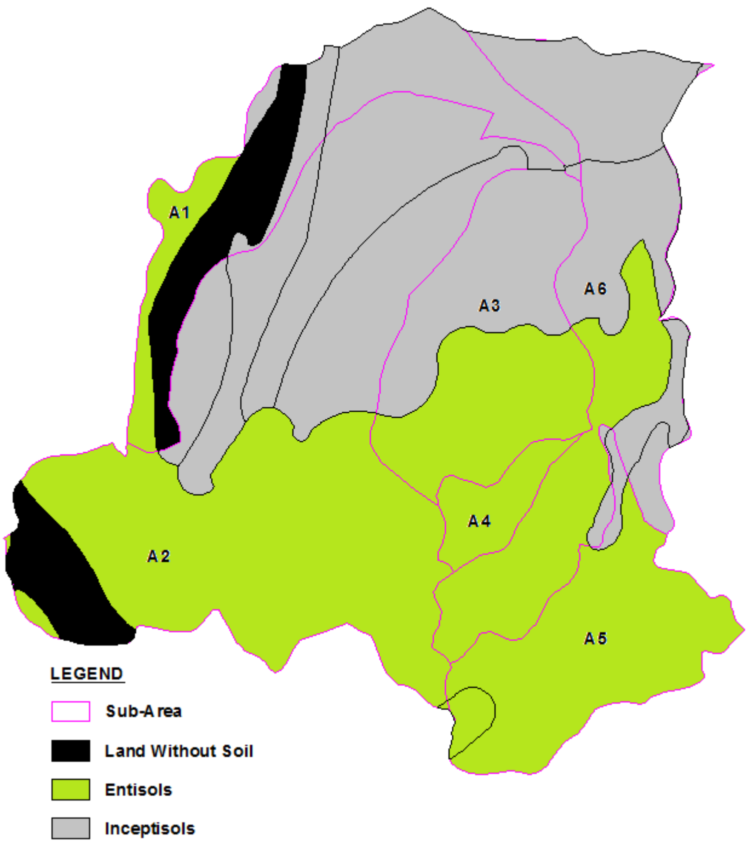


FIGURE 3.22 Soil order map of Shetrunji watershed

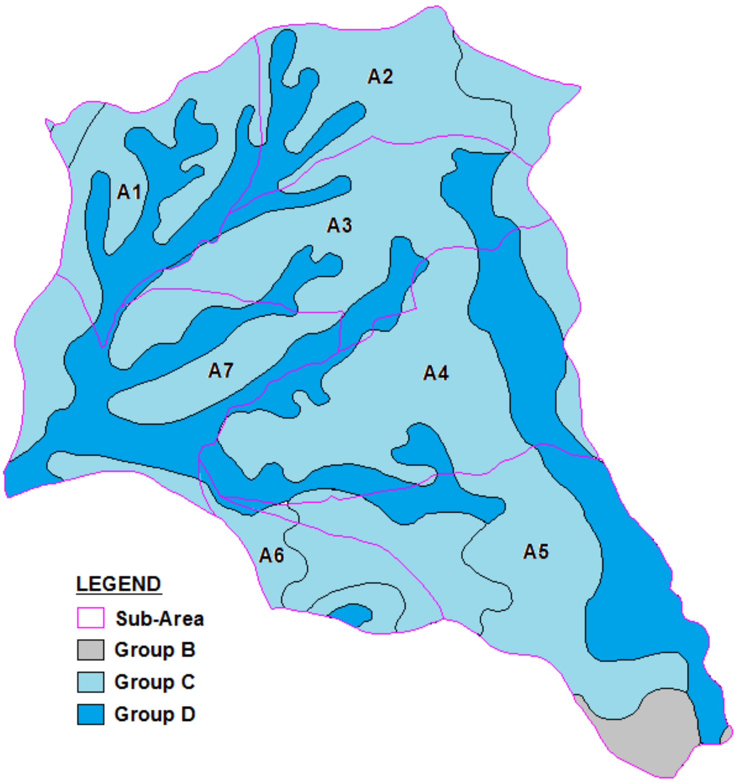


FIGURE 3.23 HSGs map of Ozat watershed

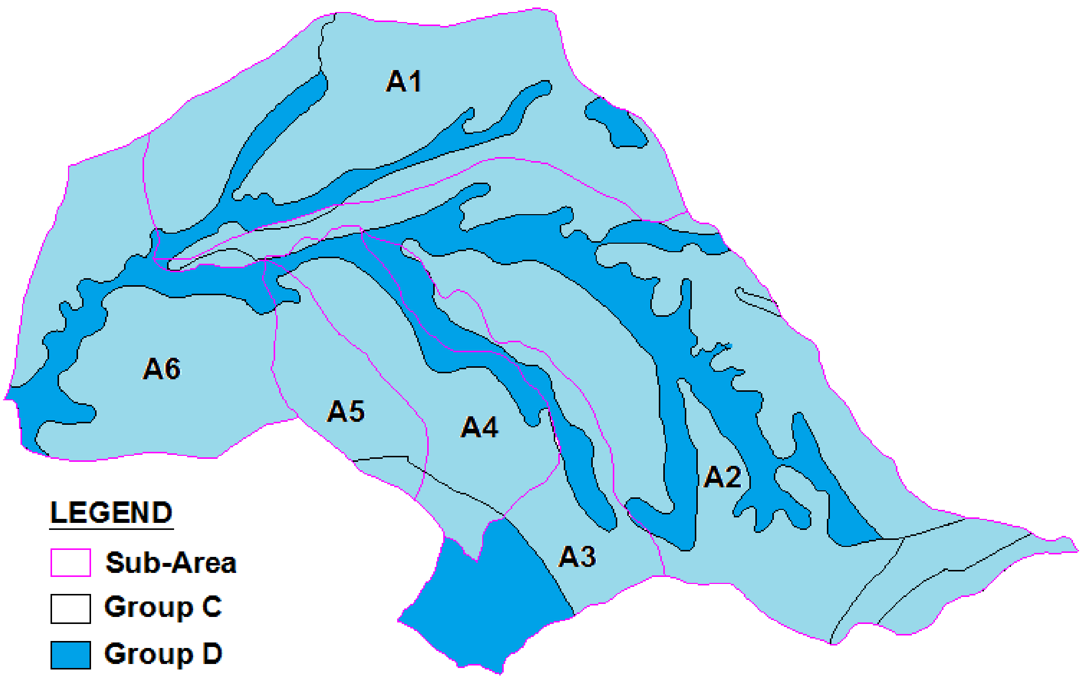


FIGURE 3.24 HSGs map of Uben watershed

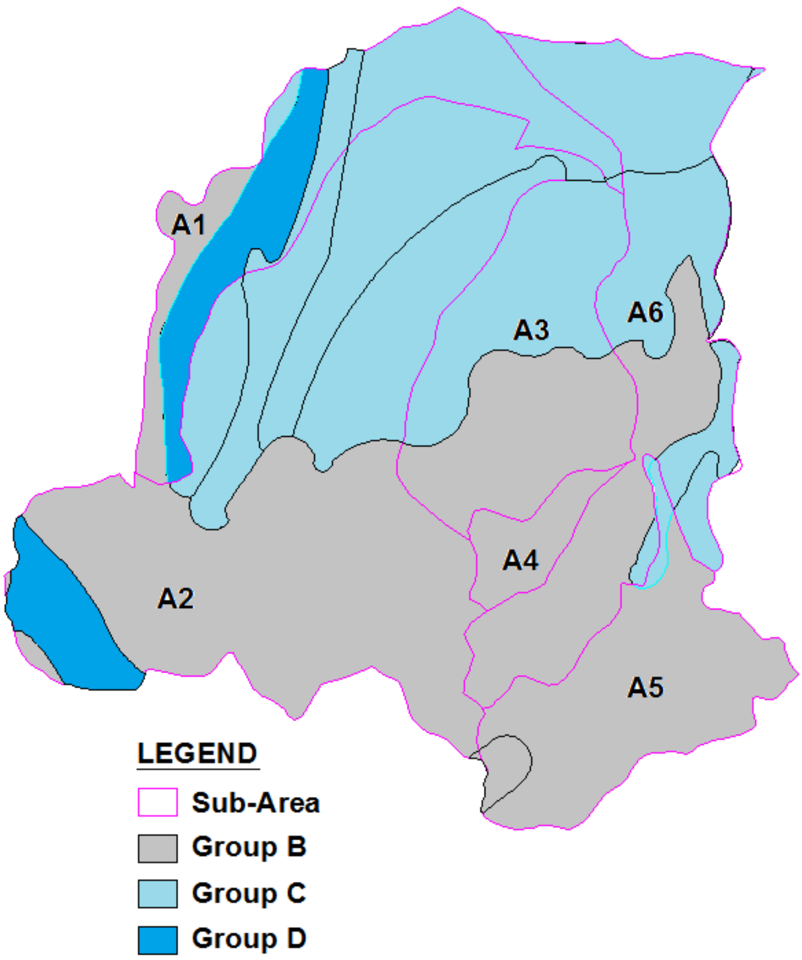


FIGURE 3.25 HSGs map of Shetrunji watershed

HSGs map was developed by integrating soil maps and LULC maps of the study region. The spatial variation of these HSGs in the Ozat, Uben and Shetrunji watersheds are shown in Fig. 3.23-3.25.

3.2.6 Soil Maps and HSG Maps Analysis

LULC maps, soil maps and HSGs maps were compiled in a GIS-based database. The HSG was assigned to each sub watershed based on LULC and soil of each sun-watershed. The area covered by HSG in the sub watersheds was calculated for all three test watersheds and are presented in Tables 3.13-3.15.

Table 3.13 shows that HSG 'C' is dominant in all sub watersheds of Ozat watershed. From Table 3.14, it is observed that except sub watershed A3, HSG 'C' occupied the remaining areas of the Uben watershed. Tabel 3.15 reveals that HSG 'B' and 'C' are dominant in Shetrunji watershed.

TABLE 3.13 HSG area for sub watersheds of Ozat watershed

Sub Watersheds	HSG Area in Sq. Km			
	B	C	D	Total
A1	0.0000	23.6980	17.0179	40.7159
A2	0.0000	33.1737	7.4783	40.6520
A3	0.0000	35.7921	13.7847	49.5768
A4	0.0000	47.1180	26.1705	73.2885
A5	7.4891	43.3702	24.3370	75.1963
A6	0.0000	17.1407	1.4200	18.5607
A7	0.0000	29.6873	23.3859	53.0732
Total	**7.4891**	**229.9799**	**113.5943**	**351.0633**

TABLE 3.14. HSG area for sub watersheds of Uben watershed

Sub Watersheds	HSG Area in Sq. Km			
	B	C	D	Total
A1	0.0000	88.3410	18.0503	106.3912
A2	0.0000	139.4054	46.9953	186.4007
A3	0.0000	23.0040	31.9326	54.9367
A4	0.0000	36.7622	8.5326	45.2948
A5	0.0000	22.6828	1.1309	23.8138
A6	0.0000	64.2889	15.4188	79.7077
Total	**0.0000**	**374.4843**	**122.0605**	**496.5448**

TABLE 3.15 HSG area for sub watersheds of Shetrunji watershed				
Sub Watersheds	**HSG Area in Sq. Km**			
	B	C	D	Total
A1	5.0522	13.9165	9.6150	28.5837
A2	47.8679	44.5381	6.4056	98.8116
A3	15.8610	15.9009	0.0000	31.7619
A4	5.3244	0.0000	0.0000	5.3244
A5	25.8653	0.8556	0.0000	26.7210
A6	19.3141	23.6046	0.0000	42.9188
Total	**119.2849**	**98.8157**	**16.0206**	**234.1213**

The RS and GIS provide better alternative on the tedious and time consuming conventional soil survey method in the accurate delineation of boundary. The spatial variations of the soil properties (soil order and soil depth) and HSG in the test watersheds were quantified and are given in Tables 3.16-3.18.

Table 3.16 shows that major portion of the Ozat watershed is covered with Inceptisols (with moderately shallow soil) (65.51%) following by Vertisols (with deep soil) (21.27%). The major part of the watershed is covered by HSG ‘C’. It is worth mentioning here that out of 65.51% Inceptisols, 53.85% soils of vertic ustochrepts sub group type soil.

TABLE 3.16. Spatial variation of soil properties and HSG in the Ozat watershed						
Soil Order						
Area	**Land Without Soil**	**Entisols**	**Inceptisols**	**Vertisols**		**Total**
Km^2	38.9145	7.4891	229.9799	74.6798		**351.0633**
%	11.08	2.13	65.51	21.27		**100.00**
Soil Depth						
Area	**Land Without Soil**	**Shallow**	**Moderately Shallow**	**Moderately Deep**	**Deep**	**Total**
Km^2	38.9145	7.4891	229.9799	0.00	74.68	**351.0633**
%	11.08	2.13	65.51	0.00	21.27	**100.00**
HSG						
Area	**A**	**B**	**C**	**D**		**Total**
Km^2	0.00	7.4891	229.9799	113.5943		**351.0633**
%	0.00	2.13	65.51	32.36		**100.00**
229.9799 Km^2 Inceptisols comprising 189.0421 Km^2 (53.85%) Vertic Ustochrepts sub group soils						

TABLE 3.17. Spatial variation of soil properties and HSG in the Uben watershed						
Soil Order						
Area	**Land Without Soil**	**Entisols**	**Inceptisols**	**Vertisols**		**Total**
Km^2	29.5016	0.00	374.4843	92.5589		**496.5448**
%	5.94	0.00	75.42	18.64		**100.00**
Soil Depth						
Area	**Land Without Soil**	**Shallow**	**Moderately Shallow**	**Moderately Deep**	**Deep**	**Total**
Km^2	29.5016	0.00	295.7471	78.7372	92.5589	**496.5448**
%	5.94	0.00	59.56	15.86	18.64	**100.00**
HSG						
Area	**A**	**B**	**C**	**D**		**Total**
Km^2	0.00	0.00	374.4843	122.0605		**496.5448**
%	0.00	0.00	75.42	24.58		**100.00**
374.4843 Km^2 Inceptisols comprising 193.2063 Km^2 (38.91%) Vertic Ustochrepts sub group soils						

TABLE 3.18 Spatial variation of soil properties and HSG in the Shetrunji watershed						
Soil Order						
Area	**Land Without Soil**	**Entisols**	**Inceptisols**	**Vertisols**		**Total**
Km^2	16.0206	119.2849	98.8157	0.0000		**234.1213**
%	6.84	50.95	42.21	0.00		**100.00**
Soil Depth						
Area	**Land Without Soil**	**Shallow**	**Moderately Shallow**	**Moderately Deep**	**Deep**	**Total**
Km^2	16.0206	119.2849	60.8424	37.9734	0.00	**234.1213**
%	6.84	50.95	25.99	16.22	0.00	**100.00**
HSG						
Area	**A**	**B**	**C**	**D**		**Total**
Km^2	0.00	119.2849	98.8157	16.0206		**234.1213**
%	0.00	50.95	42.21	6.84		**100.00**
98.8157 Km^2 Inceptisols comprising 60.8424 Km^2 (25.99%) Vertic Ustochrepts sub group soils						

Table 3.17 indicates that Uben watershed have 75.42% Inceptisols comprising of 38.91% vertic ustochrepts sub group type soil. 59.56% soils have moderately shallow soil and 75.42% soils have HSG ‘C’.

Table 3.18 specifies that major portion of the Shetrunji watershed contained 50.95% Entisols (HSG ‘B’) and 42.21% Inceptisols (HSG ‘C’). The soils of the watershed have shallow (50.95%) to moderately shallow (25.99%) depth. 98.8157 Km^2 Inceptisols of the watershed contained 60.8424 Km^2 (25.99%) Vertic ustochrepts sub group type soil.

3.2.7 Geology of the Study Region

The geological formation of the Middle South Saurashtra consists of Basaltic rocks commonly called ‘Deccan Traps” occupy almost on the entire area. Quartz, zeolite and abundant veins of calcite are observed. The basalt is prone to fast weathering, the resultant product being montmorillonitic clay rich in calcium carbonate. It may be defined as mafic lavas in which plagioclase feldspars and other mafic minerals like augite, olivine and iron oxide, hypersthene and hornblende occur in approximately equal quantities. Biotite, occurs only in the term basalt is applied to the simple mixture of labradorite, augite and iron oxide. Fig. 3.26 shows the geological formation of the study region.

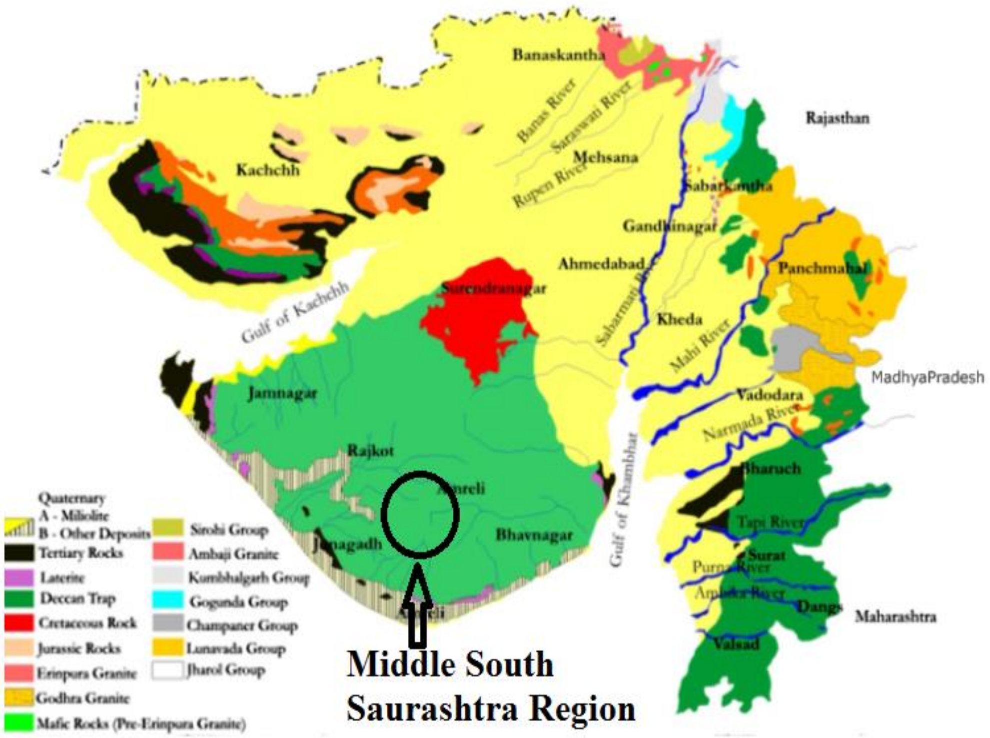


FIGURE 3.26 Geology of the study region (Source: Gujarat Ecology Commission, Vadodara)

3.2.8 Climate

The study region has mean maximum temperature 33.70^{0}C (years 1980 to 2010) with maximum temperature recorded 45.70^{0}C in April, 2002 and mean minimum temperature 22.47^{0}C (years 1980 to 2010) with minimum temperature recorded 7.20^{0}C in January, 2008. This region is characterized by a semi-arid climate, with warm and dry summers and mild winter conditions. The study region has three pronounced seasons, the monsoon season of mid-June to early October; the dry winter season, which follows through until February and the hot dry season from March to mid-June. The most predominant wind speed in the region is 1-37 km/h. The highest mean annual wind speed was observed 12.84 km/h in the month of June whereas lowest mean annual wind speed was observed 3.10 km/h in the month of November. The mean relative humidity has been changed from 12.88% to 89.81% in the region. Mean daily pan evaporation of the region ranges from 1.90 mm in winter to 14.91 mm in summer. The region has shallow medium black calcareous soils with clay loam to clay texture. The main crops grown in the region are Groundnut, Wheat, Bajra and cotton.

3.2.9 Rainfall

Rainfall is the principle phenomenon of hydrologic cycle and generally assigned to watersheds based on their proximity to recording meteorological gauge stations. The semiarid study region can be characterized by erratic and inadequate rainfall with periodic drought years. The south-west monsoon season is from June to September and is followed by the post monsoon season from October to November. The major portion of the precipitation occurs during the four months of June to September by south-west monsoon. Periodic deficient rainfall pattern, threats of floods, limited capacity of aquifer water and natural water retention are key points for this region. Most of the rainfall events of the recorded dataset did not produce a runoff. Only few events with good rainfall produce runoff above 1 mm. Therefore, to minimize uncertainty in the determination of the storm event discharge, storms events with $P \geq 12.5$ mm have been considered to determine *CN* values in calibration period for this study. The average annual rainfall of the region is found to be 672 mm and average rainy days are observed 16 (from years 1980 to 2010).

3.2.10 Ground Water Hydrology

The region is underlain by Deccan trap lava flows, supra trappeans, Gaj beds, Miliolite Limestone and recent unconsolidated deposits. Ground water in the region occurs under unconfined to confined conditions in weathered, fractured and jointed basalt, vesicular basalt fractured dykes, sand and conglomerates of supra trappeans, porous limestone of Gaj beds, silt and clay of alluvium. Ground water condition varies with the lithological characteristics of the Geological total depth of bores ranges from 100 to 300 m depth bgl (below ground level). Generally, depth of wells ranges from 10 to 25 m depth bgl and depth of bores ranges from 50 to 100 m bgl. The average yield in the wells is approximately 50 to 400 liters/minute. Occurrence of ground water in the Gaj beds confined within the limestone. Due to problem of insufficient yield and non-potable ground water, the most of the villages are getting drinking water from various regional water supply schemes with sources as reservoirs. In general, the ground water quality in the region is found to be in compliance with IS: 10500 Standard for Drinking Water.

3.3 Data Collection

Daily meteorological data, including air temperature, wind speed, relative humidity, bright sunshine hours and evaporation were collected from Junagadh Agro meteorological Cell and Amreli Agricultural Research Station of Junagadh Agricultural University, Junagadh. Junagadh station is located at latitude of 21^0 31’ N, longitude of 70^0 33’ E, 61m msl while the Amreli station is located at latitude of 21^0 35’ N, longitude of 71^0 12’ E, 130m msl. The associate parameters like solar radiation, saturation vapour pressure and vapour pressure deficit were computed with standard meteorological formula as described in FAO (Food and Agricultural Organization).

The hydrological data daily rainfall (mm) and runoff (m^3/s) of Ozat, Uben and Shetrunji watersheds were collected from the State Water Data Centre (SWDC), Gandhinagar (Gujarat). The officials of the SWDC have determined the Gauge Discharge Station Runoff using Area Velocity Method. The cross sectional area of the stream is measured at Gauging Site and stream water velocity is measured using current meter at each subsection of the cross sectional area. The runoff depth is calculated by dividing the discharge by watershed area. The information related to watershed characteristics, namely, physiography, number of streams of different orders, their length, slope and area contributing runoff to these streams were obtained from the topographic maps of the watershed.

Information about soil and land use has been collected from maps of NBSS & LUP (ICAR) (1994) and satellite imageries. Ozat, Uben and Shetrunji watersheds represent the Middle South Saurashtra region and have been delineated and prepared in GIS environment at BISAG, Gandhinagar (Gujarat-India).

The daily rainfall, runoff and temperature data for all test watersheds were obtained for two different periods as sown in Table 3.19. 50% of recorded data set was used for model calibration and remaining data set was utilised for validation of the models. The objective of calibration was to maximizing the model efficiencies and to determine optimum value of the parameter. The obtained optimised parameter value then validated by testing the model with remaining data set.

TABLE 3.19 Description of data used for test watersheds

River	River Gauge Station	Area (Sq. Km.)	Most Influenced Surrounding Rain Gauges Stations	Period	Calibration	Validation
Ozat	Khambhaliya	351.0633	Uben, Visavadar, Munjiyasar	1980-2010	1980-1995	1996-2010
Uben	Majevadi	496.5448	Uben, Bhesan, Junagadh	2001-2010	2001-2005	2006-2010
Shetrunji	Dhari	234.1213	Dhari, Ambajal, Raval	1987-2004	1987-1995	1996-2004

3.3.1 Data Generation

The author has developed prediction model to generate missing data of daily maximum and minimum temperature time series. The daily maximum temperature time series (MXTTS) for period 1980 to 1983 and minimum temperature time series (MNTTS) for period 1980 to 1986 were predicted by applying the triple exponential smoothing techniques (Holt Winters method) using Excel spread sheet.

Common characteristics of the test watersheds, location of gauging site and rainfall distribution patterns are described below.

3.3.2 Ozat Watershed

Ozat is a river flowing in western India in Gujarat state whose origin is near Visavadar and meets in Arebian Sea. Ozat is third largest river of Saurashtra region after Bhadar and Shetrunji rivers. Ozat watershed considered in this study geographically locates within the latitudes $21^{0}19'$ N to $21^{0}33'$ N and the longitudes $70^{0}39'$ E to $70^{0}56'$ E respectively as can be seen from toposheet no 41K (10-11-14 and 15) of scale 1:50000. The length of Ozat river from origin to gauge site is 36.62 Km. The gauge discharge site (GDS) is located near Khambhaliya village (21^{0} $23'$ $46''$ N, 70^{0} $39'$ $29''$ E) at bridge of Junagadh to Visavadar Road 33 km away from Junagadh. Average annual rainfall of the area is 785 mm (1980-2010), mean maximum temperature 33.34^{0}C and mean minimum temperature 24.30^{0}C. The area has the high annual variability of rainfall from 211 to 2216 mm. It is characterized by erratic rainfall pattern.

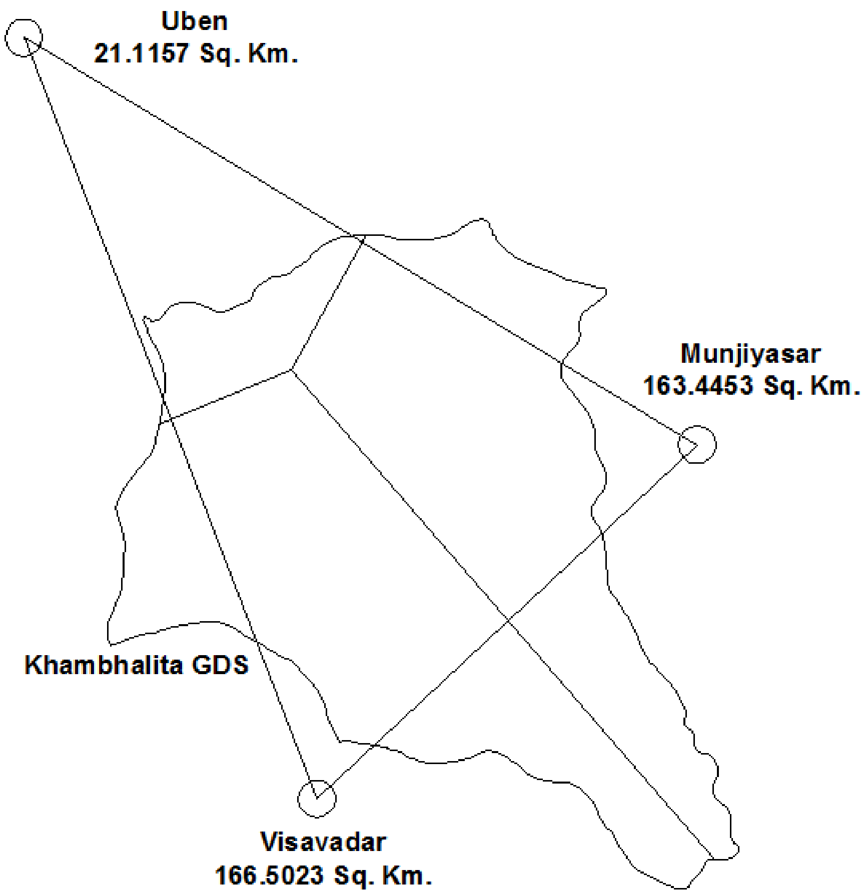


FIGURE 3.27 Thiessen polygon for Ozat watershed

The Thiessen Polygon Method is used to calculate the spatial distribution of rainfall. This method is based on arithmetic mean approach and which may account for orographic effects and storm morphology (Bedient and Huber, 1992). Significant uncertainty can be expected in precipitation data due to measurement error and spatial variability where, relative uncertainties of 10% are common (Neitsch et al., 2011). There are three most influenced rain gauges stations Uben, Visavadar and Munjiyasar located around Ozat watershed were considered to make Thiessen polygon.

In the Thiessen polygon method, weight of station is calculated based on the area of each station. Each weight is then multiplied by the station rainfall to obtain the areal average rainfall. The Study area divided into three parts by Thiessen Polygon as shown in Fig. 3.27 Corresponding areas of Thiessen polygon are computed and the spatial average precipitation $\bar{P}$ is calculated using Thiessen formula (Equation 3.1).

$$\bar{P}=\frac{\sum_{i=1}^{n} A_i P_i}{\sum_{i=1}^{n} A_i} \quad (3.1)$$

3.3.3 Uben Watershed

Uben watershed lies in Northern side of the Girnar Mountain in Junagadh district in Gujarat state of India and locates within the latitudes 21^0 31'N to 21^0 43'N and the longitudes 70^0 25'E to 70^0 45'E respectively as can be seen from toposheet no 41K (6 and 10).

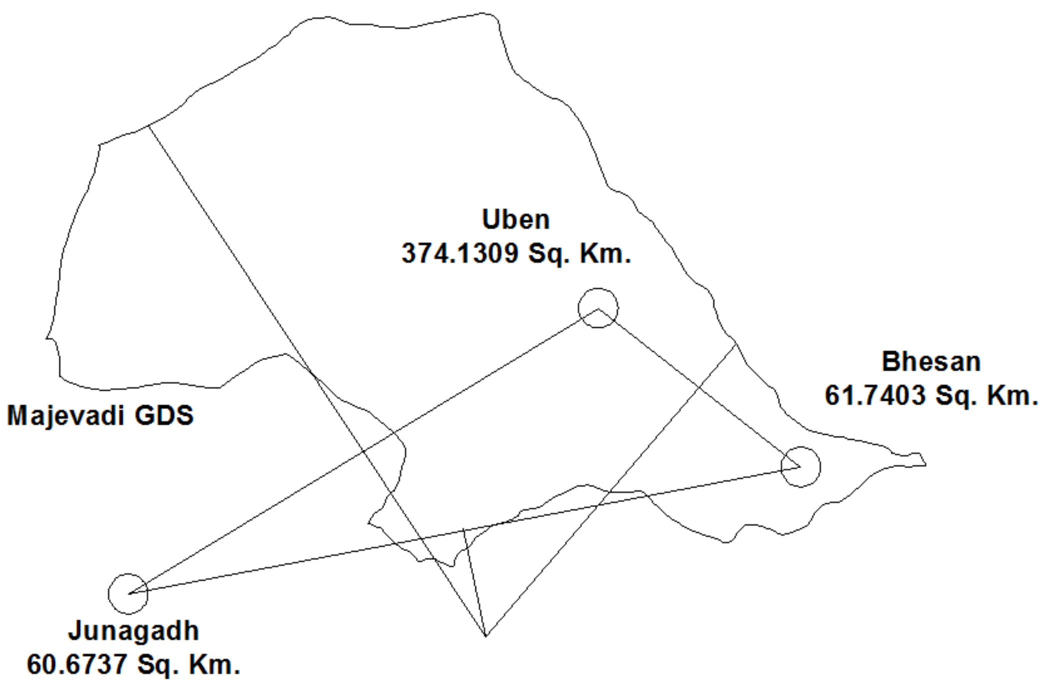


FIGURE 3.28 Thiessen polygon for Uben watershed

The length of Uben river from origin to gauge site is 44.14 Km. The GDS is located on Uben River Bridge on Makhiyala-Majevadi Road near village Majevadi (21^0 36' 35" N,

70^0 24' 42" E). The average annual rainfall of the area is 861 mm (2001-2010). Using location information of Uben, Bhesan and Junagadh stations, Thiessen polygons are generated as shown in Fig. 3.28. The spatial average precipitation $\overline{P}$ for the Uben watershed is calculated using (Equation 3.1).

3.3.4 Shetrunji Watershed

Shetrunji is second largest river of Saurashtra region after Bhadar. The length of the Shetrunji River from origin to gauge site is 26.50 Km. Shetrunji catchment consists dense and fairly mix jungle in hills of Gir forest region, open scrubs, stony waste and agricultural land in plain terrain. The catchment falls in the leeward side of Gir forest. The river basin locates within the latitude and longitude from 21^o 10'N to 21^o 20'N and from 70^o 50'E to 71^o 5'E respectively as can be seen from toposheet no 41K (15-16-0-3). The GDS is located near Dhari village (21^0 19' 51" N, 71^0 00' 55" E) at bridge of Dhari to Visavadar road. The area has mean annual rainfall of 559 (1987-2004) mm. Fig. 3.29 shows the watershed of Dhari GDS and three rain gauge stations Dhari, Ambajal and Raval along with Thiessen polygon. (Equation 3.1) is used to compute the spatial average precipitation $\overline{P}$ for Shetrunji watershed from three polygons.

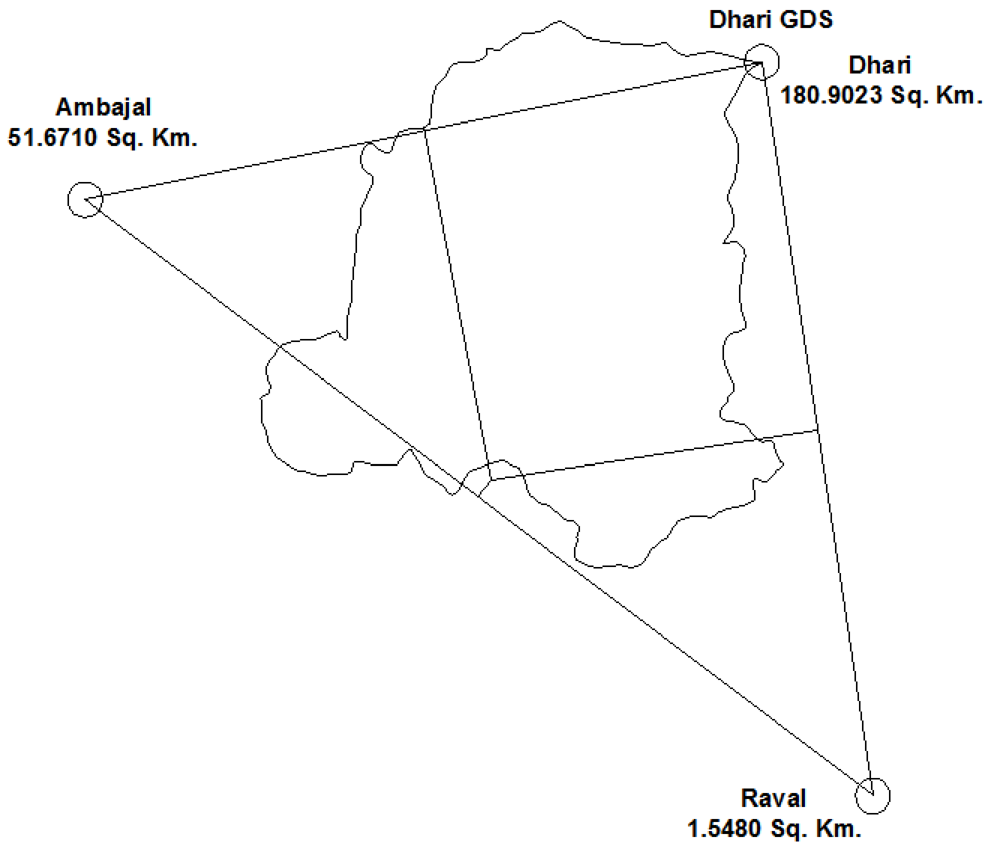


FIGURE 3.29 Thiessen polygon for Shetrunji watershed

3.3.5 Base Flow Separation

The stream flow discharge is composed entirely of base flow (long-term delayed flow from natural storage of aquifers) in most of the dry season of the year. Overland flow together with inter flow (Lateral flow in the soil profile) makes direct flow. Stream flows can be affected by modified base flow due to abstraction and use of water resources directly from the stream or from ground water storage. It can also be affected by interruption of the direct flow due to diversion of runoff and water harvesting mechanisms. Therefore, separation of the direct and base flow from a stream flow is necessary to identify most dominant component which are more influential on the stream flow.

Filtering separation method and statistical method (Frequency-Duration analysis) are often used methods for stream flow separation. In this study the (Nathan and McMohan, 1990) filtering method (Equation 3.2) is used to separate base flow from stream flow.

$$Q_{d(i)} = \alpha Q_{d(i-1)} + \beta(1+\alpha)(Q_{T(i)} - Q_{T(i-1)}) \qquad (3.2)$$

Where,

Q_d = Direct flow which is subjected to $Q_d \geq 0$ for the time i in days

Q_T = Total flow (i.e base flow + direct flow)

α = a coefficient with value 0.925

β = a coefficient with value 0.5

3.4 Closure

This chapter elaborates in depth the information of the study region and data collection. Topography, climate, geology, land use, soil characteristics and geomorphologic characteristics of the study region have been discussed in length. The soil taxonomy and its formative elements also described to elaborate and classify soil types of the study region. Various hydro-meteorological data collection procedures for selected test watersheds have also been explained in this chapter. The next chapter discusses the proposed methodology and models development in detail.

CHAPTER 4

Methodology

4.1 General

This chapter discusses the problems associated with the application and selection of appropriate model to estimate the runoff for the Middle South Saurashtra region (Gujarat-India). Model selection mainly depends on the type of problem, the prevailing runoff mechanisms, available expertise and computational facility, availability of data and budget. Review of past studies show that the SCS-CN method is simple, widely used and computationally efficient method for surface runoff estimation. The main focus of this study is to improve performance of the SCS-CN method by modifying *CN* to extend their applicability in the study region. The procedure of determination of composite *CN* in GIS environment is elaborated. The three independent methods developed by integrating the effect of cumulative rainfall-runoff ordered data, morphometric parameters of the watershed and evapotranspiration loss in *CN* determination procedure are also described in separate sections.

4.2 Model Selection

Estimation of direct runoff is often necessary in small to medium-sized watersheds. Runoff estimates are based upon the soil types, land-use practices within a basin and the influence of the antecedent soil moisture conditions for a specific storm. Many models are used in practice for these purposes, depending on the type of problem, the prevailing runoff mechanisms, available expertise and computational facility, availability of data and budget. These models are reliable for the area and over the period for which they were developed. Each model has its own strengths and weaknesses. Selection of a suitable model among variety of different models is a challenging task. Mainly three methods are used to compute runoff (i) SCS-CN method (ii) Horton's equation, and (iii) Continuous soil moisture balance. Out of these methods, the SCS-CN method is widely used to estimate runoff due to its flexibility, simplicity, convenience, and world-wide acceptability. It accounts for major runoff-generating watershed characteristics, viz. soil type, land use/treatment, surface condition and antecedent moisture conditions. Further, it requires readily available inputs and gives versatility and consistent runoff estimation.

The Middle South Saurashtra region of Gujarat (India) is characterised by periodic inadequate rainfall pattern, limited water storage capacity of aquifer and natural water conservation, limited ground water yield and non-potable quality of ground water. Mostly, the problems associated with the application of rainfall- runoff models to arid and semiarid areas are:

1. Inadequate model representation of the prevailing watershed processes.
2. Insufficient representation of the spatial variability of runoff generation process.
3. Inadequate representation of the spatial and temporal variability in input data viz. rainfall, temperature, evapotranspiration, etc.
4. Inadequate estimation of model parameter values. This problem associated with limited data availability. Adequate data set should be available for calibration so that the rainfall-runoff relationships reflected in the observed data are sufficiently attributed the model parameter.
5. Over parameterisation, more input data requirements, dependency on complex and costly software and capability of the model users are major constraint for models.

Therefore, simple user friendly model which has Less and readily available input data requirement, normal software necessity, giving robust, reasonable and consistent results, acceptability among both researcher and practitioner community, and easy to apply is realistic choice for watershed having inadequate data resources. The SCS-CN method simulates the rainfall-runoff relationship at watershed level by considering the physiographic heterogeneity of the watershed. Following points are considered for selection of suitable model for the study region:

1. Many researchers have suggested that the SCS-CN method produces satisfactory runoff estimates for many agricultural and urban watersheds (Ponce and Hawkins, 1996; Yuan et al., 2001; Gassman et al., 2007; Hawkins et al., 2009; Wang et al., 2009).

2. Walker et al. (2000), Chatterjee et al. (2001), Ashish et al. (2003), Gupta and Panigrahy (2008), Soulis et al. (2009), D'Asaro and Grillone (2010), and Pradhan et al. (2010) have noted that the SCS-CN method provides consistently useable results.
3. The SCS-CN method is simple method and it can also be used for water resources management and urban storm water modelling because of its versatility (Durrans, 2003; Liu and Li, 2008; Hawkins, 1993; Greene and Cruise, 1995; Mishra et al., 2005; Tsihrintzis and Hamid, 1997; Lewis et al., 2000; Sharma et al., 2001; Chandramohan and Durbude, 2001; Sharma and Kumar, 2002; He, 2003).
4. The SCS-CN method adequately integrates the most important runoff generating processes in a scientifically reasonable way.
5. Currently the SCS-CN method is embedded in extensively used hydrological software, like WinTR55, WinTR20, HEC-HMS, EPA-SWMM, SWAT, GLEAMS, EPIC, NLEAP, and AGNPS (De Paola et al., 2013) which divulges that it is popular and well accepted method for runoff estimation.

6. The attractive feature of the SCS-CN method is that it integrates the complexity of runoff generation into single parameter *CN*.

Considering the above points and research objective, it seems that the SCS-CN method is more suitable for this research to predict runoff.

4.3 Original SCS-CN Method

Out of many methods for runoff estimation, the Natural Resources Conservation Service Curve Number (NRCS-CN) (formerly called as SCS-CN) method developed by the U. S. Department of Agriculture (USDA) still remains the most popular, fruitful and recurrently used method. The major reasons for this popularity may be attributed to ease of use, less number of input parameters, easy to modify, robustness of model results, and acceptability among both researcher and practitioner community. The SCS-CN method is based on the principle of the water balance (Equation 4.1) and two fundamental hypotheses. (i) The ratio of direct runoff to potential maximum runoff is equal to the ratio of infiltration to potential maximum retention (Equation 4.2). The initial abstraction is proportional to the potential maximum retention (Equation 4.3).

$$P = I_a + F + Q \tag{4.1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{4.2}$$

$$I_a = \lambda S \tag{4.3}$$

Where, P is the total precipitation (mm), I_a is the initial abstraction before runoff (mm), F is the cumulative infiltration after runoff begins (mm), Q is direct runoff (mm), S is the potential maximum retention (mm), and λ is the initial abstraction (ratio) coefficient. SCS (2004) introduced general equation (Equation 4.4) by combining (Equation 4.1) and (Equation 4.2).

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad for\ P > I_a \tag{4.4}$$

$$= 0 \text{ otherwise}$$

The potential maximum retention S (mm) can vary in the range of $0 \leq S \leq \infty$, and it directly linked to CN. Parameter S is mapped to the CN using (Equation 4.5) as:

$$S = \frac{25400}{CN} - 254 \tag{4.5}$$

The CN which is a function of LULC, soil type, hydrologic soil group and antecedent moisture condition (AMC) is a key factor of the SCS-CN method, and it can vary from 0 to 100. Three AMCs were defined as dry (lower limit of moisture or upper limit of S), moderate (normal or average soil moisture condition), and wet (upper limit of moisture or lower limit of S), and denoted as AMC I, AMC II, and AMC III, respectively (Mishra and Singh, 2003). Higher AMC and CN value would indicate the more runoff potential and vice versa, therefore, median CN obtained from array of CN values would commonly be adopted for the watershed (Hawkins et al., 1985; Hjelmfelt, 1991; Schneider and McCuen, 2005). The CN is usually calculated from available tables in the National Engineering Handbook, Section 4 (NEH-4) as well available curves; however, this procedure is very tedious, laborious, and time consuming. Further, large errors can be expected in surface runoff estimation where, the validity of the hand book tables for CN was not verified. It faces problems of ambiguous calculation associated to the soils outside the classified hydrological soil groups. The SCS-CN method does not adequately model all of the important physical processes of runoff generation. Thus, it would benefit to larger research and practitioner community to modify the SCS-CN method to encompass these processes.

The SCS-CN method assimilates the convolution of runoff generation into *CN*. However, lumped conceptual approach and simplicity of a single parameter introduces great uncertainty to estimate runoff in practical applications. In last four decades, extensive research work has been conducted to overcome existing demerits of the SCS-CN method. It does not adequately model the impact of land use changes, morphometric parameters, and long term evapotranspiration loss. In spite of many modifications done in the SCS-CN method, a need of its further improvement has always been expected to satisfy unresolved challenges. To modify the existing SCS-CN method towards better runoff prediction is reliable and feasible solution to cope problems of poor hydrologic analysis.

Recent modifications in determination of *CN* are reported by slope adjustment procedure (Sharpley and Williams, 1990; Huang et al., 2006), asymptotic determination of *CNs* from measured rainfall-runoff data (Hawkins et al., 1993, 2009; Bonta, 1997; Hjelmfeld et al., 2001; Kowalik et al., 2015), two-*CN* system approach (Soulis and Valiantzas, 2012), determination of *CN* by incorporating *ET* for continuous hydrological simulation (Kannan et al., 2008; Jajarmizadeh et al., 2012), composite *CN*-generation using RS variables sensing variables like vegetation, impervious surface, and soil (Fan et al., 2013). For complex watersheds with high temporal and spatial variability in soil and land use, the SCS-CN model integrated into the RS/GIS system (Zhan and Huang, 2004; Geetha et al., 2007; Viji et al., 2015). In conventional *CN* determination procedure, the impact of land use change, long memory characteristics and variance heterogeneity of watershed due to accumulation of soil moisture does not address. It also does not take into account the effect of slope, stream length and other morphometric parameters which are highly influenced on runoff generation. Further, it does not incorporate long-term losses such as evaporation and evapotranspiration. Therefore, it is necessary to modify the *CN* to improve performance of the SCS-CN method.

4.4 *CN* Determination for Different AMC

AMC indicates watershed wetness and the moisture content of soil prior to a storm. The AMC is explained variation in *CN* at different time step. Based on rainfall magnitude of previous five days and season (dormant season and growing season), three AMC levels (AMC I, AMC II & AMC III) were documented by SCS Table 4.1. AMC I, AMC II and AMC III were defined as dry (lower limit of moisture or upper limit of *S*), moderate (normal or average soil moisture condition), and wet (upper limit of moisture or lower limit of *S*) respectively. SCS-CN manual provides the average condition of a watershed AMC II (CN_{II}) value (USDA, 1985). The *CN* value of AMC I (CN_I) and AMC III (CN_{III}) can be adjusted by applying the (Equation 4.6) and (Equation 4.7) (Chow et al., 2002) respectively:

Table 4.1 AMC for *CN* determination

AMC	Total Rain in Previous 5 days	
	Dormant Season	Growing Season
I	< 13mm	< 36mm
II	13 to 28mm	36 to 53mm
III	>28mm	> 53mm

$$CN_I = \frac{4.2\ CN\ II}{(10 - 0.058\ CN\ II)} \tag{4.6}$$

and

$$CN_{III} = \frac{23\ CN\ II}{(10 + 0.13\ CN\ II)} \tag{4.7}$$

4.5 Methodology to Modify *CN*

To meet the objectives of the research, three different methods are developed by modifying *CN* which provide better options to the user for runoff estimation. The relevant data e.g. rainfall-runoff, temperature, satellite images, toposheets and NBSS & LUP reports for the study region are collected from different sources. Composite *CN* for AMC II is determined by using these data. The chart in Fig. 4.1 depicts the overall methodology applied to estimate runoff.

4.6 Composite *CN*

Three test watersheds Ozat, Uben and Shetrunji watersheds are selected from the study region. Satellite imageries of soil type and land use were first obtained and compiled in a GIS environment. To detect variability due to alternate land-use scenarios, LULC maps of the test watersheds were developed for different time periods. HSG maps were prepared for the selected watersheds based on land use maps of different period, soil order, infiltration rate, soil depth, and soil characteristics of the watershed. The test watersheds were divided into sub watersheds by adopting 3rd order stream. The intersection of HSG and LULC field, *CN* values were assigned based on standard NRCS table for each sub watershed Table 3.7. Weighted *CN* value for each sub watershed was calculated by multi-plying weights in proportion to the area associated with each LULC class and the corresponding *CN* (Equation 2.3). Thereby a composite CN_{II} was calculated for each sub watershed as well as for entire watershed for AMC II. The composite CN_{II} values were converted into corresponding *CN* values for AMC I and AMC III by using the (Equation 4.6) and (Equation 4.7) respectively. The composite CN_{II} values of selected watersheds for different time periods are shown in Table 4.2.

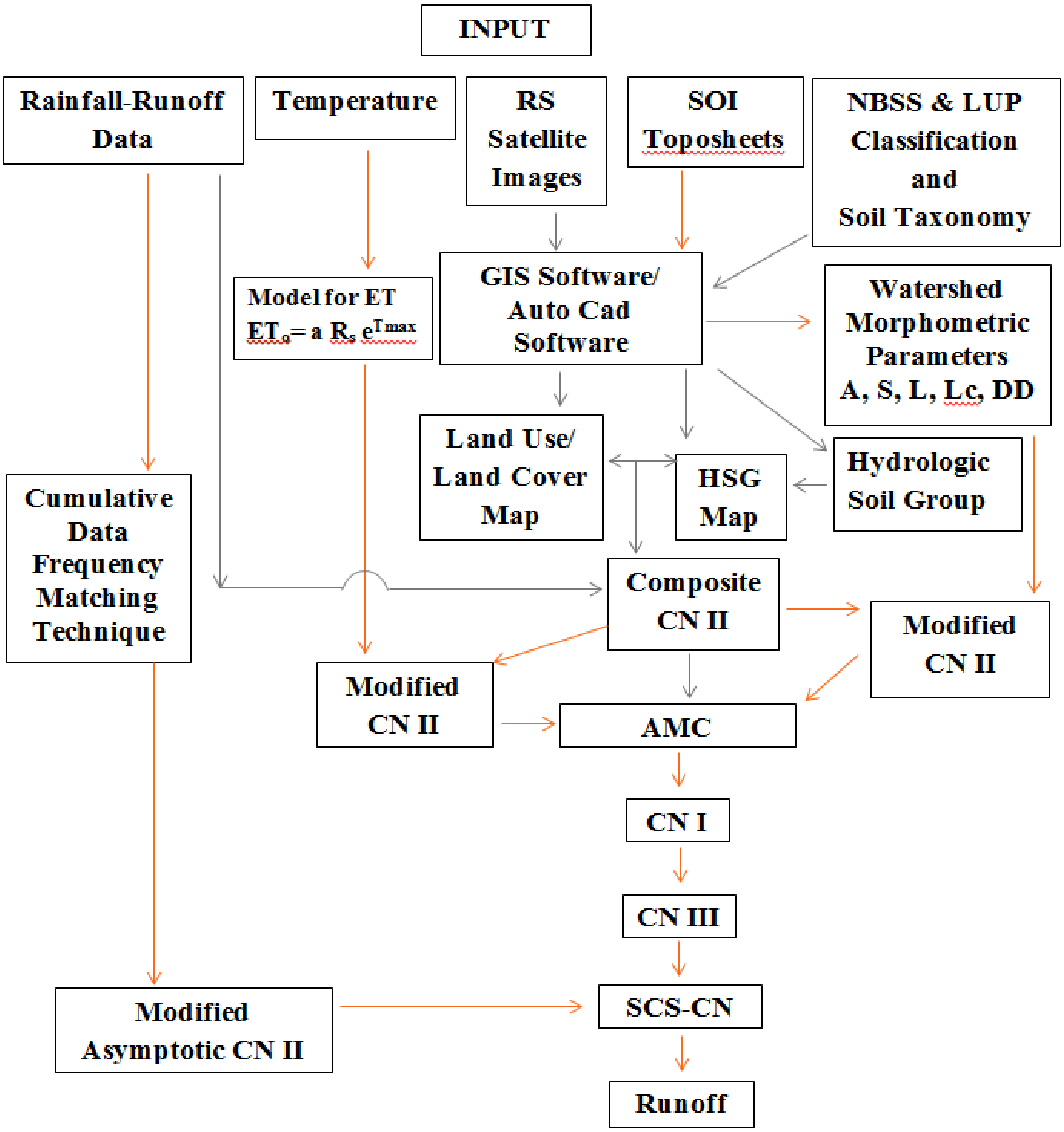


FIGURE 4.1 Methodology adopted for runoff estimation

TABLE 4.2. Alternate LULC scenarios (Areas in Km^2) and composite *CNs* values of test watersheds

Land Use Land Cover	(Ozat) 1994-95	(Ozat) 2005-06	(Ozat) 2009-10	(Shetrunji) 1994-95	(Shetrunji) 2005-06	(Shetrunji) 2009-10	(Uben) 2001-02	(Uben) 2005-06	(Uben) 2009-10
Agriculture	277.0739	291.6939	277.6910	86.9192	144.9282	139.5485	408.7282	415.5799	399.6672
Built-up	0.0000	4.2587	6.6156	0.0000	2.1850	3.3915	0.0000	5.7088	11.3266
Forest	0.0000	0.0000	0.0000	99.2376	45.2687	49.4142	41.5711	39.0348	41.3003
Others	0.0000	0.0540	0.0000	0.0000	0.6298	0.0000	0.0000	1.9325	0.0000
Wastelands	73.9895	48.0306	53.1671	47.9644	37.2948	34.4491	46.2455	27.9515	33.0752
Water Bodies	0.0000	7.0261	13.5896	0.0000	3.8148	7.3180	0.0000	6.3374	11.1755
Total Area	351.0633	351.0633	351.0633	234.1213	234.1213	234.1213	496.5448	496.5448	496.5448
Composite CN_{II}	81.64	81.58	81.97	65.43	72.39	72.13	79.17	79.26	79.03
Composite CN_{I}	65.13	65.04	65.63	44.29	52.41	52.08	61.48	61.61	61.28
Composite CN_{III}	91.09	91.06	91.27	81.32	85.78	85.62	89.73	89.79	89.66

4.7 Asymptotic *CN*

When rainfall-runoff data are available for a watershed, the potential retention *S* characterizing the watershed can be determined by using *P* and *Q* pairs (Chen, 1982) as:

$$S = \frac{P}{\lambda} + \frac{(1-\lambda)Q - \sqrt{(1-\lambda)^2}\, Q^2 + 4\,\lambda\, PQ}{2\,\lambda^2} \tag{4.8}$$

CN value can be directly calculated from rainfall-runoff data by substituting value of *S* in (Equation 4.8) and rearranging it as:

$$CN = \frac{25400}{\frac{P}{\lambda} + \frac{(1-\lambda)Q - \sqrt{(1-\lambda)^2}\, Q^2 + 4\,\lambda\, PQ}{2\,\lambda^2} + 254} \tag{4.9}$$

Hawkins (1990) showed that the *CNs* decrease with increment in *P*, but approaching asymptotic value at larger storms. These observations were often used to match *P* and *Q* depths with the same return period using frequency matching technique. Asymptotic *CNs* determine by using *P-Q* ordered data and plotting *CNs* obtained by (Equation 4.9) against the causative rainfall *P*.

4.7.1 Asymptotic *CN* (Hawkins)

Hawkins (1993) used 'frequency matching' approach in determination of asymptotic *CN*. This popular approach known by standard asymptotic fit method (AFM). In this method, *P* and *Q* data are re-aligned on rank-order basis using the rainfalls and runoff separately, and reassembling them as rank-ordered pairs (ordered *P–Q* data). When *CN* is determined by observed rainfall-runoff data, a secondary relationship almost emerges between the *P* and *CN* from ordered *P–Q* dataset. Different watersheds show the different *P-CN* behaviours. Mainly three possible typical *P-CN* responses are observed.

The first most common *P-CN* behaviour scenario is shown standard response, in which *CNs* approach a constant value at large storm with increasing *P*. This standard response is described by (Equation 4.10).

$$CN(P) = CN_{\propto} + (100 - CN_{\propto})\, e^{-kp} \tag{4.10}$$

(Equation 4.10) has the algebraic structure of the Horton infiltration equation. In the standard response, the *CN* as a function of rainfall *P* decreases to an asymptotic constant CN_∞ with *k* (the fitting coefficient or rate constant in the units of 1/*P*) that describes the *CN* approach to the asymptotic constant CN_∞. Optimized values of CN_∞ and *k* are obtained by fitting (Equation 4.10) using least-squares procedure.

The second *P-CN* variation is the violent behaviour, in which the observed *CNs* rise abruptly at some threshold value and later asymptotically approach a constant value at low *P*. The following (Equation 4.11) has been used to determine the *CN* value.

$$CN(P) = CN_\propto[1 - e^{-kp}] \tag{4.11}$$

The third *P-CN* response is complacent behaviour, characterized by steady declination of observed *CNs* with increasing *P* but failing to approach a constant value. In such case asymptotic *CN* value cannot be adequately defined in form of the algebraic structure of the Horton infiltration equation.

The AFM is advantageous over the conventional method, as it uses the observed field rainfall-runoff data. Further, it is possible to assess the degree of accuracy of the results obtained and also check the stability of fit. This technique is recommended to NRCS as the preferred technique for *CN* estimation (Woodward, 2010).

4.7.2 Modified Asymptotic *CN* (CN_{asy})

The asymptotic *CN* approach fails to describe the watershed response in small and medium rainfall events as temporal variability is not essentially taken into account. Ordinary *P–Q* ordered data used to determine asymptotic *CN* in standard AFM have not much explanatory power to describe complex long term soil moisture condition of the watershed. Due to spatial and temporal variability of rainfall, and the variability of antecedent rainfall and the associated soil moisture amount, the *CN* has sufficient room for variability. The antecedent condition is taken to vary from previous 5 days to 30 days, NEH-4 (SCS, 1971) uses the antecedent 5 days rainfall for AMC, and it is usually practiced. Hope and Schulze (1982) used a 15-day antecedent period in an application of the SCS procedure in the humid east of South Africa, and Schulze (1982) found a 30-day antecedent period to yield better simulation of direct runoff in humid areas of the USA, but a 5-day period to be applicable in arid zones. However, there is no explicit guideline for soil moisture fluctuation with the antecedent rainfall of certain duration and the possible long-term cumulative effect of certain parameters. Furthermore, there is no known statistical method to model these effects. To fill this gap, a new model (CN_{asy}) is propose to determine asymptotic *CN* based on cumulative rainfall-runoff ordered data of different day durations.

The antecedent precipitation index plays significant influences in *CN* determination. Daily *P–Q* data set not have much explanatory power to describe complex hydro meteorological characteristics of watershed, therefore, it might be failed to capture the cumulative effect. Further, long-term cumulative effects have not been adequately modelled by existing methodologies. The 5-day is used as an antecedent precipitation index in the original *CN* method to classify AMC conditions. Beside the antecedent period (5, 15 and 30 days); the use of AMC classes in 5-day period is also under discussion: Some researchers claimed that AMC classes should be considered (Boonstra, 1994) while the rest reported that it had no effect. The soils in the watershed are practically saturated from antecedent rainfalls (i.e. the soil moisture content is at field capacity). Cumulative rainfall-runoff data provides information about the maximum amount of water that can be stored in the watershed. Based on the soil characteristics, every watershed has different storage capacity. In order to select the most appropriate AMC level, effect of cumulative rainfall (Equation 4.12) and cumulative runoff (Equation 4.13) data set of different daily duration are incorporated in asymptotic *CN* determination.

$$P_n = \sum_{i=1}^{N} p_i \tag{4.12}$$

and

$$Q_n = \sum_{i=1}^{N} Q_i \tag{4.13}$$

Where, N is number of cumulative days. In this study, cumulative P_n–Q_n ordered data are used in place of ordinary *P–Q* ordered data to determine asymptotic *CN* for the study region.

4.8 *CN* by Incorporating Morphometric Parameters

The *CN* is function of land type, land use and its characteristics, therefore, geomorphological parameters can play significant role in determining water movement within the watershed. Morphometric analysis is an important tool which provides information about the hydrological nature of the watershed. Very few attempts have been made to include morphometric parameters in *CN* determination. Considering to all these facts a study was undertaken with the objective to estimate the surface runoff using *CN* obtained from morphometric parameters.

4.8.1 Slope Adjusted *CN* (Huang)

CN values of NEH-4 table are presumably valid for the watershed slope less than 5%. (Mahboubeh et al., 2012) suggested that *CN* values must be adjusted for watershed slope if it is higher than 5%. Sharpley and Williams (1990) incorporated the watershed slope in determination of *CN* to improve the surface runoff estimation and provided (Equation 4.14).

$$CN_{II\alpha} = \frac{1}{3}(CN_{III} - CN_{II})(1 - 2e^{-13.86\alpha}) + CN_{II} \tag{4.14}$$

Where, $CN_{II\alpha}$ is the value of CN_{II} for a given slope and α is slope (m/m).

In china, Huang et al. (2006) studied the effect of slope on runoff and developed a slope-adjusted equation (Equation 4.15) to adjust the CN_{II} values for watershed slopes.

$$CN_{II\alpha} = CN_{II}\,\frac{322.79 + 15.63\alpha}{\alpha + 323.52} \tag{4.15}$$

(Equation 4.14) and (Equation 4.15) were used to adjust the CN_{II} values for watershed slopes, assuming that CN_{II} obtained from the Hand book table (SCS, 1972) corresponds to a slope 5%. However, these relations are yet to be verified experimentally in Indian watersheds. In the present study, slope-adjusted (Equation 4.15) is used to study the effect of slope and estimate the surface runoff for the test watersheds of the study region having slope less than 5%.

4.8.2 Modified *CN* by Incorporating Morphometric Parameters (CN_{mor})

The watershed morphometric parameters represent watershed attributes and are directly or indirectly employed in synthesizing hydrological response. These parameters play significant role in determining water movement within the watershed. Five major morphometric parameters viz. watershed area (*A*), channel slope (*Sl*), total length of main stream (*L*), length to the centroid of area (L_{ca}) and drainage density (*DD*) were incorporated to modify *CN*. The (*Sl*) is determined as the elevation difference between the end points of the main channel divided by the channel length. (L_{ca}) is the distance measured along the main channel from the basin outlet to the point on the main channel opposite the centroid of the area. (*DD*) has the units of the reciprocal of length and it is the ratio of the total length of streams within a watershed to the area of the watershed. A watershed with a high drainage density would indicate a relatively high density of streams and thus it is characterized by quick and peaked runoff response. The runoff increases with the area and slope of the watershed. Larger the main stream length leads to smaller elongation ratio and larger the length to the centroid of area gives less opportunity time to infiltration thus, they generate more runoff. Therefore, all the five morphometric parameters have direct relationship with *CN*. Previous studies deal with the investigation of the relations between watershed parameters and hydrologic indices (Gregory and Walling, 1973; Cooke and Doornkamp, 1990) and have tried to establish the link between the hydrological response of a watershed and descriptors of its physical attributes (Karymbalis et al., 2012; Post and Jakeman, 1996, 1999; Runge and Nguimalet, 2005; Gajbhiye, 2015). Considering to all these facts a model (CN_{mor}) is attempted by introducing the morphometric parameters of the watershed in *CN* determination for enhancement of conventional SCS-CN method.

The values of the selected five major morphometric parameters of Ozat, Uben and Shetrunji watersheds were calculated with the help of respective drainage maps Fig. 3.2-3.4 and ArcGIS tools in GIS environment for different periods. A weighted CN_{II} (CN_{IImor}) was determined for entire watershed by using morphometric parameters and individual CN_{II} for each sub watershed. The CN_{IImor} is calculated by (Equation 4.16).

$$CN_{IImor} = \frac{\sum_{i=1}^{n} CN_{IIi} x A_i x Sl_i x L_i x L_{ci} x DD_i}{A_o x Sl_o x L_o x L_{co} x DD_o} \tag{4.16}$$

Where, CN_{IImor} is the weighted *CN* of the watershed; CN_{II} is *CN* of sub-area for AMC-II; A_i is the sub-area of the watershed; Sl_i is the slope of each sub watershed; L_i is total length of main stream; L_{ci} is length to the centroid of each sub watershed; DD_i is the drainage density of each sub-area; A_o, Sl_o, L_i, L_{co} and DD_o are corresponding morphometric parameters for entire watershed and n is the number of sub watersheds in the watershed. With this modified CN_{IImor}, surface runoff is then simulated by the SCS-CN method for the study region. The values of morphometric parameters and CN_{IImor} are presented in Tables 4.3-4.5.

TABLE 4.3 CN_{IImor} and morphometric parameters of Ozat watershed							
Sub Watersheds	**Area (Sq. Km)**	***Sl* (%)**	***L* (Km)**	**L_c (Km)**	***DD* (Km/Km^2)**	**CN_{II} 1994-95**	**CN_{II} 2005-06**
A1	40.7159	0.4711	9.5524	5.4790	0.9383	81.35	81.05
A2	40.6520	0.4115	18.4691	12.4261	0.9810	82.04	81.10
A3	49.5768	0.4659	15.8848	10.0806	1.4593	81.32	81.53
A4	73.2885	0.4643	16.1549	9.8970	0.8679	81.34	81.56
A5	75.1963	0.5866	32.9036	14.8001	1.1406	81.80	82.12
A6	18.5607	0.6409	10.6103	6.5458	1.2206	81.58	80.98
A7	53.0732	0.4621	14.4987	7.5694	0.7498	82.08	81.89
Overall	**351.0633**	**0.6581**	**34.9508**	**16.7711**	**0.9131**	**81.64**	**81.58**
				Huang	$CN_{II\alpha}$	**61.21**	**61.17**
				CN_{mor}	CN_{IImor}	**27.99**	**28.03**

TABLE 4.4 CN_{IImor} and morphometric parameters of Uben watershed							
Sub Watersheds	**Area (Sq. Km)**	***Sl* (%)**	***L* (Km)**	**L_c (Km)**	***DD* (Km/Km^2)**	**CN_{II} 2001-02**	**CN_{II} 2005-06**
A1	106.3912	0.3345	22.4217	11.5607	0.4889	80.94	80.81
A2	186.4007	0.3020	38.4064	17.2366	2.2791	80.99	81.03
A3	54.9367	4.0212	25.6640	15.2134	1.1377	71.56	71.72
A4	45.2948	3.1564	15.7774	11.1996	1.5215	76.51	76.58
A5	23.8138	6.9299	11.7607	7.0845	1.4225	74.77	76.45
A6	79.7077	0.1690	10.6520	5.6192	0.6520	80.62	80.60
Overall	**496.5448**	**1.6980**	**49.0585**	**22.9737**	**0.8591**	**79.17**	**79.26**
				Huang	$CN_{II\alpha}$	**56.38**	**56.75**
				CN_{mor}	CN_{IImor}	**22.92**	**22.99**

TABLE 4.5 CN_{IImor} and morphometric parameters of Shetrunji watershed							
Sub Watersheds	**Area (Sq. Km)**	***Sl* (%)**	***L* (Km)**	**L_c (Km)**	**_DD_ (Km/Km^2)**	**CN_{II} 1994-95**	**CN_{II} 2005-06**
A1	28.5837	0.7229	19.2271	7.0830	0.9009	82.34	80.63
A2	98.8116	1.6050	25.2343	13.9839	1.0107	57.83	72.29
A3	31.7619	0.8683	10.7102	6.0460	1.2554	77.96	78.42
A4	5.3244	2.1715	8.0588	3.9108	1.3341	39.08	76.89
A5	26.7209	1.6544	11.4846	6.2504	1.2450	49.56	50.16
A6	42.9188	0.9576	10.9654	5.3805	1.0814	75.51	75.94
Overall	**234.1213**	**1.7793**	**25.2343**	**15.3671**	**1.0699**	**65.43**	**72.39**
				Huang	$CN_{II\alpha}$	**44.98**	**51.57**
				CN_{mor}	CN_{IImor}	**23.53**	**28.37**

4.9 *CN* by Incorporating Evapotranspiration

Evapotranspiration (*ET*) is second largest term after precipitation in the terrestrial water budget and also significantly influenced on the water balance of a watershed. About 70% of the mean annual rainfall is gone back to atmosphere as *ET* (Brutsaert, 1982, 1986; Kustas, 1990; Philip, 2002). Therefore, Long-term loss like evaporation and *ET* are essential to incorporate in continuous hydrological modelling for seasonal yield evaluation. Quantitative estimation of *ET* is of great significance in hydrological modelling, water resource planning, estimation of crop water requirements for irrigation, agricultural production forecasting. Unfortunately, most of the *ET* estimation methods are parameter rich methods and not feasible for application in data scarce regions. The FAO-56 Penman-Monteith method (Penman, 1948) is ranked as the best physical, reliable, mostly used method and well accepted as a standard to verify other empirical methods. However, it needs expertise and a lot of different input parameters. Thus, the usefulness such complex method in *ET* estimation seems to be questionable. This problem nurtures a need for development of simpler methods which compatible enough with the complex methods and derive ET representing the whole watershed. The Middle South Saurashtra region, a water scarcity-prone region of Gujarat state and has only limited number of weather stations facilitated to measure relevant meteorological variables. Therefore simple methods with based on available meteorological data are better choice than standard FAO-56 Penman-Monteith method to estimate ET in such situation.

4.9.1 Estimation of *ET*

The reference evapotranspiration (ET_o) is a function of local weather, represents the evapotranspiration (*ET*) from a defined vegetated surface, and serves as an evaporative index by which engineers, hydrologists, and practitioner community can predict *ET* for agricultural or landscaped areas. ET_o is a key parameter in hydrological and meteorological studies and used to determine the actual water use rate for various crops. It is an important element in the hydrologic cycle that integrates atmospheric demands and surface conditions. ET_o is of great significance for understanding climate change and its impacts on hydrology. It is an important agro-meteorological parameter and can be defined as the *ET* rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation (Allen et al., 2005). ET_o describes the evaporative power of the atmosphere independently of crop type, crop development and management practices and can be computed from weather data. Thus, it is considered that the insertion of ET_o estimates into the daily water balance made an equivalent soil water regime as that derived by using actual *ET*. American Society of Civil Engineers Evapotranspiration (ASCE-ET) members include renowned scientists and engineers, and both researchers and practitioners has developed standardized ET_o equations for calculating hourly and daily *ET* for both a short reference crop and a tall reference crop ET_o for a short crop having an approximate height of 0.12 m (similar to grass) while for a tall crop having an approximate height of 0.50 m (similar to alfalfa). The ET_o was calculated by standard FAO Penman Monteith (Equation 4.17).

$$ET_o - PM = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{\mathrm{C_n}}{\mathrm{T} + 273} \mathrm{u}_{2(\mathrm{e_s} - \mathrm{e_a})}}{\Delta + \gamma(1 + \mathrm{C_d u_2})} \quad (4.17)$$

Where,

ET_o-PM	Short or tall reference crop evapotranspiration [mm day^{-1}]
R_n	Net radiation at the crop surface [MJ m^{-2} day^{-1}]
G	Soil heat flux density at the soil surface [MJ m^{-2} day^{-1}]
T	Mean daily or hourly air temperature at 1.5 to 2.5m height [°C],
u_2	Mean daily or hourly wind speed at 2m height [m s^{-1}],
e_s	Mean saturation vapour pressure at 1.5 to 2.5m height [KP_a];
e_a	Mean actual vapour pressure at 1.5 to 2.5m height [KP_a],

Δ	Slope of the vapour pressure-temperature curve [$KP_a\ ^{\circ}C^{-1}$],
γ	Psychrometric constant [$KP_a\ ^{\circ}C^{-1}$],
C_n	Numerator constant for reference type and calculation time step, and
C_d	Denominator constant for reference type and calculation time step.

Values for the constants C_n and C_d are provided in Table 4.6.

Table 4.6 Values for C_n and C_d in (Equation 4.17)

Calculation Time Step	**Short Reference, *ET_o***		**Tall Reference, *ET_o***		**Units for *ET_o***	**Units for R_n, G**
	C_n	C_d	C_n	C_d		
Daily or Monthly	900	0.34	1600	0.38	mm day^{-1}	MJ m^{-2} day^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during night time	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

The dependency of controlling meteorological variables like air temperature, vapour pressure and relative humidity on ET_o were analysed and compared using dataset of two existing weather stations, Junagadh and Amreli of Junagadh Agricultural University, Junagadh. Maximum air temperature (T_{max}) and radiation (R_s) were found to be the most significant factors influencing ET_o-*PM* when tested by dependence analysis on the dataset of from calibration period in the study region. Two weather stations Junagadh and Amreli of Junagadh Agricultural University, Junagadh are existed in the study region. The Penman equation yields the most accurate estimates of ET_o from saturated surface, if sufficient input data are available. However, in most cases limited reliable input data are available. Therefore, FAO-56 PM method is not practical in many such situations Further, due to high cost involved in instrumentation and maintenance of gauging stations, it is not possible to set up and maintain the stations over many locations for a long period of time. Thus, the usefulness of complex methods having more input data requirement in ET_o estimation seems to be controversial and therefore, a need for development of simpler methods to derive ET_o representing the whole catchment and compatible with the available complex methods. The authors were compared five different alternative modified equations (viz. Turc, 1961; Jensen and Hasie, 1963; Hargreaves and Samani, 1985; Priestley and Taylor, 1972; Makkink, 1957) methods and developed a model which has fewer input parameters to estimate ET_o at daily time scale based on the most dominant meteorological variables for the study region (Equation 4.18).

$$ET_o = \mathrm{a}(\mathrm{R_s e^{oT_{max}}}) \tag{4.18}$$

Where, T_{max} is the maximum temperature in ^{0}C, 'a' is the calibration constant, R_s Solar radiation [MJ m^{-2} day^{-1}] and e^{oTmax} is saturation vapour pressure at daily maximum temperature in [KP_a]. The proposed model with single calibration parameter performed outstandingly best for Junagadh (d_r=0.84 and MAE=0.73 mm) and Amreli (d_r=0.85 and MAE=0.46 mm) stations. Values of calibration constant 'a' were found 0.0799 for Junagadh station and 0.0666 for Amreli station. Estimated values of ET_o are used as *ET* in the models considered in this study.

4.9.2 *ET-CN* Relationship

The event-based SCS-CN methodology was formerly suggested by Ponce and Hawkins (1996) for small ungauged agricultural watersheds having areas less than 250 Sq. Km. However, Williams and LaSeur (1976), Hawkins (1978), Soni and Mishra (1985), Mishra and Singh (2004b), Geetha et al. (2008) and Mishra et al. (2008) have employed it for long-term hydrologic simulation in larger size catchments. Ponce and Hawkins (1996) worked on the applicability of curve number and considered the *CN* method as one of the useful tool for calculating runoff depths. This technique was already adopted for various regions, land uses and climate conditions (Mishra and Singh, 1999). Many researchers (Patil et al. (2008), Kumar et al. (2010), Geena and Ballukraya (2011), Nayak et al. (2012), Gajbhiye et al. (2013), Mishra et al. (2013), Mishra and Kansal (2014), Thakuriah and Saikia (2014), Vaishali and Regulwar (2015) Viji et al. (2015) Gajbhiye (2015)) applied this technique in Indian watersheds and found satisfactory results. Mishra et al. (2014) revealed in their study that *ET* and *CN* have inverse relationship. They show that, *CN* increases and *ET* decreases with increasing relative imperviousness of the area for urban land, cultivated lands (fallow, row crops, small grain crops, close seeded legumes) exhibit higher *ET* and lower *CN* while uncultivated lands (pasture or waste land) have lower *ET* and higher *CN* for agricultural lands, *ET* decreases and *CN* increases with decreasing forest coverage. NEH-4 table (SCS, 1956) also labels higher *CN* values to cultivated lands and lower *CN* values to uncultivated lands which support that *ET* to be high in low *CN* watersheds. Furthermore, the *CN* value increases from sandy (soil group A) to clayey (soil group D) while ET decrease from sandy (soil group A) to clayey (soil group D) soils.

4.9.3 Williams and LaSeur (1976) Model

Williams and LaSeur (1976) were the first to incorporate *PET* in the *CN* method. They assumed that soil moisture index vary with the lake evaporation. They were linked the parameter *S* to soil moisture depletion, rather than to soil available water capacity and developed a continuous simulation model by incorporating *S* with the soil moisture *M* in the *CN* method for computation of direct surface runoff (Equation 4.19) and (Equation 4.20). This method avoids sudden jumps in *CN* and allows it to vary widely from 33.3 to 100.

$$M = S_{abs} - S \tag{4.19}$$

$$M_t = \frac{M}{1 + \beta\, M \sum_1^n PET_t} \tag{4.20}$$

Where, M_t is the soil moisture index at any time t, β is the moisture depletion coefficient and PET_t is the average monthly lake evaporation for day t and n is number of days between storms. S_{abs} is the absolute potential maximum retention equal to 508 mm.

4.9.4 Kannan (2008) Model

Since the SCS-CN model is an infiltration loss model, it does not account for long-term losses such as evaporation and evapotranspiration. Kannan et al. (2008) observed that for shallow soils and soils with low storage, the existing methods are found less effective to reproduce the observed runoff. They developed a single parameter evapotranspiration and precipitation based continuous soil moisture accounting methodology for use in the SCS-*CN* procedure. The retention parameter *S* was initialised based on CN_{II} value. They provide expression of *S* at present time step as (Equation 4.21).

$$S_t = S_{t-1} + PET_t e^{\left(\frac{-\beta S(t-1)}{S_{max}}\right)} - P + Q \tag{4.21}$$

Where, S_t is the retention parameter at the present time step, S_{t-1} is the retention parameter at the previous time step, β is the depletion coefficient (theoretically varies from 0 to 2), *P* is the rainfall depth at the previous time step, *Q* is the runoff depth at the previous time step, and S_{max} is the maximum value of the retention parameter. However, this model does not take into account the effects current day rainfall. They were provided the expression for two different conditions. (Equation 4.22) employed for faster depletion rate under saturation.

$$S_t = PET_t - P + Q \tag{4.22}$$

(Equation 4.23) used for much slower rate as S approaches S_{max}.

$$S_t = S_{max} + PET_t e^{-B} - \mathrm{P} + \mathrm{Q} \tag{4.23}$$

4.9.5 Modified *CN* by Incorporating Evapotranspiration (CN_{temp})

Many methods have been developed to determine *CN* over the last five decades in different parts of the world but none can be recommended as the best one for any region or any season in terms of its accuracy and feasibility. In this study, the easily derivable *CN* from the long term daily rainfall-runoff data is linked with ET_o derived from dominant meteorological variable (maximum temperature). The proposed model formulation includes the SCS-CN concept revised for rainfall dependent initial abstraction and modification of *CN* by incorporating ET_o for continuous hydrologic simulation of the SCS-CN method.

INITIAL ABSTRACTION (I_a)

Initial abstraction is a short term loss before ponding, which includes interception, infiltration and surface storage. As reported by USDA, Initial abstraction I_a was not linearly proportional to potential maximum retention *S.* Similar conclusions were reported by other researchers (Mishra et al., 2004, 2006; Jain et al., 2006). Here, it is assumed that the initial abstraction for first five days before beginning monsoon period is a fraction of the possible retention in the soil and is computed by (Equation 4.24) as:

$$I_a(t) = \lambda\, S_t, if\ t \le 5\ days \tag{4.24}$$

After five days, the initial abstraction is obtained by incorporating precipitation (*P)* as well as retention storage (*S)* and expressed it as (Equation 4.25).

$$I_a(t) = \lambda\, S_t \frac{P_t}{P_t + S_t}, if\ t > 5\ days \tag{4.25}$$

Initial abstraction (ratio) coefficient (λ) = 0.2 was assumed in the original SCS-CN method. In the present study performance of all the methods were tested with λ=0.05, λ=0.1 and λ=0.2, however, λ=0.2 was adopted to compared the results of different models.

MODIFIED *CN* DETERMINATION (CN_{temp})

The computation of daily soil moisture accounting is essential in a daily continuous hydrologic simulation. Williams et al. (2012) seen that the soil-moisture concept based method have been predicted too much runoff in shallow soils. The past studies shown that *CN* has inverse relationship with *ET*. ET_o represents the loss of water from reference surface and it significantly influence on the water balance of a watershed. Thus, increases in ET_o should lead to decreases in runoff. This effect could be counterbalance by decreases in *CN*. ET_o is a function of local weather and its value is less dependent on soil storage and more dependent on antecedent climate, therefore, calculation of the daily CN_{II} value as a function of ET_o would provide more realistic runoff estimation. Therefore, in this study *CN* is modified by incorporating ET_o by (Equation 4.26) as:

$$CN_{temp} = \frac{CN_{II}}{1 + \beta\ CN_{II}\ ET_o} \tag{4.26}$$

Where, CN_{temp} is the modified CN_{II}, β is the *CN* depletion coefficient and ET_o is the reference evapotranspiration. The model has an upper limit CN_{II} for AMC II condition and allows *CN* values to vary with the rate of ET_o. Equation (4.26) is analogues to the (Equation 4.20) of soil moisture index given by Williams and LaSeur (1976). The only parameter adjusted for calibrating surface runoff is depletion coefficient β. The model calibration is based on the adjustment of depletion coefficient β until the predicted daily surface runoff closely matches the observed value.

4.10 IHACRES Model

Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Stream flow data (IHACRES) is a parsimonious, hybrid conceptual-metric rainfall-runoff model that has been evaluated in a wide range of climates and catchments. It has been developed collaboratively by the Institute of Hydrology and the Centre of Resource and environmental Studies at the Australian National University (CRES at ANU), Canberra. Several versions of the non-linear loss module have been developed in the last years. The (Ye et al., 1997) version has been reformulated by Croke et al. (2005) to enable the mass balance parameter c to be estimated from the gain of the transfer function, and to reduce the interaction between the c and ρ parameters. The effective rainfall u_k (mm) in the revised model is proposed by (Equation 4.27):

$$u_k = [c(\emptyset_k - l)]^{\rho} r_k \qquad (4.27)$$

Where, r_k is the observed rainfall in mm on day k, c (mass balance), l (soil moisture index threshold), and ρ (non-linear response terms) are parameters. The parameters l and ρ are specifically used for ephermal catchments. The soil moisture index $\emptyset_k$ is described by (Equation 4.28):

$$\emptyset_k = r_k + \left(1 - \frac{1}{\tau_k}\right)\emptyset_{k-1} \qquad (4.28)$$

The drying rate τ_k as determined by (Equation 4.29):

$$\tau_k = \tau_w e^{\left(0.062 f (T_r - T_k)\right)} \qquad (4.29)$$

Where, τ_w (reference drying rate at reference temperature ^{0}C), f (temperature modulation $^0C^{-1}$), T_k (observed temperature ^{0}C), and T_r (reference temperature ^{0}C) are parameters. This formulation enables the gain of the transfer function to be directly related to the value of the parameter c, thus simplifying model calibration. The parameter f, mainly affected by climate, land use and land cover relates to seasonal variation of evapotranspiration. The parameter τ_w affects the variation of soil drainage and infiltration rates.

4.11 Statistical Criteria

The existing and developed models were tested for selected watersheds of the study region. The performances of the models were evaluated using three popular statistical criterion refined Willmott's index (d_r) (Willmott et al., 2012), mean bias error (MBE) (Addiscott and Whitmore, 1987), and mean absolute error (MAE) (Shaeffer, 1980). MBE and MAE express average interpolator error in the units of the variable of interest.

4.11.1 Willmott's Index (d_r)

The d_r is dimensionless statistic which provides a relative model evaluation assessment. It is applied to quantify the degree to which observed values of runoff are captured by the proposed models. The d_r is expressed as shown in (Equation 4.30).

$$d_r = \begin{cases} 1 - \dfrac{\sum_{i=1}^{n} \lceil P_i - O_i \rceil}{2\sum_{i=1}^{n} \lceil O_i - \bar{O} \rceil}, \text{when } \sum_{i=1}^{n} \lceil P_i - O_i \rceil \leqslant 2\sum_{i=1}^{n} \lceil O_i - \bar{O} \rceil \\ \dfrac{2\sum_{i=1}^{n} \lceil O_i - \bar{O} \rceil}{\sum_{i=1}^{n} \lceil P_i - O_i \rceil} - 1, \text{when } \sum_{i=1}^{n} \lceil P_i - O_i \rceil > 2\sum_{i=1}^{n} \lceil O_i - \bar{O} \rceil \end{cases} \tag{4.30}$$

Where, P_i and O_i are the i^{th} observations of datasets *P* and *O*, and *n* is number of the observations. $\bar{O}$ is observed mean.

The range of d_r is from −1.0 to 1.0. A d_r of 1.0 describes perfect agreement between observed and estimated runoff while d_r of −1.0 indicates either lack of model fitting or insufficient variation in observations to adequately test the model. It is more rationally index related to model accuracy than the other existing indices.

4.11.2 Mean Bias Error (MBE)

MBE represents the deviation of the mean and eliminates the positive and negative differences between observations and usually intended to measures the model bias. In fact, it is merely the difference between the mean values of the two datasets. MBE test provides information on the long-term performance. Ideal value of MBE is zero; however, a low MBE is desired. A positive value gives the average amount of over-estimation in the calculated value and vice versa. It is expressed by (Equation 4.31) as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) = \bar{P} - \bar{O} \tag{4.31}$$

$\bar{P}$ and $\bar{O}$ are model-predicted and observed means.

4.11.3 Mean Absolute Error (MAE)

MAE is the most natural and unambiguous error index statistic used to represent the average difference between model computed and observed values. The MAE provides a more robust measure of average model error than the root mean square error (RMSE), since it is not influenced by extreme outliers (Legates and McCabe, 1999). Unlike RMSE, it is unequivocal and a more natural measure of average error. A higher MAE value indicates poor model performance and vice versa. MAE=0 indicates a perfect fit. MAE is given by (Equation 4.32) as:

$$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}|\mathrm{P_i} - \mathrm{O_i}| \tag{4.32}$$

4.11.4 F-Test

F-test is used to compare nested models or methods. The F-test is conducted to see which method is statistically better. It gives a definitive answer and does not rely on arbitrary interpretation of residual plot. In the present study, the F-test is performed to test the hypothesis and to decide the developed model is statistical significant or not. The F-test is based on the difference between the sum-squares of the two models with taking in account their degrees of freedom. The F ratio (Equation 4.33) equals the relative difference in sum-of-squares divided by difference in degrees of freedom.

$$\mathrm{F} = \frac{(SS_{nul} - SS_{alt})/SS_{alt}}{(DF_{nul} - DF_{alt})/DF_{alt}} \tag{4.33}$$

Where, SS_{nul} and DF_{nul} are sum-of-squares and degrees of freedom of simpler model (null hypothesis), and SS_{alt} and DF_{alt} are sum-of-squares and degrees of freedom of more complex (alternate hypothesis) model. The p value can be calculated from known F distribution and DF. If the p value is less than the set significance level (usually 0.05), concluded the alternative model fits the data significantly better than the simple model.

4.11.5 Akaike Information Criterion (AIC)

Unlike the F-test, AIC method (Akaike, 1973) can be used to compare either nested or non-nested models. AIC method is based on information theory, maximum likelihood theory, and the concept of the entropy of information and it is a powerful tool for comparing models. In this method, the "best" model is determined by an AIC score (Equation 4.34):

$$\Delta\mathrm{AIC} = AIC_B - AIC_A = N\, ln\left(\frac{SS_B}{SS_A}\right) + 2(K_B - K_A) \tag{4.34}$$

Where, N is the number of data points, K is the number of fit by the regression plus one, and *SS* is the sum-of-squares of the vertical distances of the points from the curve, Subscript A stands for simpler model and B for more complex model.

Hurvich and Tsai (1989) further refined this estimate to correct for small data samples (Equation 4.35):

$$AIC_c = \text{AIC} + \left(\frac{2K(K+1)}{N-K-1}\right) \tag{4.35}$$

Where, AIC_c is corrected Akaike's Information Criterion. AICc does not reach conclusions about "statistical significance" and does not "reject" any model. The model with the lowest AICc score is most likely to be correct. The main advantage of the AICc approach is that it tells you how much more likely the model and it is easily extended to compare more than two models. The evidence ratio (ER) is based on the absolute difference between AICc scores, representing the evidence about fitted models as to which is better in an information criteria sense. Kass and Raftery (1995) categorised the comparison based on logarithm of ER (LER) (Equation 4.36) as, 'minimal', 'substantial', 'strong', and 'decisive' to correspond approximately to LERs between model probabilities of greater than 0, 0.5, 1, and 2 respectively.

$$\text{LER} = \frac{1}{\mathrm{e}^{-0.5\,\Delta\text{AIC}_\text{c}}} \tag{4.36}$$

4.12 Closure

This chapter elaborates the existing methodology of *CN* estimation and proposed methodology for modifying *CN*. The proposed methodology has been consisted of three different approaches: connecting *CN* estimation by incorporating impact of cumulative ordered data, morphometric parameters and evapotranspiration. Fig. 4.1 provides summary of proposed methodology in the form of flow chart. The other relevant existing models are also discussed. Three popular quantitative standard statistical performance evaluation measures are discussed. The F-test and AIC_c criteria to check statically significance of the models and to decide the most appropriate model are also elaborated. The proposed methodology is applied on test watersheds of the Middle South Saurashtra region. The next chapter discusses all the results obtained for the study region.

CHAPTER 5

Results and Discussions

5.1 General

The sequential modelling approach developed in the form of proposed methodology for *CN* determination has been described in previous chapter. Study application is extremely important to know the universality of the applied methodology. To test the methodological framework and investigate its performance with respect to a real watershed environment, the proposed methods are tested on the dataset of test watersheds viz. Ozat, Uben and Shetrunji watersheds of the Middle South Saurashtra region. Performance of the each proposed method is evaluated by using statistical criterion and compared with existing methods. The results obtained are presented in form of tables as well as graphs for better understanding in this chapter.

5.2 Effect of LULC Alteration on Composite *CN*

The composite CN_{II} values were computed at sub watershed scale by integrating associate LULC and HSG maps for Ozat, Uben and Shetrunji watersheds. To detect the effect of alternate LULC change on *CN* in sub watersheds of Ozat, Uben and Shetrunji Watersheds, the composite CN_{II} values were calculated at sub watershed scale for different time periods. The scenarios of composite CN_{II} values fluctuation in different time periods are explained in Tables 5.1-5.3. Tabulated values exhibit the variation of composite CN_{II} of test watersheds in different time periods. From Fig. 5.1, it is revealed that *CN* values fluctuate more in sub watershed A2 and A6 of the Ozat watershed. Little variation of *CN* values are observed in A3 and A5 sub watersheds of the Uben watershed (Fig. 5.2). Figure 5.3 shows that are comparatively large change have been seen in A2 and A4 sub watersheds of the Ozat watershed. Table 5.1 explains that *CN* values of the watershed vary largely (65.43 to 72.13 from year 1994-95 to 2009-10) in the Shetrunji watershed, but, very little fluctuation in *CN* values have been found in the Ozat and Uben watersheds.

TABLE 5.1. Composite CN_{II} values for each sub watershed of Ozat, Uben and Shetrunji watersheds

Ozat Watershed					**Uben Watershed**				**Shetrunji Watershed**			
Sub Watersheds	**Total Area (Sq. Km.)**	**Composite CN_{II}**			**Total Area (Sq. Km.)**	**Composite CN_{II}**			**Total Area (Sq. Km.)**	**Composite CN_{II}**		
		1994-95	**2005-06**	**2009-10**		**2001-02**	**2005-06**	**2009-10**		**1994-95**	**2005-06**	**2009-10**
A1	40.7159	81.35	81.05	81.84	106.3912	80.94	80.81	80.79	28.5837	82.34	80.63	78.75
A2	40.6520	82.04	81.10	81.81	186.4007	80.99	81.03	79.94	98.8116	57.83	72.29	71.25
A3	49.5768	81.32	81.53	81.92	54.9367	71.56	71.72	73.39	31.7619	77.96	78.42	79.14
A4	73.2885	81.34	81.56	81.71	45.2948	76.51	76.58	76.07	5.3244	39.08	76.89	73.87
A5	75.1963	81.80	82.12	82.45	23.8138	74.77	76.45	76.36	26.7209	49.56	50.16	51.95
A6	18.5607	81.58	80.98	81.50	79.7077	80.62	80.60	80.93	42.9188	75.51	75.94	76.91
A7	53.0732	82.08	81.89	82.07	-	-	-	-	-	-	-	-
A	**351.0633**	**81.64**	**81.58**	**81.97**	**496.5448**	**79.17**	**79.26**	**79.03**	**234.1213**	**65.43**	**72.39**	**72.13**

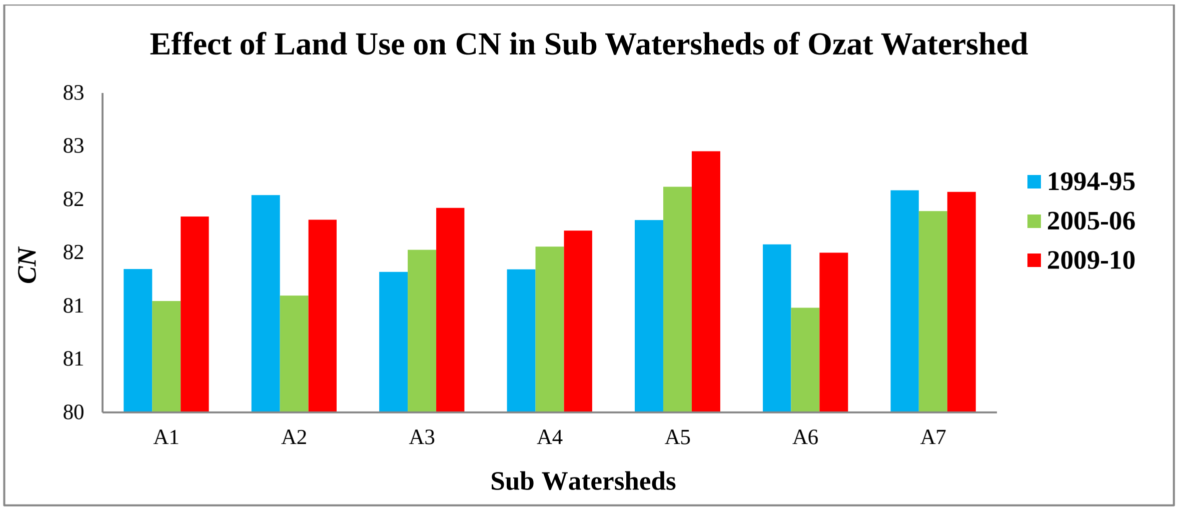


FIGURE 5.1 Effect of alternate LULC change on *CN* in sub watersheds of Ozat watershed

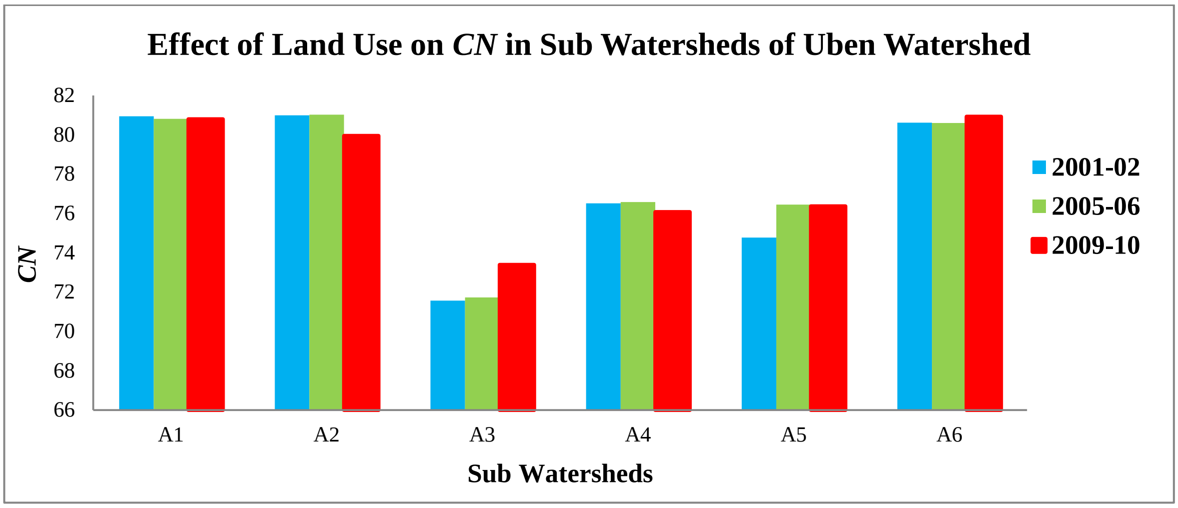


FIGURE 5.2 Effect of alternate LULC change on *CN* in sub watersheds of Uben watershed

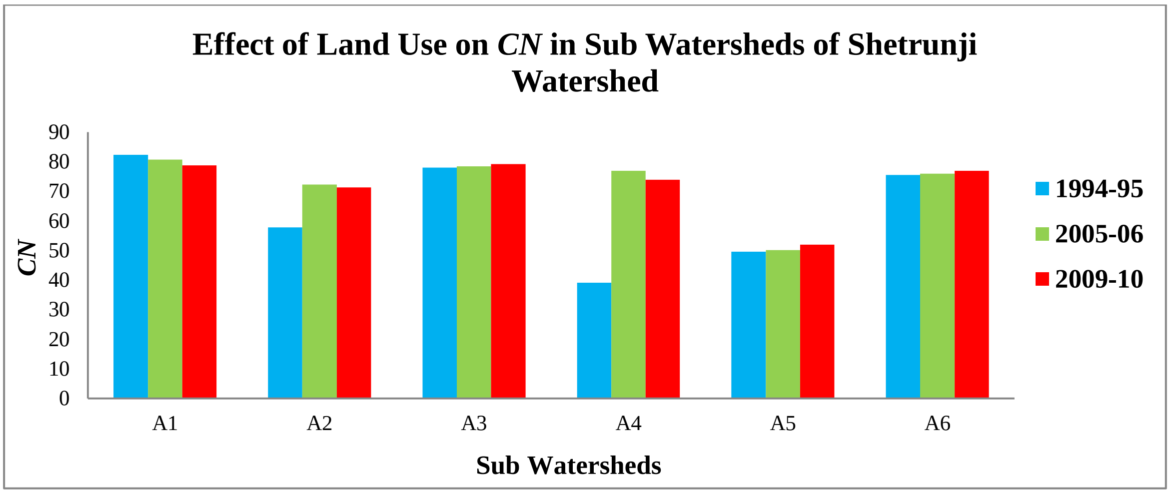


FIGURE 5.3 Effect of alternate LULC change on *CN* in sub watersheds of Shetrunji watershed

5.3 Performance of the SCS-CN Method with Composite *CN*

Initial abstraction ratio is taken as λ=0.2 and composite *CN* values are adopted as representative *CN* values to test performance of the SCS-CN method in the study region. The SCS-CN method with composite *CN* and λ=0.2 is applied on the dataset of test watersheds to estimate runoff. Table 5.2 shows the performance details of the SCS-CN method on dataset of calibration and validation periods.

TABLE 5.2. Performance of the SCS-CN method with composite *CN*

	Ozat Watershed		Uben Watershed		Shetrunji Watershed	
Area	351.0633 Sq. Km.		496.5448 Sq. Km.		234.1213 Sq. Km.	
Periods	1980-95	1995-2010	2001-05	2006-10	1987-95	1996-2004
Total Rainfall (mm)	9722	10612	2766	4208	4236	3523
Overall Observed Runoff (mm)	1575	2021	211	315	397	534
Overall Calculated Runoff (mm)	3705	3895	771	1592	637	620
CNI	65.13	65.04	61.48	61.61	44.28	52.40
CNII	84.64	81.58	79.17	79.26	65.43	72.39
CNIII	91.10	91.06	89.73	89.78	81.32	85.77
d_r	0.50	0.57	-0.10	-0.30	0.55	0.65
MAE	1.21	1.45	1.20	2.22	0.51	0.54
MBE	0.93	0.82	0.73	1.67	0.17	0.06

It is evident from Table 5.2 that the SCS-CN method produced comparatively better results for Shetrunji watershed on dataset of calibration (d_r=0.55, MAE=0.51, MBE=0.17) and validation (d_r=0.65, MAE=0.54, MBE=0.06) periods. The results for Uben watershed in calibration (d_r=-0.10, MAE=1.20, MBE=0.73) and in validation (d_r=-0.30, MAE=2.22, MBE=1.67) periods indicate poor performance of the SCS-CN method. This method produced marginally good results for Ozat watershed in calibration (d_r=0.50, MAE=1.21, MBE=0.93) and in validation (d_r=0.57, MAE=1.45, MBE=0.82) periods. The results are in good agreement to the previous study (Ponce and Hawkins, 1996), they were suggested the SCS-CN method for small ungauged agricultural watersheds having areas less than 250 Sq. Km. Further, the positive values of MBE indicate that the SCS-CN method with composite *CN* overestimated the runoff in all the three watersheds. It is understood that the d_r values are higher, whereas MAE and MBE values are very less in case of Shetrunji watershed.

Based on these inferences, it is concluded that the SCS-CN method with composite *CN* performs better on the dataset of Shetrunji watershed.

5.4 Performance of the SCS-CN Method with Modified Asymptotic *CN* (CN_{asy})

5.4.1 *P-CN* Relationship

According to NRCS, standard AFM is the preferred technique for *CN* determination. The AFM is based on ordered data and frequency matching approach method. Conventionally, the asymptotic *CN* is estimated from observed daily *P–Q* dataset. The soils in the watershed are practically saturated from successive antecedent rainfalls. The AMCs in original methodology determine correspond to low, medium and high soil moisture conditions depending on the total antecedent rainfall depth for the previous 5 days, however, the uncertainties of this concept have been questioned, and the SCS-CN method has been analyzed by many authors (Hawkins, 1983; Silveira et al., 2000; Kozlovska and Toman, 2010). Cumulative *P–Q* dataset provides the clue about the maximum amount of water that can be stored in the watershed. Based on the soil characteristics, every watershed has different storage capacity. In order to investigate the impacts of cumulative data on *CN* estimation, cumulative rainfall (P_n) and runoff (Q_n) were used in place of ordinary order *P-Q* dataset. Cumulative rainfall (P_n) and runoff (Q_n) for different daily durations were computed by using (Equation 4.12) and (Equation 4.13) respectively. Out of three well identified responses of watershed (standard, violent, and complacent) (Sneller, 1985; Hawkins, 1993), the standard response was observed in all the test watersheds. Usually, the standard response occurs when the rainfall-runoff ratio tends to attain constant value for increasing rainfall. In standard response, the *CN* describes as a function of rainfall *P*, and it is represented by the (Equation 4.10). In this study, to minimize uncertainty, $P \geq 5$ mm have been considered to determine asymptotic *CN* values.

Parameters CN_∞ and *k* were optimised by fitting (Equation 4.10) for λ=0.20. The asymptotic *CN* values were computed from cumulative ordered dataset P_n-Q_n of different day periods for test watersheds. The SCS-CN method with these asymptotic *CN* values is applied to evaluate its performance on test watersheds. Optimised values of the parameters CN_∞ and *k*, and the values of model evolution measures d_r and MAE, based on performance of the SCS-CN method with associate asymptotic *CNs* in validation period for

Ozat, Uben and Shetrunji watersheds are presented in Tables 5.3-5.5 respectively. Now, it is necessary to find out, the best performance of the SCS-CN method with cumulative ordered dataset P_n-Q_n of different day periods. Results show that performance of the SCS-CN method with AFM *CN* computed by daily *P–Q* dataset was found to be quite different from those under determined by cumulative P_n–Q_n dataset. This means that cumulative P_n–Q_n dataset play significant role in *CN* determination.

TABLE 5.3 Performance of the SCS-CN method with Composite *CN*, AFM *CN* and CN_{asy} for ordered P_n-Q_n dataset of different day periods (Ozat watershed)

P_n-Q_n	CN_∞	*k*	R^2	SE	CN_{asy}		Remarks
					d_r	MAE (mm)	**For n=1, CN_{asy} is equivalent to AFM *CN***
1	**61.73**	**0.02**	**0.90**	**2.96**	**0.68**	**1.07**	
2	56.35	0.02	0.90	3.63	0.71	0.97	
5	50.96	0.02	0.91	4. 6	0.74	0.87	**SCS-CN with Composite *CN*, d_r=0.57 and MAE=1.45 mm**
10	45.16	0.02	0.91	4.86	0.75	0.8	
12	43.68	0.02	0.91	5.09	0.75	0.82	
13	43.04	0.02	0.90	5.17	0.75	0.82	
14	**42.40**	**0.02**	**0.90**	**5.21**	**0.76**	**0.82**	
15	41.74	0.02	0.90	5.23	0.76	0.82	**Initial abstraction ration λ is taken as 0.20 for all cases**
20	38.34	0.02	0.91	5.40	0.76	0.82	
25	35.95	0.02	0.90	5.55	0.75	0.82	
30	34.27	0.02	0.89	5.72	0.75	0.83	

It is evident from Table 5.3 that performance of the SCS-CN method with CN_{asy} was improved up to 14 days cumulative days, after that slight decrement has been found in performance during prolonged cumulative days (d_r=0.76 and MAE=0.82 mm). This implies that the 14 days period may be more significant when taking AMC into account for Ozat watershed. The SCS-CN method with AFM *CN* (d_r=0.68 and MAE=1.07 mm) performed better than the SCS-CN with composite *CN* (d_r=0.57 and MAE=1.45 mm). Calibrated vales of parameter CN_∞ were found in ranged from 34.27-61.73 while values of *k* remained constant 0.02 for all 30 days analysis. Further, values of parameter CN_∞ decreases gradually with increment in cumulative days.

Table 5.4 demonstrates that performance of SCS-CN method with CN_{asy} gradually improved with increment in accumulation of data. However, no significant improvement has been found after attaining 29 days cumulative data (d_r=0.72 and MAE=0.44 mm). The SCS-CN method with AFM *CN* (d_r=0.09 and MAE=1.40 mm) and with composite *CN* (d_r=-0.30 and MAE=2.22 mm) were not performed well on the dataset of Uben watershed.

It has been noted that the AFM *CN* is data driven method. Its frail performance is mainly due to the availability of relatively smaller length (10 years) of dataset (2001-2010) for the Uben watershed.

TABLE 5.4 Performance of the SCS-CN method with Composite *CN*, AFM *CN* and $\mathbf{CN_{asy}}$ for ordered P_n-Q_n dataset of different day periods (Uben watershed)

P_n-Q_n	CN_∞	*k*	R^2	SE	CN_{asy}		Remarks
					d_r	MAE (mm)	**For n=1, CN_{asy} is equivalent to AFM CN** **SCS-CN with Composite *CN*, d_r=-0.30 and MAE=2.22 mm** **Initial abstraction ration λ is taken as 0.20 for all cases**
1	**72.16**	**0.05**	**0.97**	**1.32**	**0.09**	**1.40**	
2	56.91	0.04	0.95	2.58	0.35	1.00	
5	46.92	0.03	0.93	4.16	0.53	0.72	
10	40.43	0.03	0.92	.01	0.62	0.58	
15	37.35	0.03	0.91	5.42	0.66	0.53	
20	34.76	0.03	0.88	6.08	0.68	0.49	
25	31.82	0.03	0.85	6.78	0.70	0.46	
28	29.98	0.02	0.84	6.71	0.71	0.45	
29	**29.40**	**0.02**	**0.84**	**6.61**	**0.72**	**0.44**	
30	28.90	0.02	0.84	6.47	0.72	0.44	

Calibrated vales of parameter CN_∞ were found in ranged from 28.90-72.16, and values of parameter *k* were found in ranged from 0.02-0.05. It was seen that values of parameter CN_∞ and parameter *k* decrease gradually with increment in cumulative days.

Table 5.5 shows that performance of the SCS-CN method with CN_{asy} gradually improved with increment in accumulation of data. However, no significant improvement has been found after accomplishing 19 days cumulative data (d_r=0.75 and MAE=0.39 mm) for Shetrunji watershed. As compared to Ozat and Uben watershed, the SCS-CN method with AFM *CN* (d_r=0.70 and MAE=0.46 mm) and with composite *CN* (d_r=0.65 and MAE=0.54 mm) were performed better on the dataset of Shetrunji watershed. The ranges of values of the parameters CN_∞ and *k* were found 24.92-64.00 and 0.02-0.07 respectively for Shetrunji watershed. The Shetrunji watershed has smaller area (234.1213 Sq. Km) as compare to the area of Ozat (351.0633 Sq. Km.) and Uben (496.5448 Sq. Km.) watersheds. It depicts that that performance of the SCS-CN method with composite *CN* decreases with increase in the area of the watershed.

TABLE 5.5 Performance of SCS-CN with Composite *CN*, AFM *CN* and **CN$_{asy}$** for ordered P_n-Q_n dataset of different day periods (Shetrunji watershed)

P_n-Q_n	***CN_∞***	***k***	**R^2**	**SE**	**CN$_{asy}$**		**Remarks**
					d_r	**MAE (mm)**	**For n=1, CN$_{asy}$ is equivalent to AFM *CN* SCS-CN with Composite *CN*, d_r=0.65 and MAE=0.54 mm Initial abstraction ration λ is taken as 0.20 for all cases**
1	**64.00**	**0.07**	**0.84**	**4.17**	**0.70**	**0.46**	
2	54.58	0.05	0.95	3.16	0.74	0 40	
5	44.13	0.04	0.98	2.42	0.74	0.39	
10	37.09	0.03	0.98	2.64	0.74	0.39	
15	33.06	0.03	0.98	2.68	0.74	0.39	
18	30.87	0.03	0.98	2.70	0.74	0.39	
19	**30.24**	**0.03**	**0.98**	**2.70**	**0.75**	**0.39**	
20	29.65	0.03	0.98	2.71	0.75	0.39	
25	27.00	0.02	0.99	2.50	0.75	0.39	
30	24.92	0.02	0.99	2.16	0.75	0.39	

The *P–CN* relationship was analyzed by coefficient of determination (R^2) and standard error (SE). The R^2 expresses how much variation of the asymptotic *CN* is explained by an equation while SE represents the average distance that the observed values fall from the regression line. Here, main goal is to check the correlation and not so concerned more with prediction, the *P–CN* relationship with higher R^2 values is considered to be better. The best fitted *P–CN* relationship obtained by AFM and CN_{asy} for λ=0.20 on the dataset of the test watersheds are presented in Fig. 5.4-5.9.

Fig. 5.4 and Fig. 5.5 show the best fitted *P-CN* relationship for AFM *CN* and CN_{asy} respectively for Ozat watershed. R^2 =0.90 and SE varies from 2.96 to 5.21, indicating the existence of a *P-CN* relationship.

Fig. 5.6 and Fig. 5.7 show comparatively better fit the *P-CN* relationship of AFM (R^2 =0.97 and SE=1.32) over CN_{asy} (R^2=0.84 and SE=6.61), however the SCS-CN method with CN_{asy} predicted runoff far better than with AFM *CN* on the dataset of Uben watershed. Each watershed has different storage capacity based on its soil characteristics and LULC. It is to be observed in this study that Ozat watershed saturated relatively early (14 days) as compare to Shetrunji (19 days) and Uben (29 days) watersheds.

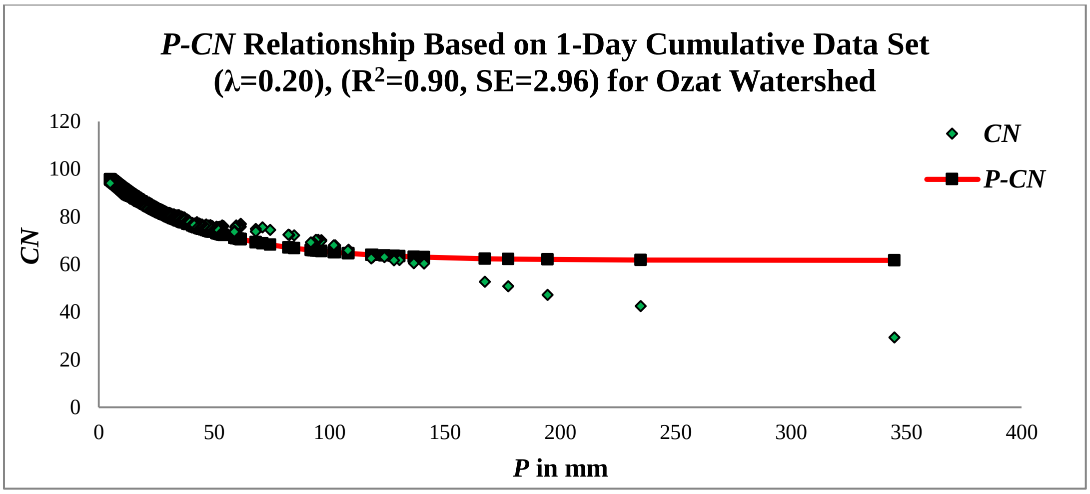


FIGURE 5.4 The best fitted *P-CN* relationship based on AFM for Ozat watershed

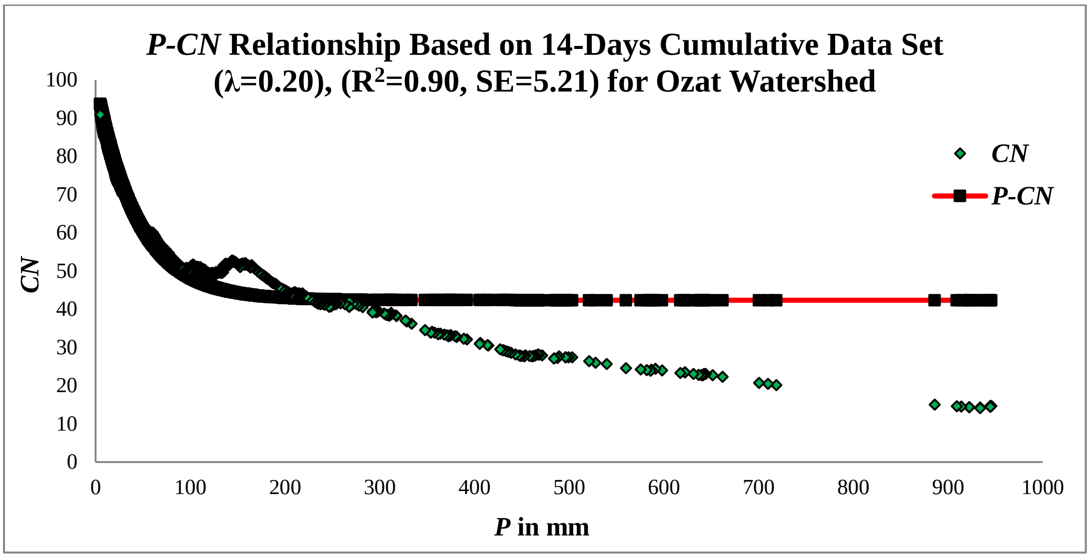


FIGURE 5.5 The best fitted *P-CN* relationship based on 14 days CN_{asy} for Ozat watershed

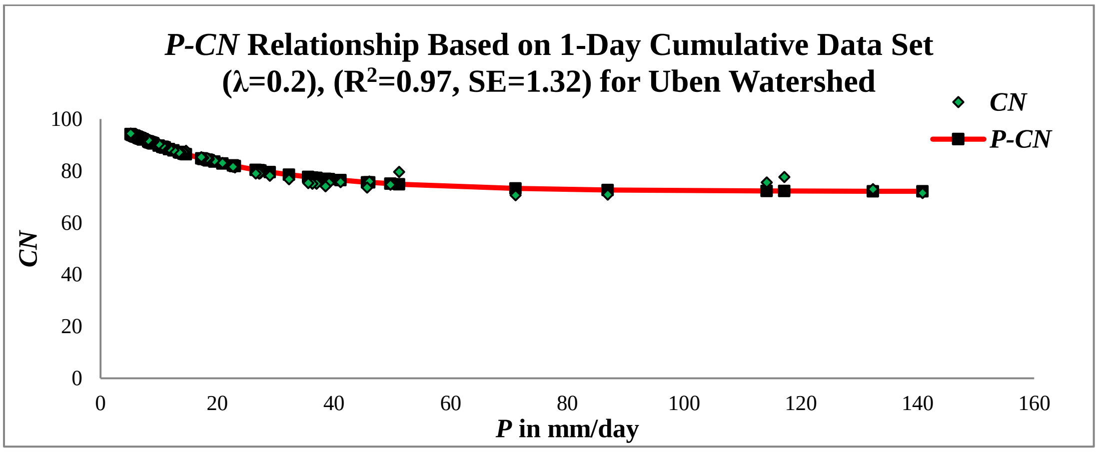


FIGURE 5.6 The best fitted *P-CN* relationship based on AFM for Uben watershed

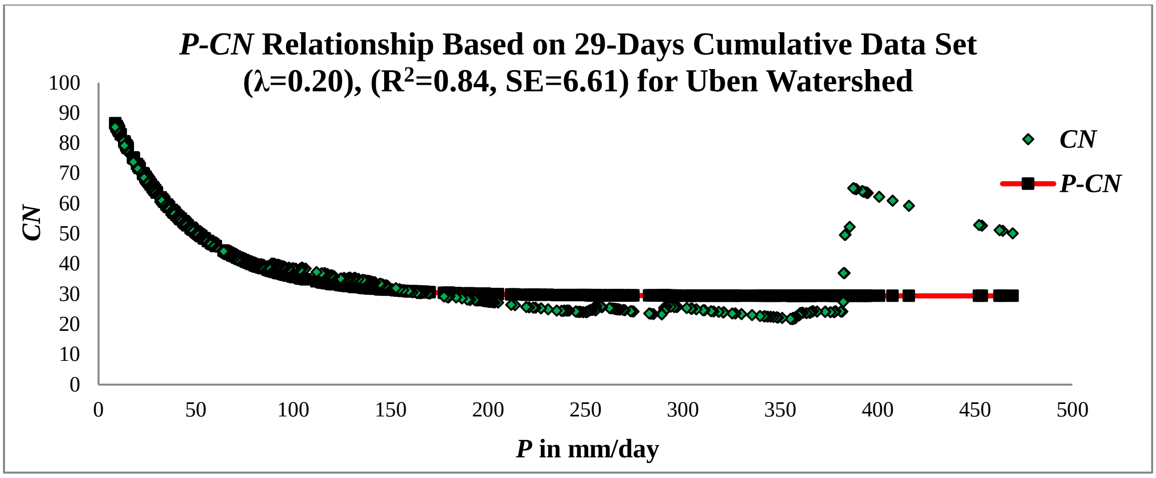


FIGURE 5.7 The best fitted *P-CN* relationship based on 29 days CN_{asy} for Uben watershed

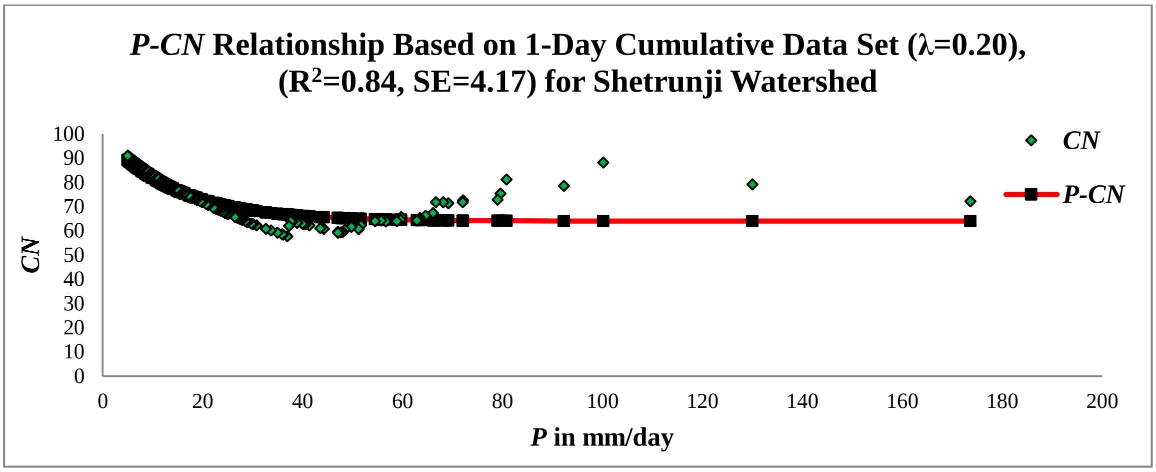


FIGURE 5.8 The best fitted *P-CN* relationship based on AFM for Shetrunji watershed

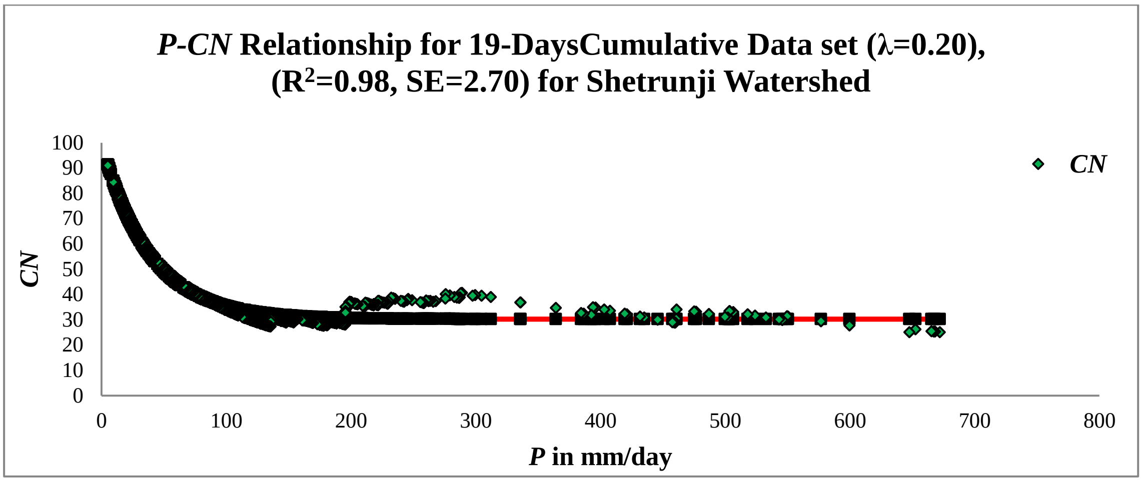


FIGURE 5.9 The best fitted *P-CN* relationship based on 19 days CN_{asy} for Shetrunji watershed

Very high R^2 and low SE were obtained when *P-CN* relationship established by CN_{asy} (R^2=0.98 and SE=2.70) than by AFM (R^2=0.84 and SE=4.17) for Shetrunji watershed. Graphical representation of *P-CN* relationships established for Shetrunji watershed by CN_{asy} and AFM are depicted in Fig. 5.8 and Fig. 5.9 respectively.

5.4.2 Evaluation of CN_{asy} and AFM *CN* in Runoff Estimation

Asymptotic *CN* is considered as a representative *CN* for a watershed in estimation of *CN* from observed field data. The *P-CN* relationships for AFM and CN_{asy} were evaluated using dataset of calibration period. Study application is very important to know the universality and to check the reliability of the applied methodology and developed model. Therefore, it is necessary to find out, which method (AFM and CN_{asy}) performs better in runoff estimation. It is checked by evaluating the results based on the statistical criteria d_r, MAE and MBE. Further, to select more likely method, two distinct approaches were adopted in this study. The first method is relying on statistical hypothesis testing (F-test) and second method is based on information theory (AIC_c criterion). The F-test helps in deciding whether the developed method have sufficient evidence to reject existing method. AIC_c describes how much more likely to be correct the proposed method as compare to existing method.

The overall performance of the SCS-CN method with composite *CN*, AFM *CN* and CN_{asy} were evaluated using the dataset of validation period for test watersheds. Sample months from validation period were selected based on maximum precipitation for hypothesis testing of the proposed method. Months having maximum rainfall (June 2005 (Ozat), July 2006 (Uben) and August 2004 (Shetrunji)) from validation period were selected for comparison of the performance of different methods at daily time scale. The value of λ was adopted 0.20 for all the watersheds. The performance of the SCS-CN method with composite *CN*, AFM *CN* and CN_{asy} were compared and evaluated based on criteria d_r, MAE, MBE, F-test, and AIC_c for Ozat, Uben and Shetrunji watersheds. Table 5.6 summarizes the results of all the three methods for the test watersheds.

TABLE 5.6 Comparison of the performance of the SCS-CN method with AFM *CN* and CN_{asy} on test watersheds in validation									
F-Test	**Ozat (June)**			**Uben (July)**			**Shetrunji (August)**		
Parameters	1	1	1	1	1	1	1	1	1
Model	**CN_{asy}**	**AFM**	**SCS**	**CN_{asy}**	**AFM**	**SCS**	**CN_{asy}**	**AFM**	**SCS**
Cumulative Day	**14**	**1**		**29**	**1**		**19**	**1**	
SS_{nul}	22095.01	22095.01		28706.69	28706.69		10400.84	10400.84	
SS_{alt}	1436.88	5563.38		476.33	18521.40		1217.03	2550.25	
Df_{nul}	28.00	28.00		29.00	29.00		29.00	29.00	
Df_{alt}	28.00	28.00		29.00	29.00		29.00	29.00	
F	15.38	3.97		60.27	1.55		8.55	4.08	
F_{cr}	15.30	15.30		56.36	56.36		8.19	8.19	
At P Value	9.38E-11	2.43E-04		3.9E-19	0.12		6.10E-08	1.51E-04	
Significant	**Yes**	**No**		**Yes**	**No**		**Yes**	**No**	
d_r	0.76	0.60	0.02	0.60	-0.46	-0.59	0.73	0.47	0.07
MAE (mm)	2.50	4.25	10.32	1.35	6.33	8.22	1.61	3.15	5.50
MBE (mm)	-1.43	3.31	10.32	-0.43	5.07	6.97	-1.57	0.53	4.24
	AIC_c	**LER**		**AIC_c**	**LER**		**AIC_c**	**LER**	
SCS-AFM	158.83	8.98	**Decisive**	200.31	2.95	**Decisive**	138.85	6.34	**Decisive**
SCS- CN_{asy}	118.21	17.80	**Decisive**	86.83	27.59	**Decisive**	115.91	14.44	**Decisive**
Overall d_r	0.76	0.67	0.57	0.72	0.09	-0.30	0.75	0.70	0.65
Overall MAE (mm)	0.82	1.11	1.45	0.44	1.40	2.22	0.39	0.46	0.54
Overall MBE (mm)	-0.60	0.21	0.82	-0.35	0.77	1.67	-0.39	-0.15	0.06

The F-test was conducted to test and to check statistically better method between CN_{asy} and AFM. This test was conducted on sample data set of test watersheds. Results of Table 5.6 show that F_{cr} values are less than the F ratio at a minimum p-values (<0.05) with associate degree of freedom for all the three watersheds. These indicate that proposed CN_{asy} method is statistically significant and better than the existing AFM method. CN_{asy} method received the lowest AIC_c scores (Ozat (118.21), Uben (86.83) and Shetrunji (115.91)), representing that this method is the most parsimonious method for the sample data. Comparatively higher substantial LER (Ozat (17.80), Uben (27.59) and Shetrunji (14.44)) confirm decisive evidence in favor of CN_{asy} method. Thus, based on AIC_c scores and LER, CN_{asy} method is more likely to be correct than AFM method in the study region.

Table 5.6 gives the details of the goodness of fit statistics d_r, MAE, and MBE calculated to evaluate the performance on sample data as well as on dataset of validation period for all the three methods. It is observed that the CN_{asy} method performs overwhelming better than AFM and conventional SCS-CN method with composite *CN* for all three test watersheds on sample data, (Ozat (d_r=0.76, MAE=2.50, MBE=-1.43), Uben (d_r=0.60, MAE=1.35, MBE=-0.43), and Shetrunji (d_r=0.73, MAE=1.61, MBE=-1.57)). This shows the improved performance of CN_{asy} method compared to AFM due to the incorporation of cumulative data in the *CN* determination. AFM produces marginally good results (Ozat (d_r=0.60, MAE=4.25, MBE=3.31), Uben (d_r=-0.46, MAE=6.33, MBE=5.07), and Shetrunji (d_r=0.47, MAE=3.15, MBE=0.53)) on the sample data. These results are in agreement with the previous findings (Woodward 2010) that AFM is preferred technique for *CN* determination when rainfall-runoff data are available. It can be seen from the results that AFM has a satisfactory performance for all three test watersheds. The SCS-CN with composite *CN* shows comparatively poorer performance (Ozat (d_r=0.02, MAE=10.32, MBE=10.32), Uben (d_r=-0.59, MAE=8.22, MBE=6.97), and Shetrunji (d_r=0.07, MAE=5.50, MBE=4.24)) on the sample data. MBE criterion shows that CN_{asy} method overestimated runoff while AFM and SCS-CN with composite *CN* methods under estimated runoff. Fig. 5.10-5.12 show the comparison of computed runoff on selected sample data by different methods along with observed runoff values for Ozat, Uben and Shetrunji watersheds respectively.

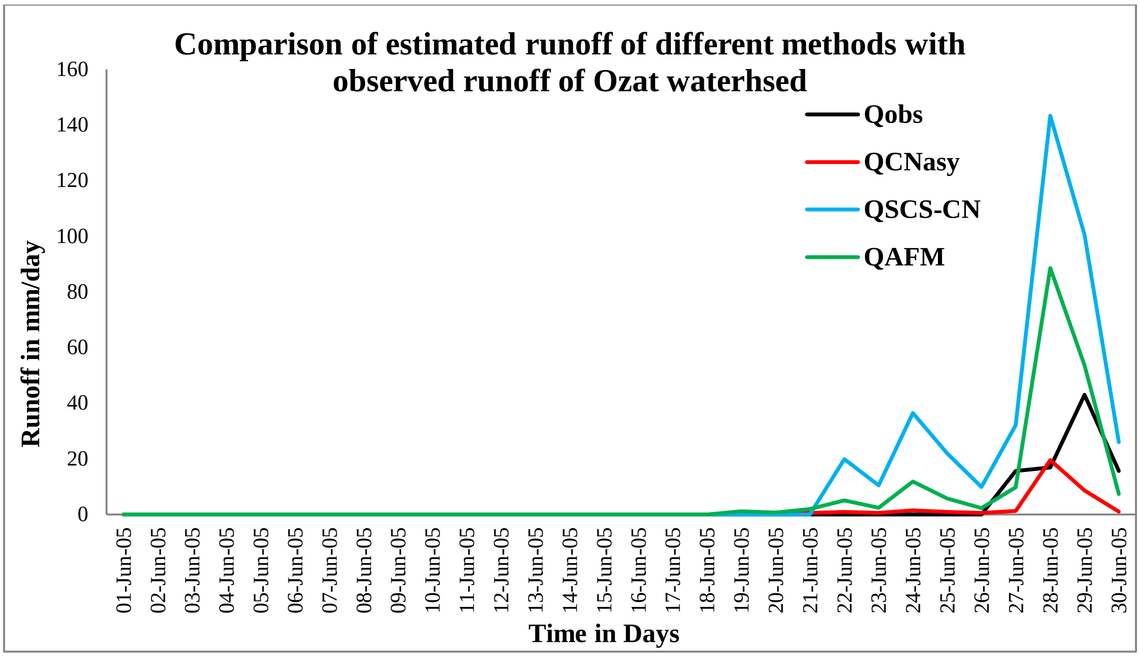


FIGURE 5.10 Performance of different methods at daily time scale on sample dataset of validation period (June, 2005) for Ozat watershed (λ=0.20)

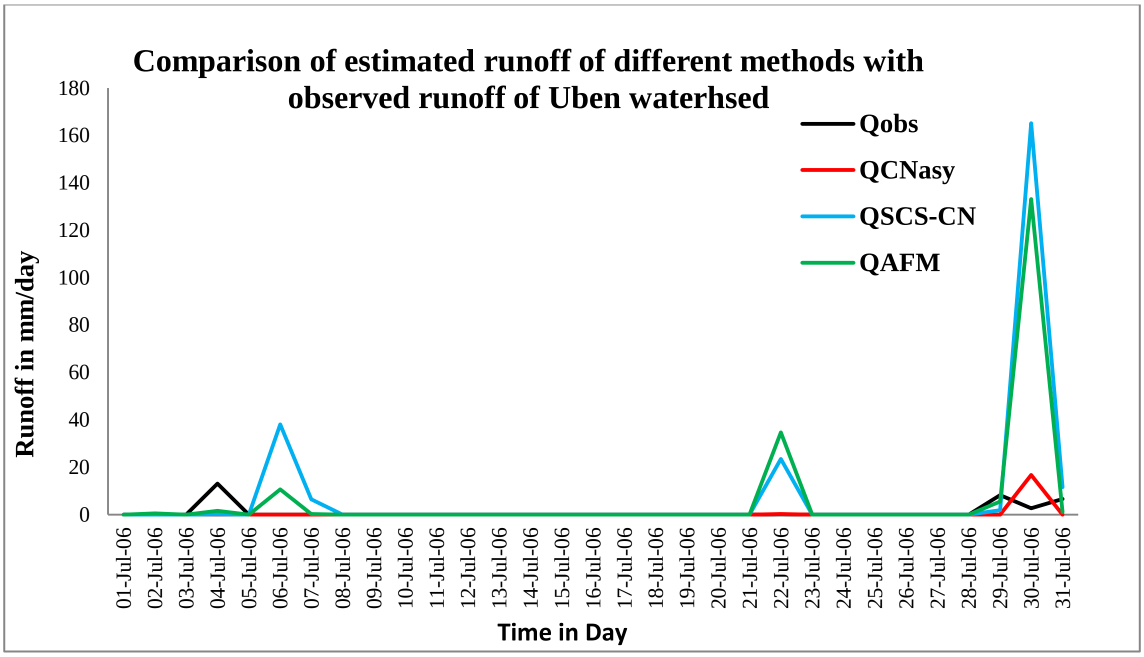


FIGURE 5.11 Performance of different methods at daily time scale on sample dataset of validation period (July, 2006) for Uben watershed (λ=0.20)

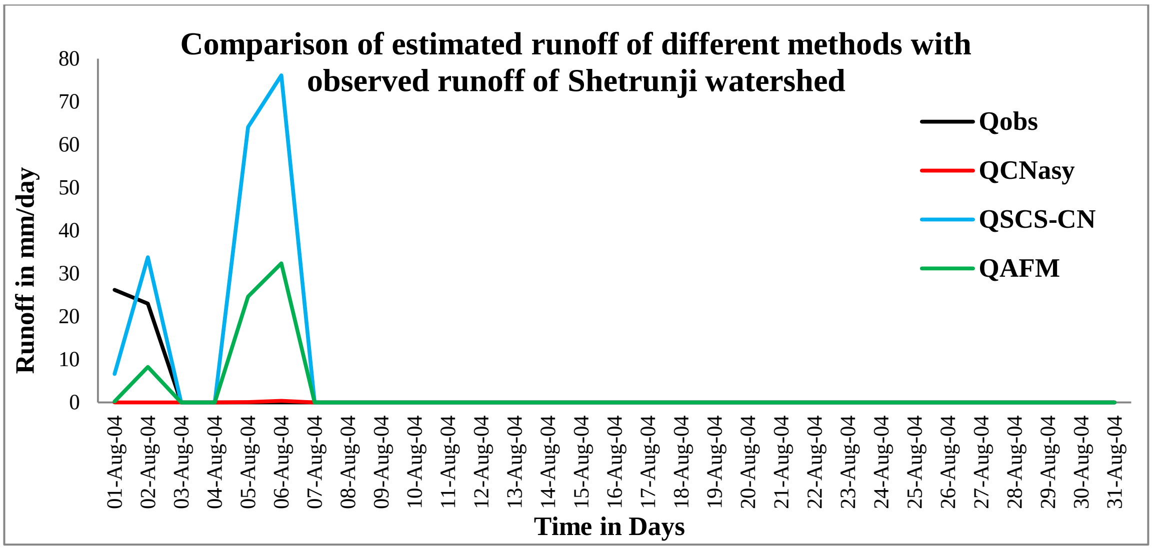


FIGURE 5.12 Performance of different methods at daily time scale on sample dataset of validation period (August, 2004) for Shetrunji watershed (λ=0.20)

It is seen from comparison of the performances of these methods on dataset of validation period for test watersheds that CN_{asy} method (Ozat (d_r=0.76, MAE=0.82, MBE=-0.60), Uben (d_r=0.72, MAE=0.44, MBE=-0.35), and Shetrunji (d_r=0.75, MAE=0.39, MBE=-0.39)) performed better than AFM (Ozat (d_r=0.67, MAE=1.11, MBE=0.21), Uben (d_r=0.09, MAE=1.40, MBE=0.77)) and SCS-CN with composite *CN* (Ozat (d_r=0.57, MAE=1.45, MBE=0.82), Uben (d_r=-0.30, MAE=2.22, MBE=1.67), and Shetrunji (d_r=0.65, MAE=0.54, MBE=0.06)) methods (Table 5.6). This shows that the performance of CN_{asy} method on sample data and validation dataset is almost similar for Ozat and Shetrunji watershed while performance of CN_{asy} method on validation dataset is improved over sample data for Uben watershed. Interestingly, it is noted that AFM not performed well on comparatively smaller length dataset of Uben watershed. From the performance indicators, it can be seen that length of dataset affects the performance of AFM. The monthly runoff depths were estimated for the validation periods and its comparisons with observed runoff for test watersheds are shown in Fig. 5.13-5.15. It can be seen from these figures that the AFM and SCS-CN with composite *CN* methods overestimated runoff while CN_{asy} method underestimate the runoff for the study region. The proposed CN_{asy} method affords comparatively more realistic results.

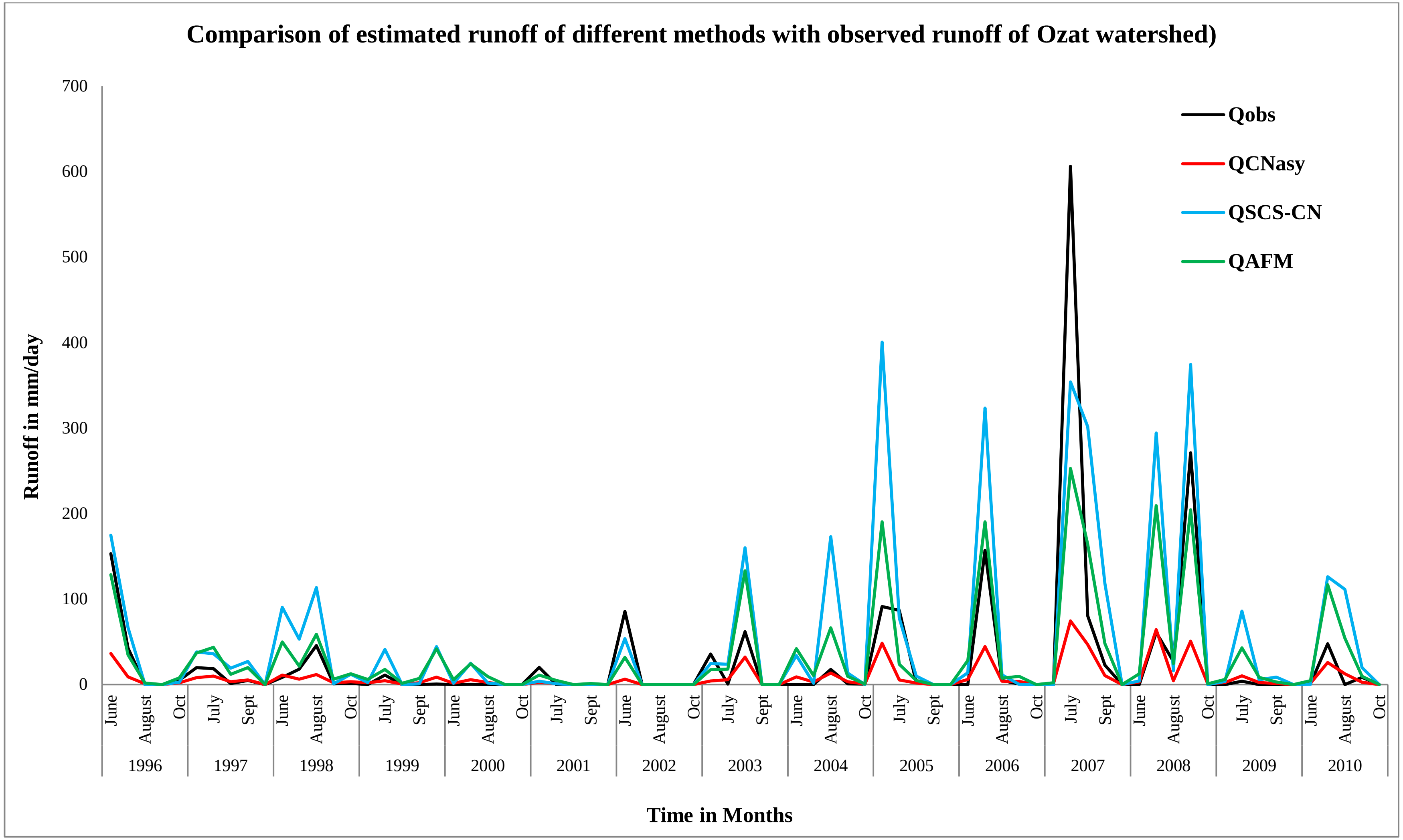


FIGURE 5.13 Performance of different methods at monthly time scale on dataset of validation period (1996-2010) for Ozat watershed (λ=0.20)

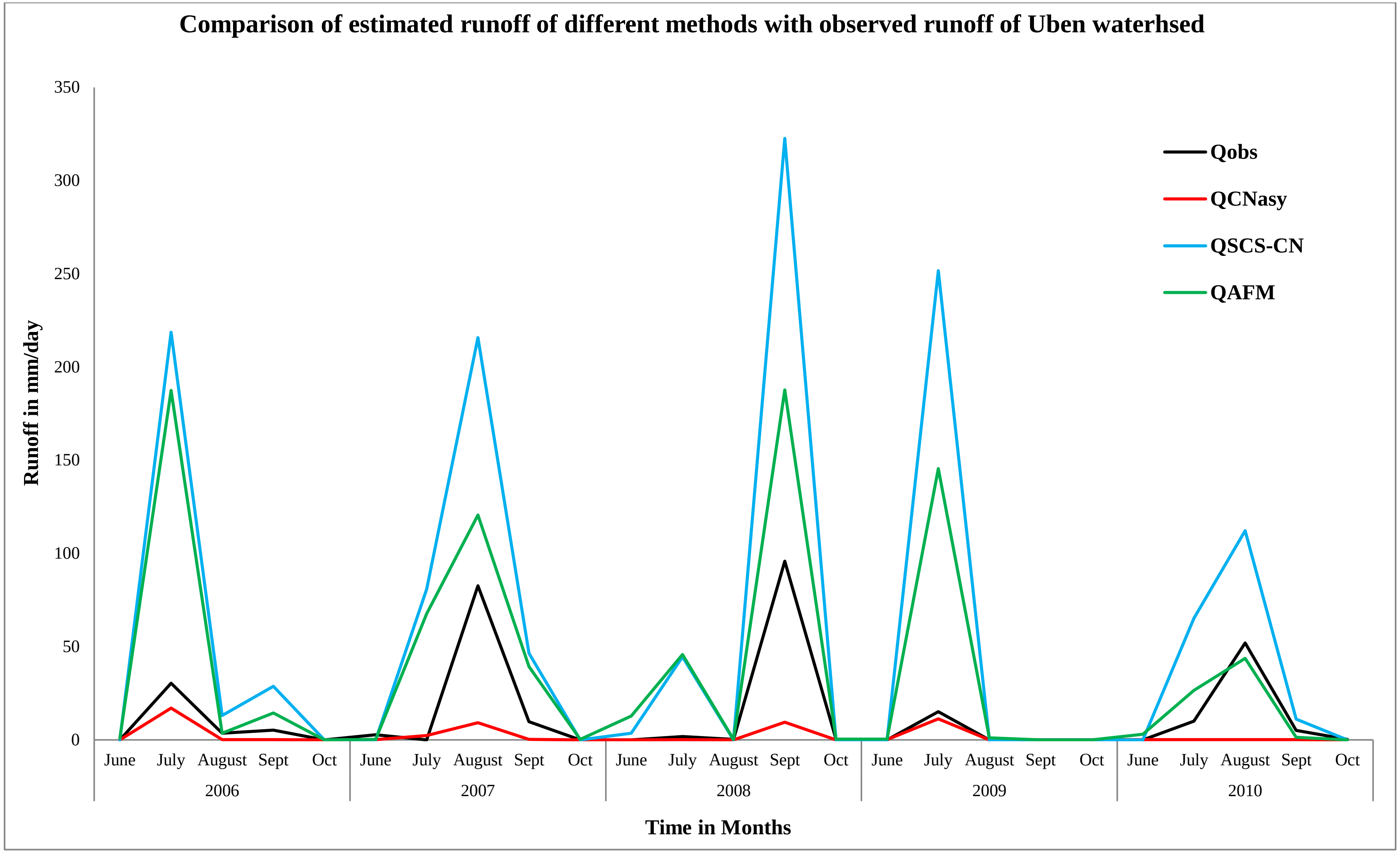


FIGURE 5.14 Performance of different methods at monthly time scale on dataset of validation period (2006-2010) for Uben watershed (λ=0.20)

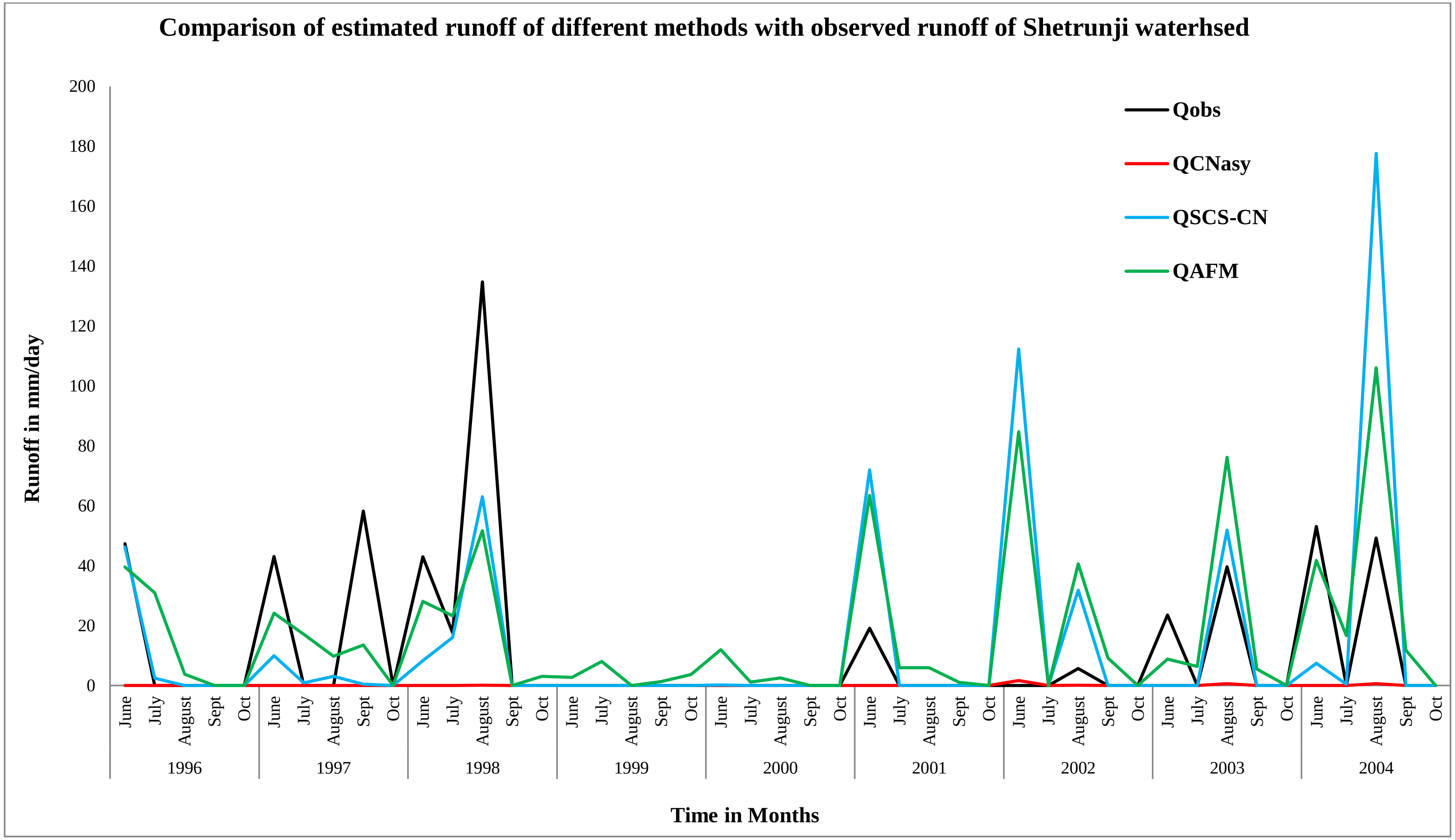


FIGURE 5.15 Performance of different methods at monthly time scale on dataset of validation period (1996-2004) for Shetrunji watershed (λ=0.20)

5.5 Performance of the SCS-CN Method with (CN_{mor})

It has been found that conventional SCS-CN method overestimated runoff significantly when applied on test watersheds of the study region. This may be due to the use of median *CN* from array of *CN* values in the SCS-CN method. This fair result could be attributable to comparatively big area. Another reason behind this fair performance may be due to lacking of an accounting for the effect of morphometric parameters of the watershed. As stated earlier in Chapter 4, Huang et al. (2006) developed (Equation 4.15) to adjust the tabulated *CN* values for the slope higher than 5% and the CN_{IImor} (Equation 4.16) proposed by introducing morphometric parameters to modify *CN*. The slope-adjusted $CN_{II\alpha}$ and CN_{IImor} values for test watersheds are listed in Tables 4.3-4.5. This proposed CN_{mor} method overtook the limitations that prevails in conventional SCS-CN method and expected to perform consistently better than the earlier Huang et al. (2006) method. The test watersheds included in the current study have slopes varying from 0.27 % to 0.64 %. However, the main purpose to evaluate the performance of these methods on such watersheds is that its results may suggest improvements that led to make the methods closer to the reality. The values of $CN_{II\alpha}$ and CN_{IImor} for AMC II for all three watersheds were calculated for calibration and validation periods and are presented in Tables 4.3-4.5.

5.5.1 Evaluation of CN_{mor} and HUANG ($CN_{II\alpha}$) in Runoff Estimation

The F-test and AIC_c were applied on sample dataset of Ozat, Uben and Shetrunji watersheds to check statically significance of the proposed method and how much it more likely to be correct. Statistical criteria d_r, MAE and MBE were calculated evaluate performance of the methods in runoff estimation. The results of the SCS-CN method with composite *CN*, $CN_{II\alpha}$ and CN_{IImor} for λ=0.20 on sample data of the test watersheds are presented in Table 5.7.

TABLE 5.7 Comparison of the performance of the SCS-CN method with HAUANG *CN* and CN_{mor} on test watersheds in validation

F-Test	**Ozat (June)**			**Uben (July)**			**Shetrunji (August)**		
Parameters	1	1	1	1	1	1	1	1	1
Model	**CN_{mor}**	**HUANG**	**SCS**	**CN_{mor}**	**HUANG**	**SCS**	**CN_{mor}**	**HUANG**	**SCS**
SS_{nul}	22095.01	22095.01		28706.69	28706.69		10400.84	10400.84	
SS_{alt}	1582.43	9353.36		279.57	9142.77		1345.44	3983.31	
Df_{nul}	28.00	28.00		29.00	29.00		29.00	29.00	
Df_{alt}	28.00	28.00		29.00	29.00		29.00	29.00	
F	13.96	2.36		102.68	3.14		7.73	2.61	
F_{cr}	12.68	12.68		91.90	91.90		6.68	6.68	
At P Value	3.08E-10	0.0132		2.07E-22	0.0015		1.94E-07	5.94E-03	
Significant	**Yes**	**No**		**Yes**	**No**		**Yes**	**No**	
d_r	0.76	0.53	0.02	0.73	-0.22	-0.59	0.64	0.38	0.07
MAE (mm)	2.53	4.90	10.32	0.93	4.38	8.22	2.11	3.70	5.50
MBE (mm)	-1.50	4.86	10.32	-0.86	2.73	6.97	-1.03	1.47	4.24
	AIC_c	**LER**		**AIC_c**	**LER**		**AIC_c**	**LER**	
SCS-HUANG	174.41	5.60	**Decisive**	178.43	7.70	**Decisive**	152.67	6.46	**Decisive**
SCS- CN_{mor}	121.11	17.17	**Decisive**	70.31	31.18	**Decisive**	119.02	13.77	**Decisive**
Overall d_r	0.76	0.44	0.57	0.67	0.17	-0.30	0.73	0.72	0.65
Overall MAE (mm)	0.80	0.97	1.45	0.50	1.28	2.22	0.41	0.43	0.54
Overall MBE (mm)	-0.73	-0.03	0.82	-0.27	0.60	1.67	-0.36	-0.19	0.06

Table 5.7 shows the F ratio at a minimum p-values (<0.05) with associate degree of freedom for HUANG ($CN_{II\alpha}$) (Ozat (2.36), Uben (3.14) and Shetrunji (2.61)) and for CN_{mor} (Ozat (13.96), Uben (102.68) and Shetrunji (7.73)). When compare these values with associate F_{cr} values, it is revealed that CN_{mor} method is statistically significant and better than the HUANG method for test watersheds. Comparing AIC_c scores of $CN_{II\alpha}$ (Ozat (174.41), Uben (178.43) and Shetrunji (152.67)) with AIC_c scores of CN_{mor} (Ozat (121.11), Uben (70.31) and Shetrunji (119.02)) shows that runoff predicted by CN_{mor} is in better agreement with observed runoff values. Further, higher LER scores (Ozat (17.17), Uben (31.18) and Shetrunji (13.77)) offer the sufficient evidence in favour of CN_{mor} method with lower AIC_c scores. Thus, based on F-test, AIC_c scores and LER scores, the proposed CN_{mor} method performed the best, followed by HUANG method whereas the SCS-CN method with composite *CN* was the poorest on sample dataset.

Furthermore, when the performances of the SCS-CN method with composite *CN*, $CN_{II\alpha}$ and CN_{IImor} for λ=0.20 are evaluated in terms of d_r, MAE, and MBE indices on sample dataset, it is observed that CN_{mor} method (Ozat (d_r=0.76, MAE=2.53, MBE=1.50), Uben (d_r=0.73, MAE=0.93, MBE=-0.86), and Shetrunji (d_r=0.64, MAE=2.11, MBE=-1.03)) performed explicitly better than HUANG method (Ozat (d_r=0.53, MAE=4.90, MBE=4.86), Uben (d_r=-0.22, MAE=4.38, MBE=2.73), and Shetrunji (d_r=0.38, MAE=3.70, MBE=1.47)) and the SCS-CN method (Ozat (d_r=0.02, MAE=10.32, MBE=10.32), Uben (d_r=-0.59, MAE=8.22, MBE=6.97), and Shetrunji (d_r=0.07, MAE=5.50, MBE=4.24)). MBE values suggest that CN_{mor} method underestimated the runoff whereas HUANG and the SCS-CN method overestimated the runoff. It is worth noting here that CN_{mor} method performed consistently better for all three test watersheds while HUANG method performed comparatively poorest for Uben watershed. This is due to the lower slope in Uben (0.26%) as compare to Ozat (0.58%) and Shetrunji (0.64%). HUANG was proposed (4.15) to determine slope-adjusted *CN* for the watershed having the slope higher than 5%, hence, it may not capture a realistic effect of slope less than 5%. Uben watershed has comparatively less drainage density 0.8324 Km/Km^2 (Appendix A-1) which indicates highly permeable subsoil material under dense vegetative cover and low relief. Thus, it is concluded that the watershed having slope less than 5%, slope-adjusted *CN* (HUANG) alone not adequately improved the performance of the SCS-CN method. Comparing Fig. 5.16-5.18 shows that runoff predicted by CN_{mor} method is in better agreement with observed runoff for all the three test watersheds.

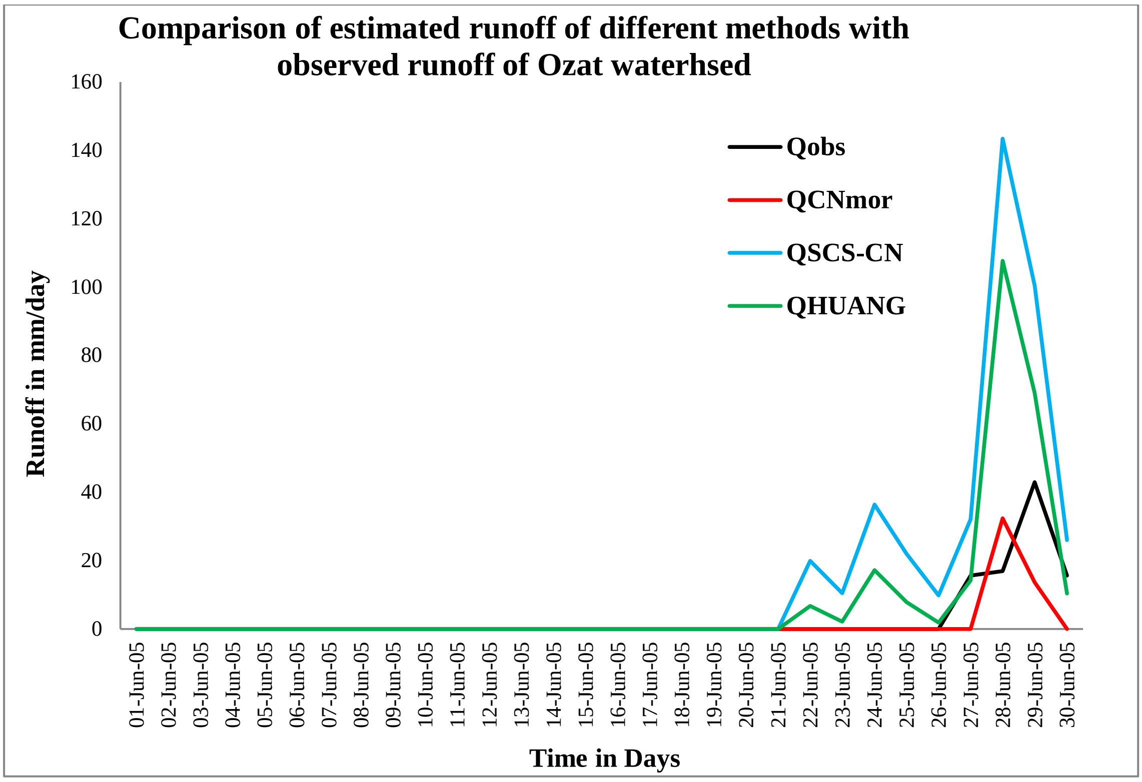


FIGURE 5.16 Performance of different methods at daily time scale on sample dataset of validation period (June, 2005) for Ozat watershed (λ=0.20)

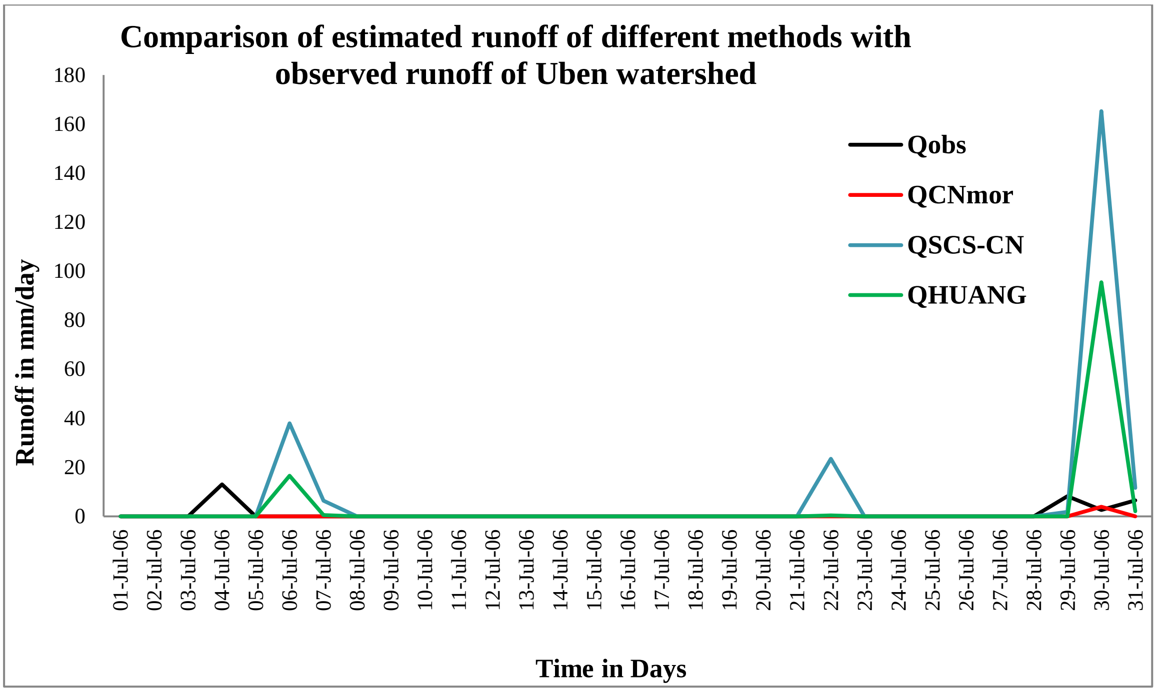


FIGURE 5.17 Performance of different methods at daily time scale on sample dataset of validation period (July, 2006) for Uben watershed (λ=0.20)

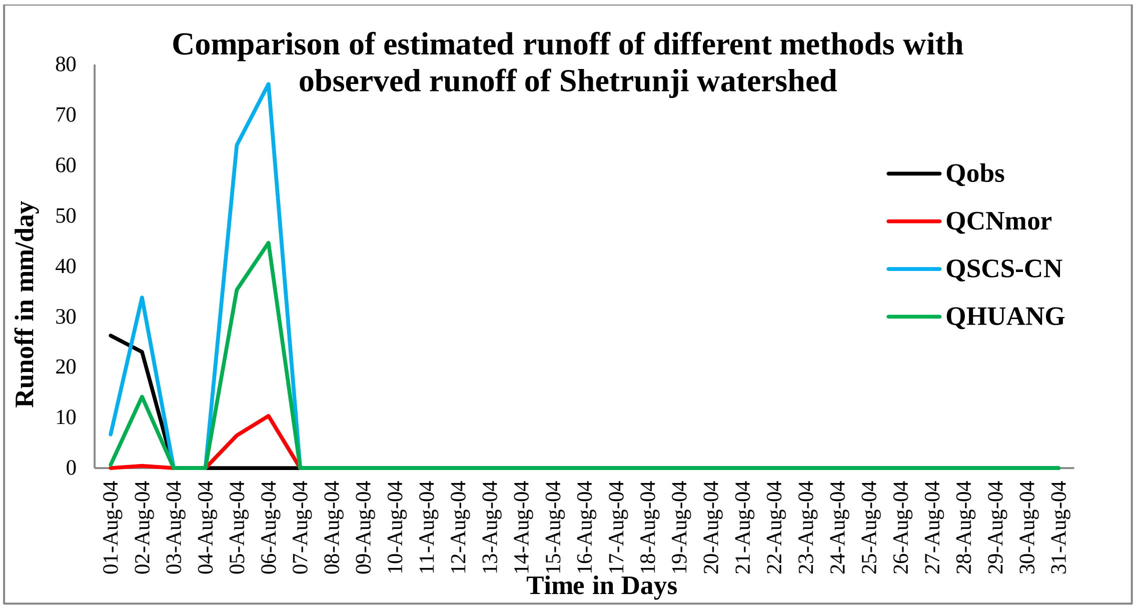


FIGURE 5.18 Performance of different methods at daily time scale on sample dataset of validation period (August, 2004) for Shetrunji watershed (λ=0.20)

Performances of the SCS-CN method with composite *CN*, $CN_{II\alpha}$ and CN_{IImor} for λ=0.20 on dataset of validation period for test watersheds were compared and the results are presented in Table 5.7. It is seen from Table 5.7 that the CN_{mor} (Ozat (d_r=0.76, MAE=0.80, MBE=-0.73), Uben (d_r=0.67, MAE=0.50, MBE=-0.27), and Shetrunji (d_r=0.73, MAE=0.41, MBE=-0.36)) performed better than HUANG (Ozat (d_r=0.44, MAE=0.97, MBE=-0.03), Uben (d_r=0.17, MAE=1.28, MBE=0.60), and Shetrunji (d_r=0.72, MAE=0.43, MBE=-0.19)) and the SCS-CN method with composite *CN* (Ozat (d_r=0.57, MAE=1.45, MBE=0.82), Uben (d_r=-0.30, MAE=2.22, MBE=1.67), and Shetrunji (d_r=0.65, MAE=0.54, MBE=0.06)). However, MBE results indicate that CN_{mor} method underestimated runoff largely in Ozat and Shetrunji watersheds. This is due to the MBE is merely account the difference between the mean values of the two datasets while MAE account absolute difference and not influenced by extreme outliers. Further, it is noticed that performance of the SCS-CN method with composite *CN* improved significantly when it applied on validation dataset than that of sample dataset. Similar to the performance on sample dataset, HUANG and the SCS-CN methods poorly performed for Uben watershed. Performance of HUANG and the conventional SCS-CN methods improved significantly when comparison made at monthly time scale. The graphical representations of the performance of all these methods at monthly time scale are presented in Fig. 5.19-5.21 for test watersheds.

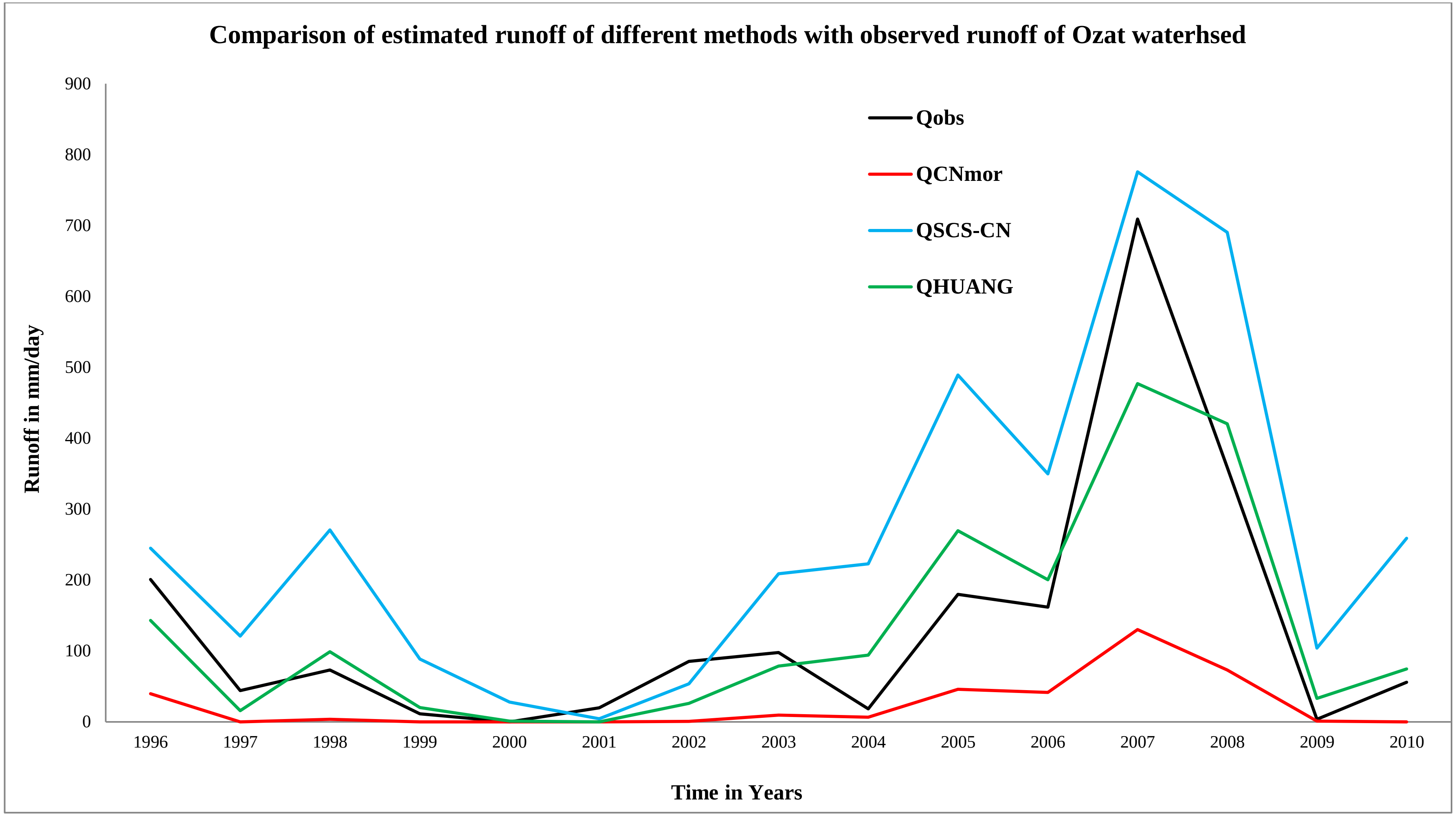


FIGURE 5.19 Performance of different methods at monthly time scale on dataset of validation period (1996-2010) for Ozat watershed (λ=0.20)

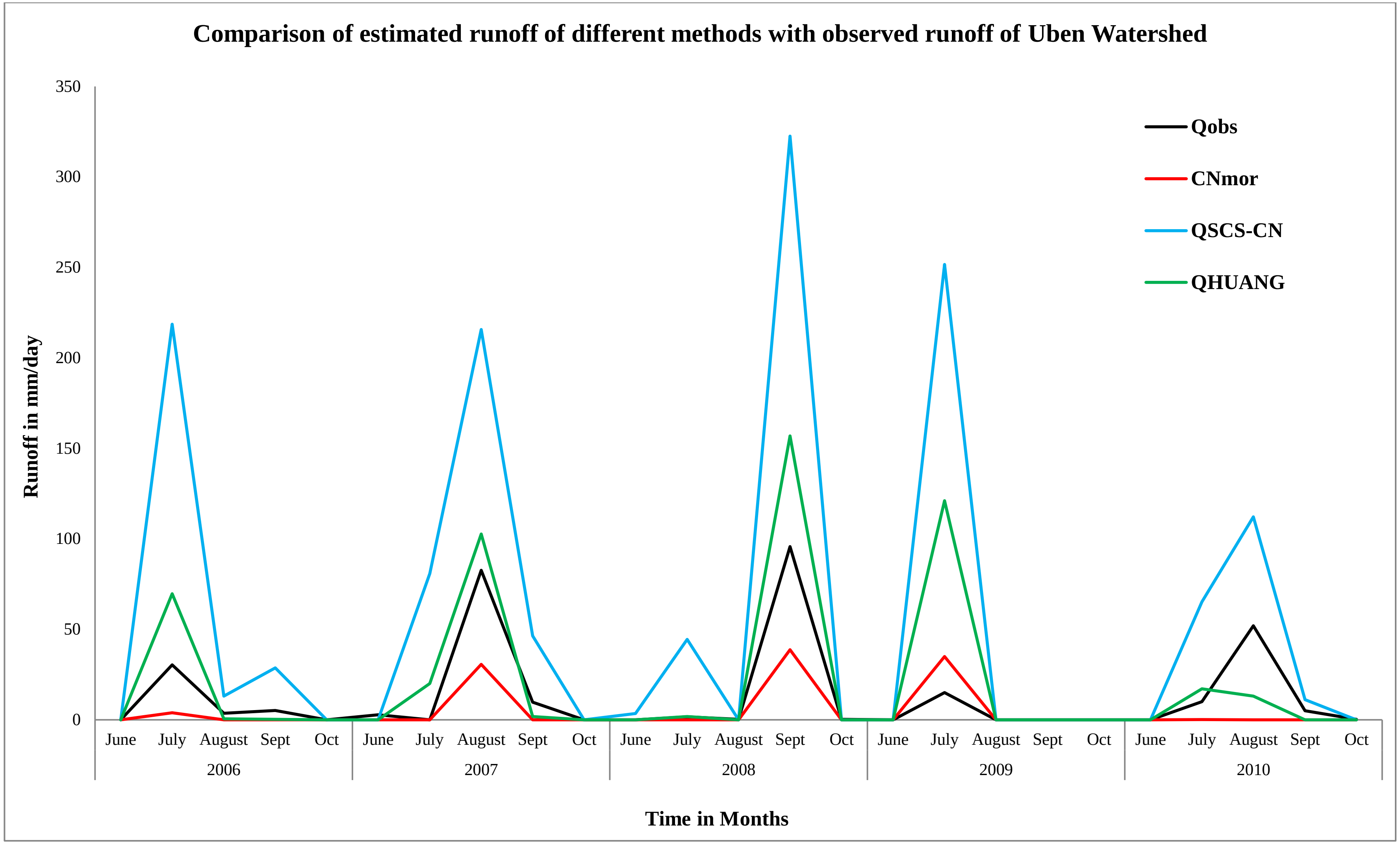


FIGURE 5.20 Performance of different methods at monthly time scale on dataset of validation period (2006-2010) for Uben watershed (λ=0.20)

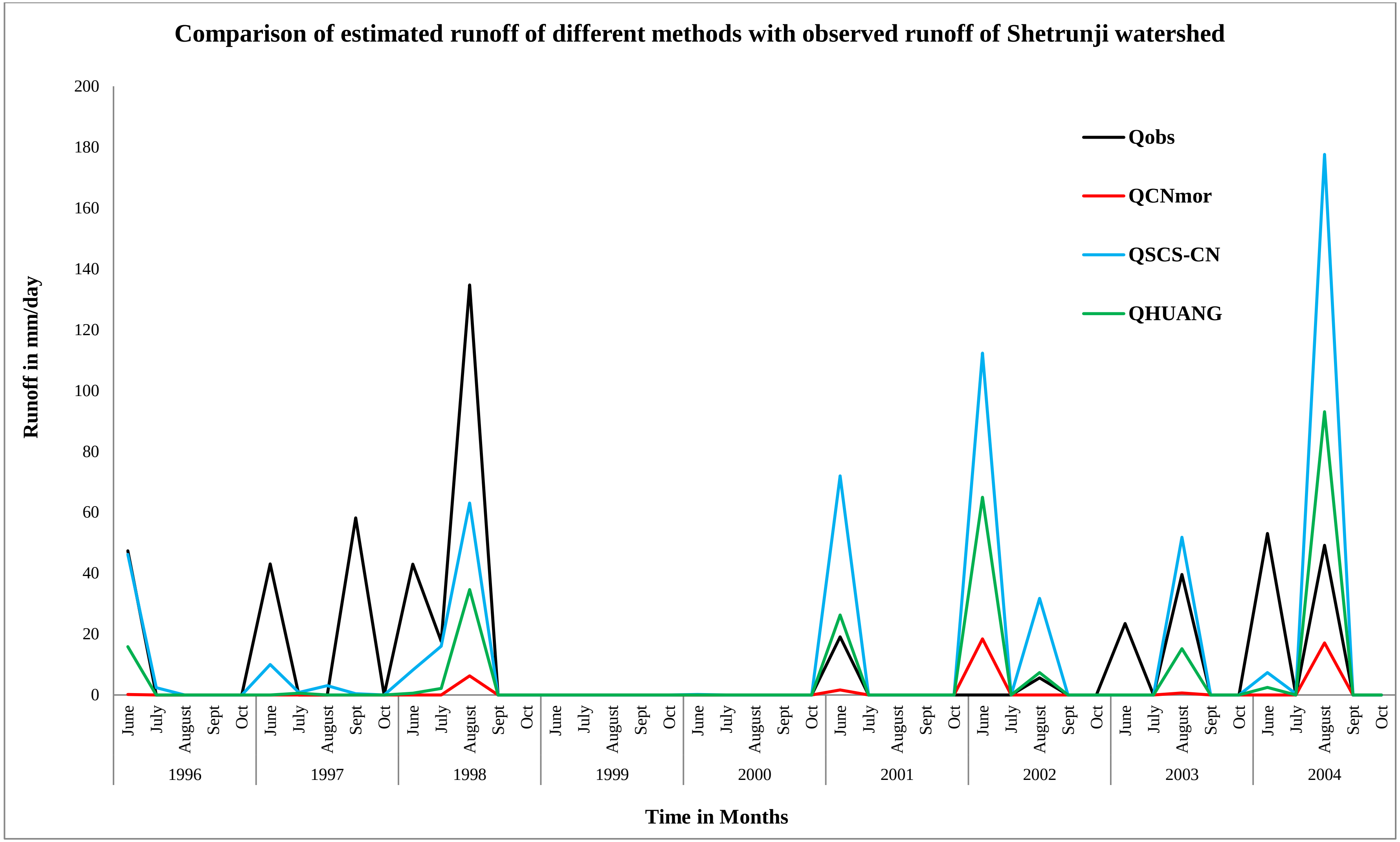


FIGURE 5.21 Performance of different methods at monthly time scale on dataset of validation period (1996-2004) for Shetrunji watershed (λ=0.20)

Figs. 5.16-5.21 show that CN_{mor} method is provided comparatively more realistic results at daily time scale than at monthly time scale. Therefore, it is concluded that the morphometric parameters *L*, L_{ca} and *DD* of the watershed contributing significantly to runoff generation, which was an improvement over the works done by Huang et al. (2006).

5.6 Performance of the SCS-CN Method with (CN_{temp})

In this study, the methodology of *CN* determination by integrating ET_o is proposed to modify the SCS-CN method for long term application. The pronounced modifications were the incorporation of daily ET_o in the *CN* computation procedure. Lysimeter is the most accurate instrument for measuring *ET*. However, it is often expensive in terms of its construction and maintenance and not feasible to install at many locations. Further, due to requirement of high operational skills it is not appropriate for routine measurements. Thus, in such situation, *ET* determines by empirical model based on available meteorological data is reliable solution in practical point of view. As discussed in previous sections 4.9.1, the empirical model (Equation 4.18) was developed based on the most dominant meteorological parameter (maximum temperature) to estimate ET_o for the study region. This model can overcome the shortage of data and will lead to minimize the time, cost, and equipment maintenance necessary for onsite monitoring. The model was applied on dataset of Junagadh and Amreli stations for calibration and validation. Calibration and validation of the proposed model were performed using data set from the year of 1992 to 2002 and from the year 2003 to 2012 respectively for both Junagadh and Amreli stations of the study region. The resulting statistical criteria for Junagadh (d_r=0.84, MAE=0.73, MBE=0.26) and for Amreli (d_r=0.85, MAE=0.46, MBE=0.27) stations in validation period strongly support the versatility of the derived model and therefore, it would be quite useful in field applications for the study region. The calibrated value of parameter 'a' containing the best fit between modeled and standard ET_o-*PM* values are found 0.0799 for Junagadh station and 0.0666 for Amreli station. The graphical representations of the performance of the model for Junagadh and Amreli stations are presented in Fig. 5.22-5.23 respectively.

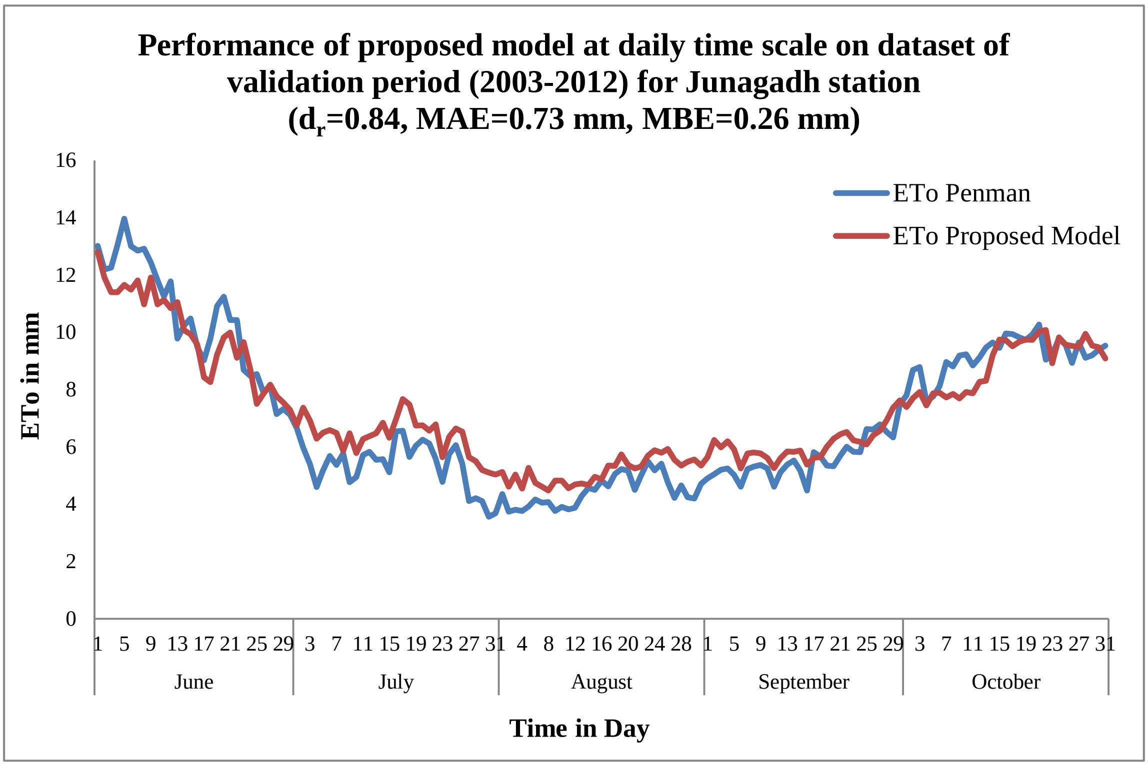


FIGURE 5.22 Performance of proposed model at daily time scale on dataset of validation period (2003-2012) for Junagadh station

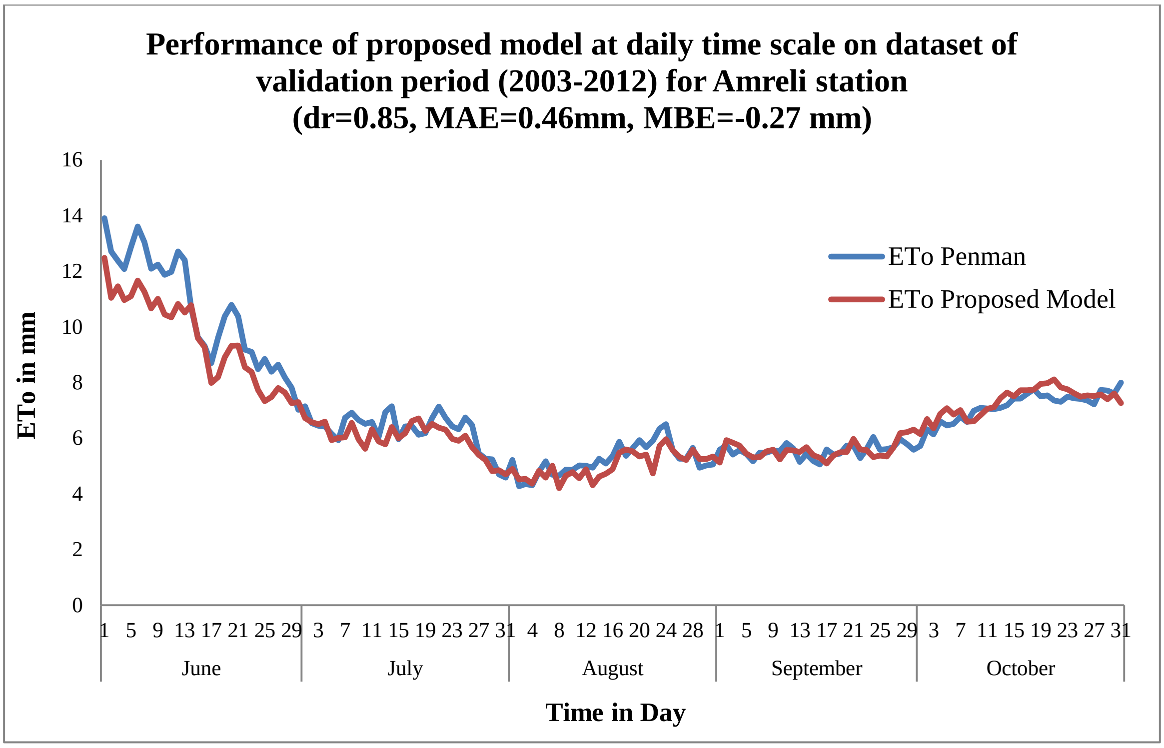


FIGURE 5.23 Performance of proposed model at daily time scale on dataset of validation period (2003-2012) for Amreli station

5.6.1 Evaluation of CN_{temp}, KANNAN and IHACRES in Runoff Estimation

The methodology developed to determine CN_{temp} has been discussed in section 4.9.5. The application of the proposed model in the context of the study region has been discussed in this section. In this method, value of λ was taken 0.2 and the I_a was calculated by using appropriate (Equation 4.24) or (Equation 4.25). CN_{temp} determined by (Equation 4.26) is considered as a representative *CN* for a watershed. Fifty per cent of the dataset is utilised for calibration and the rest is used for validation of the method. To calibrate the depletion coefficient β, Microsoft excel worksheet with solver tool was executed. The performance of proposed method is evaluated by using dataset of test watersheds and the results are compared with results obtained by existing (KANNAN and IHACRES) models.

Kannan et al. (2008) developed a model (Equation 4.21-4.23) on the SCS-CN methodology for continuous hydrologic simulation. This method consists of two unknown parameters β and S_{max} for continuous hydrologic simulation. It includes the rainfall amount of previous day and does not take into account the effects of the amount of rainfall on a given day. Value of the moisture depletion coefficient β can be calibrated by matching the predicted average surface runoff from watershed with that of observed runoff. Usaually, range of β is taken from 0 to 2 and it is initialized with 0 for CN_{temp} and Kannan methods. An initial estimate of maximum retention S_{max} was obtained based on the composite CN_{I} (AMC I).

The lumped conceptual model IHACRES (Equation 4.27-4.29) comprises a non-linear loss module and a linear unit hydrograph module is selected to compare the performances of existing and developed methodologies. IHACRES has six parameters comprising three in each module as discussed in section 4.10. It is used to account for antecedent soil moisture conditions and evapotranspiration loss. The non-linear loss module converts rainfall into runoff (effective rainfall) by considering both the infiltration rate and evapotranspiration. Therefore, only non-linear module is taken in to account for comparison of estimated runoff in this study. IHACRES is parsimonious model and requires precipitation and temperature as the only data-input. In this model, Physical Catchment Descriptors (PCDs) or Catchment Attributes are selected for watershed based on the Digital Elevation Model (DEM) of the study area. The relationships between the model parameters and the PCDs are developed by correlation analysis and these relationships are then validated by modelling daily stream flow of a gauged watershed.

All these methods were applied to test watersheds at daily time step for calibration period as mentioned in Table 3.19 to determine optimised value of their parameters. The calibrated values of parameters of all these methods are presented in Table 5.8. From the Table 5.8, it is noticeable that the Uben watershed has the highest moisture depletion rate as the value of β is 0.0705.

TABLE 5.8 Optimized values of calibrated parameters of different methods for test watersheds

Methods	Parameter	Ozat watershed	Uben watershed	Shetrunji watershed
CN_{temp}	β	0.0050	0.0705	0.0036
KANNAN	β	0.0000	0.0000	0.0265
	S_{max} (mm)	135.97	159.12	319.58
IHACRES	t_w (^{0}C)	72.1030	173.3954	13.1487
	f ($^0C^{-1}$)	3.7557	19.9977	2.1894
	c	0.0002	5.27E-05	0.0006

CN_{temp}, KANNAN and IHACRES methods with calibrated parameters were tested on dataset of Ozat, Uben and Shetrunji watersheds from validation periods and the results are presented in Table 5.9.

It is understood from the Table 5.9 that proposed CN_{temp} is statistically significant at lowest minimum p value (<0.05) with associate degree of freedom in sample dataset for all three test watersheds. Smaller p values indicate that IHACRES method is performed better than that of the KANNAN method for test watersheds. However, due to more number of calibration parameters, the degree of freedom for KANNAN and IHACRES method is lower and hence, these methods are not statically significant at minimum possible p value.

TABLE 5.9 Comparison of the performance of the IHACRES and the SCS-CN method with composite *CN*, KANNAN *CN* and CN_{temp} on test watersheds in validation

	Ozat (June)				Uben (July)				Shetrunji (August)			
Parameters	2	3	3	1	2	3	3	1	2	3	3	1
Model	**CN_{tepm}**	**KANNAN**	**IHACRES**	**SCS**	**CN_{tepm}**	**KANNAN**	**IHACRES**	**SCS**	**CN_{tepm}**	**KANNAN**	**IHACRES**	**SCS**
SS_{nul}	22095.01	22095.01	22095.01		28706.69	28706.69	28706.69		10400.84	10400.84	10400.84	
SS_{alt}	1419.54	11762.08	996.73		284.60	2307.14	267.73		1587.00	1254.92	1537.48	
Df_{nul}	28.00	28.00	28.00		29.00	29.00	29.00		29.00	29.00	29.00	
Df_{alt}	27.00	26.00	25.00		28.00	27.00	26.00		28.00	27.00	26.00	
F	393.25	11.42	176.40		2796.28	154.47	920.58		155.51	98.38879	49.96	
F_{cr}	386.11	456.81	548.13		2789.51	3525.87	4540.89		142.74	161.9375	185.60	
At P Value	7.82E-29	1.00E-08	1.31E-22		9.67E-42	1.88E-23	1E-32		3.06E-24	7.58E-21	1.84E-16	
Significant	**Yes**	**No**	**No**		**Yes**	**No**	**No**		**Yes**	**No**	**No**	
d_r	0.78	0.41	0.82	0.02	0.70	0.31	0.70	-0.59	0.57	0.70	0.58	0.07
MAE (mm)	2.34	6.25	1.89	10.32	1.03	2.35	1.01	8.22	2.54	1.80	2.51	5.50
MBE (mm)	-1.98	5.45	-1.39	10.32	-0.73	0.57	-0.66	6.97	-0.03	-1.37	-0.18	4.24
	AIC_c	**LER**			**AIC_c**	**LER**			**AIC_c**	**LER**		
SCS-IHACRES	112.02	19.15	Decisive		73.73	30.44	Decisive		127.91	11.84	Decisive	
SCS-KANNAN	186.07	3.07	Decisive		140.49	15.94	Decisive		121.61	13.20	Decisive	
SCS- CN_{mor}	120.15	17.38	Decisive		73.16	30.56	Decisive		126.43	12.16	Decisive	
Overall d_r	0.75	0.75	0.74	0.57	0.73	0.61	0.73	-0.30	0.73	0.49	0.72	0.65
Overall MAE (mm)	0.83	0.85	0.87	1.45	0.41	0.61	0.41	2.22	0.42	0.39	0.43	0.54
Overall MBE (mm)	-0.61	-0.47	-0.53	0.82	-0.36	-0.14	-0.30	1.67	-0.21	-0.37	-0.24	0.06

AIC_c scores and LER values of test result on sample dataset advocate that runoff predicted by IHACRES for Ozat watershed (AIC_c=112.02, LER=19.15), CN_{temp} for Uben watershed (AIC_c=73.16, LER=30.56) and KANNAN for Shetrunji watershed (AIC_c=121.61, LER=13.20) is in better agreement with observed runoff values. However, based on statistical criteria d_r, MAE and MBE, IHACRES for Ozat (d_r=0.82, MAE=1.89, MBE=-1.39) and Uben (d_r=0.70, MAE=1.01, MBE=-0.66) watersheds while KANNAN for Shetrunji (d_r=0.70, MAE=1.80, MBE=-1.37) watershed perform better than CN_{temp}. For Ozat and Uben watersheds, CN_{temp} and IHACRES perform comparatively better but KANNAN not perform well. Further, results show that the performance of CN_{temp} and IHACRES are almost similar. It is noted that KANNAN performs quite better for Shetrunji watershed. Shetrunji watershed characterised by larger forest area, low annual average rainfall, runoff coefficient, and covered with more entisols with shallow depth soils. The KANNAN is specially developed for shallow soils and soils with low storage. This ultimately leads to the improved performance of the KANNAN over CN_{temp} and IHACRES for Shetrunji watershed. MBE values show that CN_{temp} and IHACRES are underestimated the runoff for all the three watersheds. KANNAN is underestimated runoff for Shetrunji watershed and overestimated for Ozat and Uben watersheds. Fig. 5.24-5.26 show the performance of CN_{temp}, KANNAN and IHACRES methods at daily time scale on sample dataset of validation period for Ozat, Uben and Shetrunji watersheds respectively.

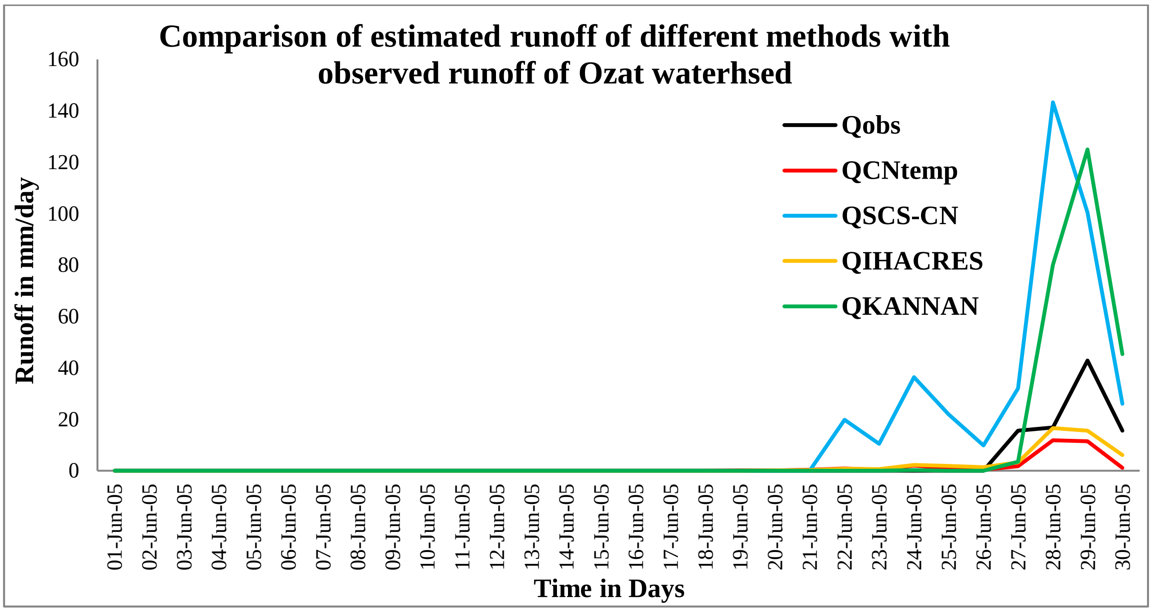


FIGURE 5.24 Performance of different methods at daily time scale on sample dataset of validation period (June, 2005) for Ozat watershed (λ=0.20)

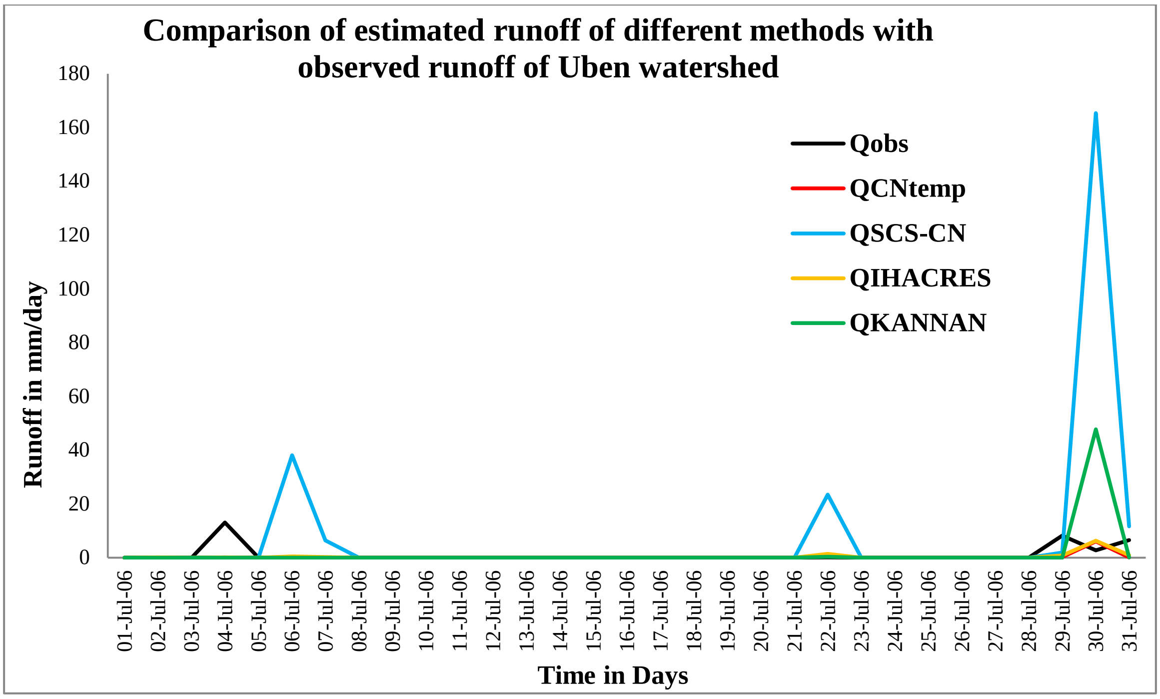


FIGURE 5.25 Performance of different methods at daily time scale on sample dataset of validation period (July, 2006) for Uben watershed (λ=0.20)

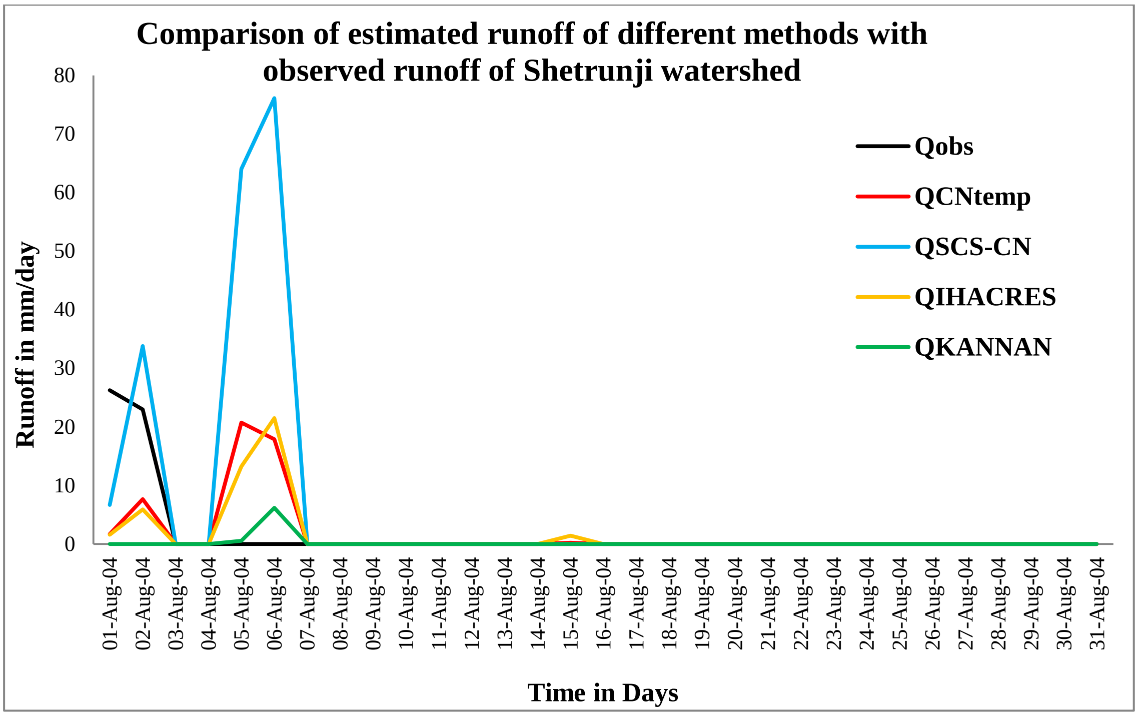


FIGURE 5.26 Performance of different methods at daily time scale on sample dataset of validation period (August, 2004) for Shetrunji watershed (λ=0.20)

Form the Fig. 5.22-5.24, it can be seen that CN_{temp} and IHACRES perform quite better for Ozat and Uben watersheds while KANNAN performs better for Shetrunji watershed.

Table 5.9 shows the performances of CN_{temp}, KANNAN, IHACRES and the SCS-CN method with composite *CN* for λ=0.20 on dataset of validation period for test watersheds in terms of d_r, MAE and MBE. It is revealed from Table 5.9 that performance of CN_{temp} (d_r=0.75, MAE=0.83, MBE=-0.61), KANNAN (d_r=0.75, MAE=0.85, MBE=-0.47), and IHACRES (d_r=0.74, MAE=0.87, MBE=-0.53) are almost similar for Ozat watershed. CN_{temp} (Uben (d_r=0.73, MAE=0.41, MBE=-0.36), Shetrunji (d_r=0.73, MAE=0.42, MBE=-0.21)) and IHACRES (Uben (d_r=0.73, MAE=0.41, MBE=-0.30), Shetrunji (d_r=0.72, MAE=0.43, MBE=-0.24)) perform better than KANNAN (Uben (d_r=0.61, MAE=0.61, MBE=-0.14), Shetrunji (d_r=0.49, MAE=0.39, MBE=-0.37)). It is also observed that CN_{temp} and IHACRES perform consistently better on sample as well as on validation dataset while performance of KANNAN and SCS-CN with composite *CN* differ significantly on sample and on validation dataset of the test watersheds. The SCS-CN with composite *CN* performs better for Ozat and Shetrunji watersheds than for Uben watershed on validation dataset. This shows that for larger size watershed (Uben) performance of the SCS-CN with composite *CN* (d_r=-0.30, MAE=2.22, MBE=1.67) decline significantly. The performance of these methods at monthly time scale on dataset of validation period of the test watersheds for λ=0.20 are presented in Fig. 5.27-5.29.

From Fig. 5.27-5.29, CN_{temp} performs equivalent to IHACRES on the dataset of the test watersheds. It is to emphasize further that the proposed method CN_{temp} has only two parameters (i.e. *CN* and β) while IHACRES has three parameters (i.e. t_w, f, and c). Though CN_{temp} has two parameters compared to three parameters IHACRES, it overcomes most of the limitations prevailing in the SCS-CN method. Despite its simplicity, CN_{temp} performed comparatively better, therefore, CN_{temp} is considered as more reliable method for the study region.

Comparison of the observed runoff and computed runoff by different methods at daily time scale for selected sample month from validation period for all test watersheds are presented in Appendix A-4-A-6.

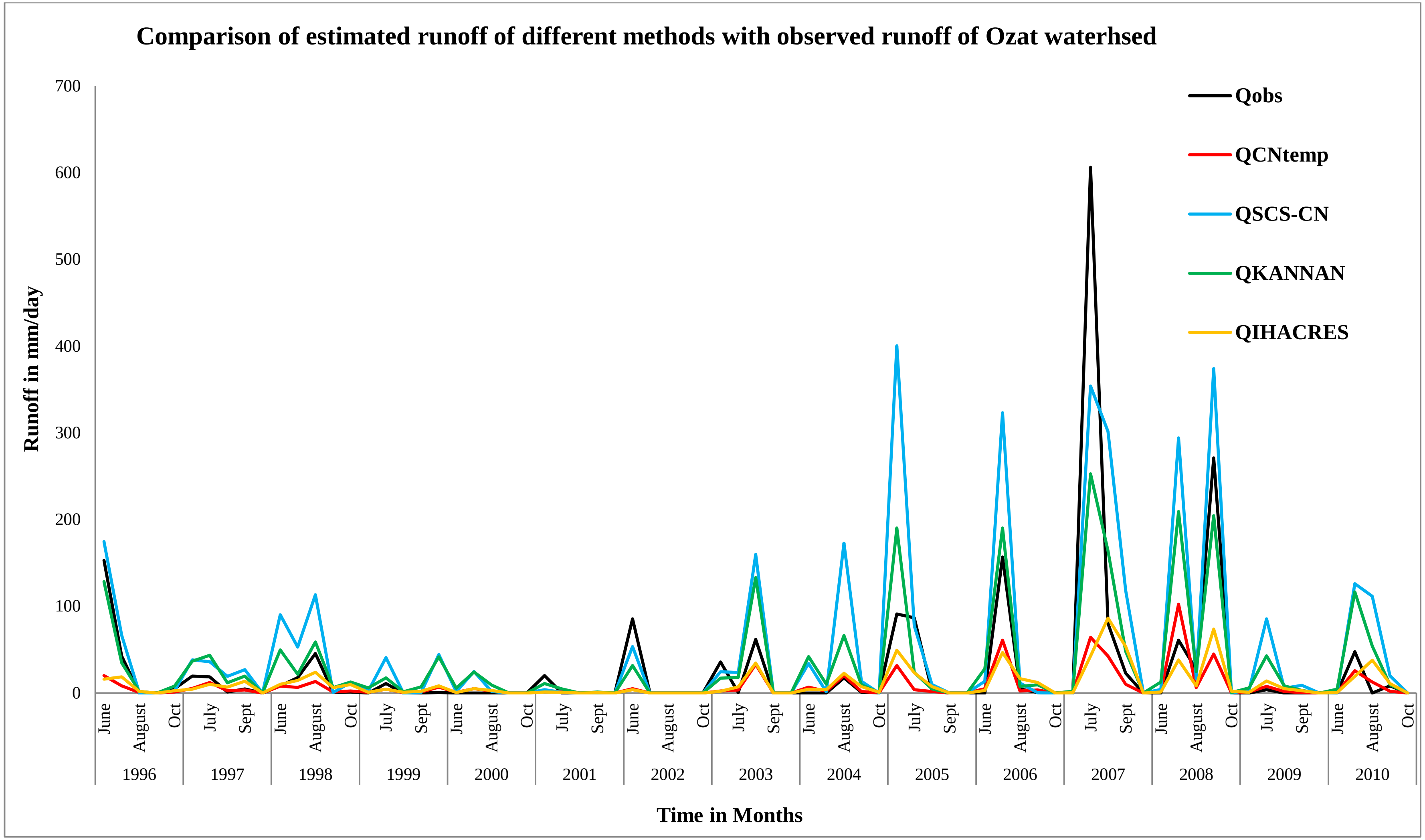


FIGURE 5.27 Performance of different methods at monthly time scale on dataset of validation period (1996-2010) for Ozat watershed (λ=0.20)

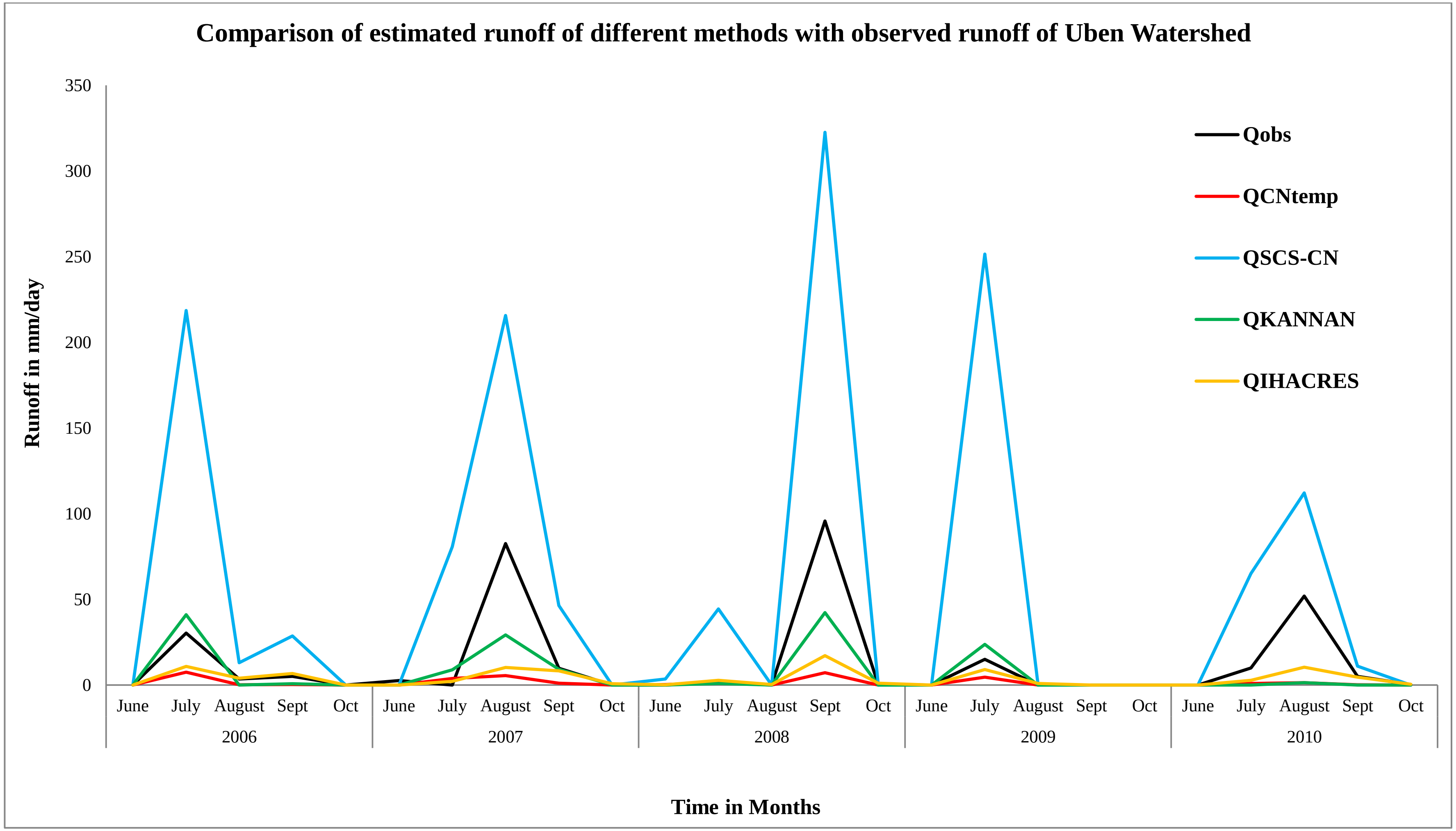


FIGURE 5.28 Performance of different methods at monthly time scale on dataset of validation period (2006-2010) for Uben watershed (λ=0.20)

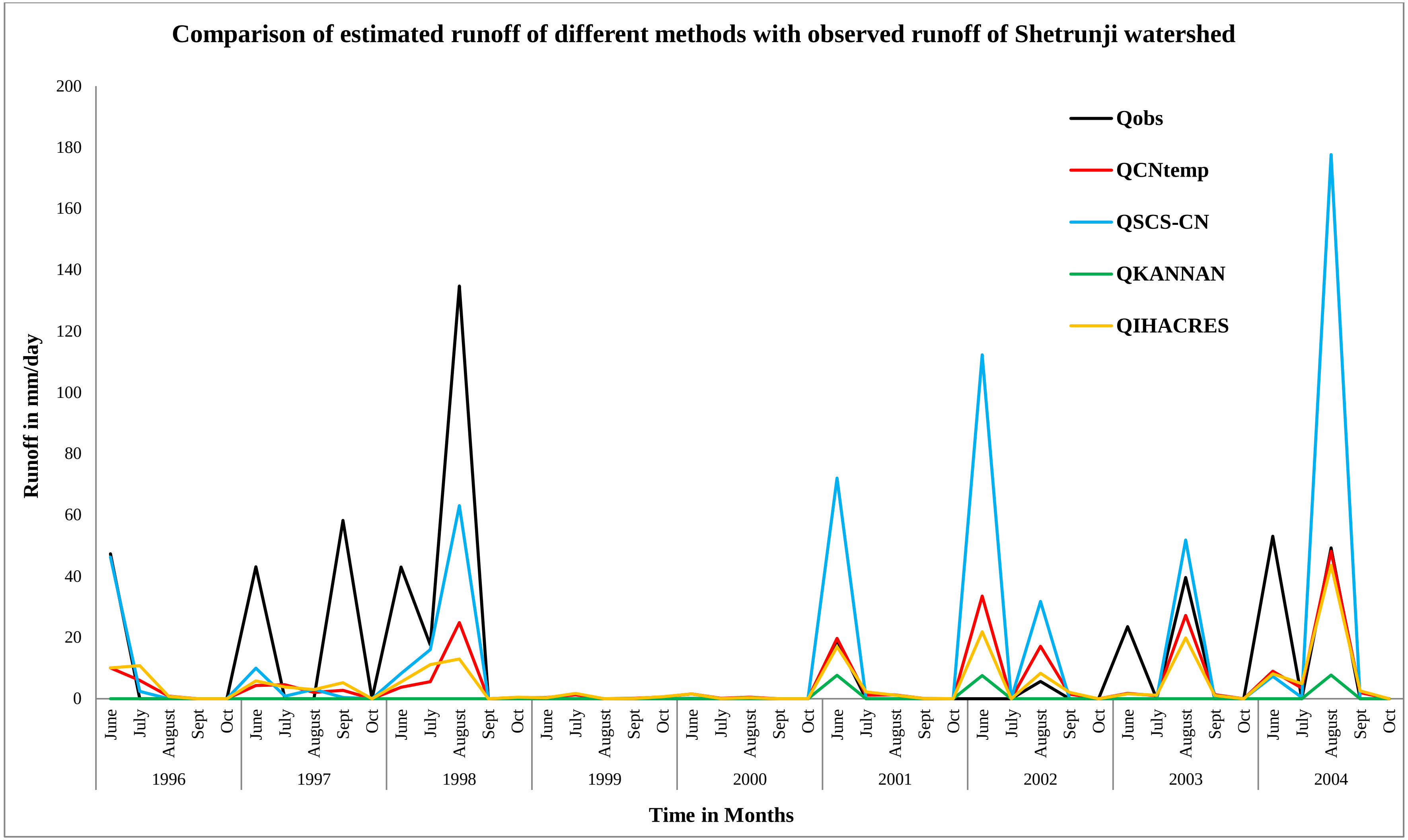


FIGURE 5.29 Performance of different methods at monthly time scale on dataset of validation period (1996-2004) for Shetrunji watershed (λ=0.20)

5.7 Comparison of the Performance of Different Methods

To compare and evaluate the overall performance of the different methods, the resulting values of the statistical criteria d_r, MAE and MBE are considered. MBE is a signed error measure that summarises the average error. It is a measure of overall bias error or systematic error between the observed and the predicted values, whereas MAE is a measure of how far the predicted value is from the actual value. It measures the average magnitude of the errors without considering their direction. It accounts for the summarised absolute error between observed and predicted values. d_r is a reliable estimator and provides a relative measure of the model performance (0 to 1) compared with other absolute measures (e.g. MAE, MBE). Overall, the method is considered perfect when the value of d_r is close to 1 and the value of MAE is close to zero. An appropriate rank is assigned to the method based on the d_r and MAE values; however, MBE values are accounted when methods have equal d_r and MAE values. The resulting values of statistical measures d_r, MAE and MBE and appropriate rank of the different methods for Ozat, Uben and Shetrunji watersheds are presented in Table5.10.

TABLE 5.10 Comparison of the performance of different methods on dataset of validation Period for test watersheds

Methods	**Ozat**			**Uben**			**Shetrunji**		
	d_r	**MAE (mm)**	**MBE (mm)**	**d_r**	**MAE (mm)**	**MBE (mm)**	**d_r**	**MAE (mm)**	**MBE (mm)**
SCS-CN with Composite *CN*	0.57	1.45	0.82	-0.30	2.22	1.67	0.65	0.54	0.06
AFM	0.67	1.11	0.21	0.09	1.40	0.77	0.70	0.46	-0.15
CN_{asy}	0.76	0.82	-0.60	0.72	0.44	-0.35	0.75	0.39	-0.39
CN_{mor}	0.76	0.80	-0.73	0.67	0.50	-0.27	0.73	0.41	-0.36
HUANG	0.44	0.97	-0.03	0.17	1.28	0.60	0.72	0.43	-0.19
CN_{temp}	0.75	0.83	-0.61	0.73	0.41	-0.36	0.73	0.42	-0.21
KANNAN	0.75	0.85	-0.47	0.61	0.61	-0.14	0.49	0.39	-0.37
IHACRES	0.74	0.87	-0.53	0.73	0.41	-0.30	0.72	0.43	-0.24
RANK	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Methods	**CN_{mor}**	**CN_{asy}**	**CN_{temp}**	**IHACRES**	**CN_{temp}**	**CN_{asy}**	**CN_{asy}**	**CN_{mor}**	**CN_{temp}**

Based on the rank of the different methods (Table 5.10), it is obvious that the CN_{asy} method consistently performs better for all three watersheds. However, CN_{asy} method has ranked second for Ozat and ranked third for Uben watersheds, but differed very little compared to first ranked methods. CN_{temp} methods stand third in Ozat and Shetrunji watersheds and has got second rank in Uben watershed with marginally differed from IHACRES. CN_{mor} method has ranked first for Ozat and ranked second for Shetrunji watershed with marginally differ in MAE. CN_{mor} method does not get rank in Uben watershed. IHACRES stands first in Uben watershed with marginal difference in MBE but does not achieve rank in Ozat and Shetrunji watersheds. Therefore, based on these inferences, it is observed that the CN_{asy} is the best-performing method for the Middle South Saurashtra region followed by CN_{temp} and CN_{mor} method.

5.8 Closure

This chapter presents the results of application of the proposed methodology as explained in Chapter-4. The methodology is proposed to improve the performance of the SCS-CN method by modifying *CN* for the study region. The results obtained after application of the proposed methods and existing methods on dataset of test watersheds of the Middle South Saurashtra region of Gujarat (India) are presented in the form of several tables and also they are graphically represented. The successful application of the proposed methodology on the study region shows the capability of its application on any similar hydro-meteorological regions, which has potential demand for many hydrologic applications. This methodology can be used among the engineers to estimate the runoff at watershed level. The next chapter presents the summary, conclusions, recommendations for future work and advantages of proposed methods.

CHAPTER 6

Summary and Conclusions

6.1 General

In the preceding chapters, a research work has been carried out to develop methodology to modify *CN* for efficient estimation of runoff. The proposed methodology consists of three approaches to determine *CN* viz. modifying *CN* by using cumulative rainfall-runoff ordered data, by integrating morphometric parameters, and by incorporating evapotranspiration. The dataset of Ozat, Uben and Shetrunji watersheds of the study region were used to test the performance of the proposed methodology and the results are presented in chapter 5. When compare with existing methods, the developed methods are provided more reliable results and have very limited set of calibration parameters to be adjusted. This chapter provides summary, conclusions, contributions of the research work, recommendations for the future work and limitations of the present work.

6.2 Summary

The important problems faced by the Middle South Saurashtra region of Gujarat (India) in the context of watershed development have been discussed in the section 1.2. Inappropriate modelling of the distinctive features of the watershed and insufficient data often leads towards poor hydrologic analysis in such region. The main intention of this research was to contribute to the rainfall-runoff modeling and to develop efficient, convenient and simple methods for runoff estimation. The study was set out to explore the methodology of *CN* determination and to improve competency of the SCS-CN method by modifying *CN* for better runoff prediction in the study region.

The soil characteristics of the study region were identified based on the soil taxonomy and its formative elements. The study depicts that major portion of the Ozat and Uben watersheds are covered by Inceptisols and remaining parts are comprised of Vertisols. No Entisols have been found in these watersheds. In contrast, major portion of the Shetrunji watershed is occupied by Entisols and remaining part is encompassed by Inceptisols, but no Vertisols have been found. The study reveals that HSGs are explicitly assigned in associations with soil orders. The finding shows that based on the soil characteristics and infiltration rate, HSG 'B', 'C' and 'D' are assigned to Entisols, Inceptisols and Vertisols (or land without soils) respectively. LULC maps were prepared in GIS platform for two different periods to incorporate the impact of alternate LULC change in composite *CN* determination.

The proposed methodology (ref: Fig.4.1) consists of three approaches to modify *CN*. In first approach, existing AFM *CN* was modified by using cumulative rainfall-runoff ordered data. *CN* value was modified by integrating physical characteristics of the watershed in *CN* determination procedure in second approach. In third approach, the evapotranspiration was introduced to modify *CN*. The statistical significance of the proposed methods was tested by applying it on sample dataset of the three test watersheds of the study region. The performances of the proposed methods were also tested on dataset of validation period at daily time scale, and the results are presented in chapter 5. The results show that the proposed methods perform better than the existing methods in the test watersheds. The following conclusions may be specifically drawn from the development and application of the proposed methods.

6.3 Conclusions in the Context of Composite *CN*

1. Impact of dynamic LULC change over a temporal scale in sub watershed is detected. The composite CN_{II} of some sub watersheds is found more sensitive to LULC change.
2. Vertisols is characterized by slow infiltration rate; therefore, watershed having more Vertisols generates more runoff.
3. Entisols have moderately rapid infiltration rate, hence, watershed having more Entisols generates less runoff. However, due to shallow depth and low water storage capacity, in prolong continuos rainfall, it generate comparatively more runoff.

4. Dense vegetation cover facilitates low surface runoff conditions whereas surface runoff is relatively high in sparse vegetation cover and bare surface. Shetrunji watershed has large forest area; hence, it has low runoff potential.

6.4 Conclusions in the Context of (CN_{asy})

1. Cumulative P_n–Q_n ordered data eliminate long memory characteristics due to accumulation of soil moisture and significantly improve the performance of the SCS-CN model.
2. CN_{asy} method attained relatively lower asymptotic *CN* value than AFM *CN*. Due to this it reduces overestimation of the conventional SCS-CN method.
3. CN_{asy} method is consistently performed better for all three test watersheds.
4. AFM method is poorly performed for Uben watershed. AFM is data driven method and only 5 years dataset were available in Uben watershed. Asymptotic *CN* was determined based on this limited dataset. This short length of dataset does not adequately describe the *P-CN* relationship. CN_{asy} method overcomes most of the limitations prevailing in the AFM method as it incorporates cumulative P_n–Q_n ordered data in the formulation.

6.5 Conclusions in the Context of (CN_{mor})

1. CN_{temp} method performed better than HUANG model on dataset of the test watersheds. This shows that the prediction accuracy of the SCS-CN method improved greatly when slope, stream length and drainage density are taking in to account in *CN* determination.
2. The study depicts that for watershed having slope less than 5%, slope-adjusted *CN* (HUANG) alone not adequately improved the performance of the SCS-CN method.
3. HUANG model performed better for watersheds having comparatively larger slope (performed better in Shetrunji (0.64%) watershed as compare to Ozat (0.58%) and Uben (0.26%) watersheds).

6.6 Conclusions in the Context of (CN_{temp})

1. Maximum temperature was found to be the most dominant meteorological parameter influencing ET_o in the study region.
2. Maximum temperature based sub model is developed to estimate daily ET_o.
3. Major part of the Shetrunji watershed is covered by shallow depth Entisols. Shetrunji watershed is characterised by large forest area, low annual average rainfall and low runoff coefficient. KANNAN model was developed for shallow soils and soils with low storage. Therefore, it is understood that KANNAN model perform better on sample dataset of Shetrunji watershed. However, due to one more calibration parameter than CN_{temp}, it is not statically significant better than the $CN_{temp.}$ CN_{temp} model comparatively performed poor in Shetrunji watershed. This is due to the reason that the Shetrunji watershed has larger forest area. In dense vegetation, temperature can not be adequately influenced on the rate of evapotranspiration loss and *CN* value.
4. Due to more calibration parameters, IHACRES model is not statically significant in F-test. It depicts that more parameters do not produce better prediction results; that is not to say however, that the inclusion of further process descriptions in a model is not a worthy activity. From a scientific point of view, the inclusion of more parameters in the model makes it a better representation of reality, but it does not make it better able to predict runoff.

For a semi-arid region like the Middle South Saurashtra region, precise estimation of runoff is very essential for efficient utilization and management of scarce water resources. The present study is a successful attempt in this direction. The results show that CN_{asy} method is found to be performing the best among the methods considered so far. The statistical comparison of these methods reveals that CN_{mor} and CN_{temp} perform marginally better than existing methods. Therefore, these proposed modified methods are recommended for field applications.

6.7 Contributions of Research Work

In the present work, three methods are developed to modify *CN* which provide better options to the user for runoff estimation. The research made following original contributions as listed below:

1. HSG maps are developed for the test watersheds of the study region based on the soil maps; NBSS & LUP soil classification, formative elements of soil taxonomy, infiltration rate, and soil characteristics.
2. RS and GIS techniques effectively integrated in *CN* determination procedure to explore the impact of dynamic LULC change over a temporal scale.
3. CN_{asy} method is proposed by modifying existing AFM Method.
4. Cumulative P_n–Q_n ordered data are replaced with ordinary P–Q ordered data in modified method to incorporate long-term accumulative effects of soil moisture.
5. Watershed morphometric parameters based method CN_{mor} is attempted which makes more accurate physical representation than conventional SCS-CN model.
6. The maximum temperature was found to be the most dominant meteorological variable affecting ET_o through dependency analysis. An empirical sub model is developed to estimate ET_o for the study region.
7. CN_{temp} method is developed for long-term hydrologic simulation by incorporating ET_o in *CN* determination.

6.8 Advantages of Proposed Methods

1. Proposed methods viz. CN_{asy}, CN_{mor} and CN_{temp} will be practically more useful as they are based on widely used the SCS-CN method.
2. Proposed methods have comparatively less input data requirements thus suitable for data scared region.
3. Based on the type of available data, the proposed methodology provides better options to the users.
4. Proposed methods are user friendly, efficient enough, and convenient in the field applications.
5. Results show that the proposed methods also performed better for large size watershed (> 250 Sq. Km.).
6. Proposed methods provide realistic and consistent results**.**

6.9 Recommendations for Future Work

This research provided useful insight into the runoff estimation by modified SCS-CN method in the Middle South Saurashtra region. The present study opens scope for further research in the area of modelling runoff, some of the recommendations for future works are listed below:

1. Additional parameters such as soil moisture, wetness index, climate variability (other than *ET*) and groundwater variables (infiltration rate, water table, hydraulic conductivity, field capacity etc.) can be included as input parameters in the SCS-CN based methods.
2. The secondary hydrological and meteorological data were obtained from various government agencies and are used in the present study. The main source of error for recorded flow is long-time intervals (three times a day) in between stream stage observations. Many times, due to lack of electronic data recorder some important data might be missed, in particular during the adverse weather conditions. Establishing electronic data recorders with the ability to store the stage measurements on regular smaller intervals can provide a more reliable base for further hydrological studies, especially for flood predictions.
3. Impact of LULC change, hydrological, meteorological and morphometric parameters on *CN* can be more prominently identified by measuring rainfall-runoff at hourly time scale for each sub watershed.
4. The research methods developed in this study can be extended to either Saurashtra region or similar hydro-meteorological regions.
5. It is recommended that planning and management should be carried out at watershed scale rather than geographical area scale.
6. The potential uses of these models are to extend to fill missing flow data.
7. They can also be used for flood forecasting if coupled with a rainfall forecasting system.

6.10 Limitations of Proposed Methods

1. The proposed methods also have some limitations such as they do not consider the spatial effect of rainfall intensity or duration on runoff.
2. Beside rain fall and runoff data, temperature data are needed for CN_{temp}.

3. The proposed methods are not effective in snowmelt runoff simulation.
4. The methods only compute direct runoff and do not consider sub-surface and groundwater flow.
5. Like to the standard AFM approach, the proposed CN_{asy} method also does not suitable for watershed which shows complacent response for which a consistent *CN* cannot be adequately defined.
6. The problem of simulating the peaks is still persisted in these methods.
7. Similar to the conventional SCS-CN method, the proposed methods are not applicable at sub-daily time resolution (Woodward et al. 2010).

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List of Publications

International Journals

1. Gundalia, M. J., and Dholakia, M. B. (2012). "Prediction of maximum/minimum temperatures using Holt Winters Method with Excel Spread Sheet for Junagadh Region." *International Journal of Engineering Research & Technology,* Vol. 1 (6), pp. 1-8. ISSN: 2278-0181. Impact factor 1.76.
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International Conferences

1. Gundalia MJ, Dholakia MB, and Majumdar PK (2015) ‘Runoff estimation with modified asymptotic curve number in Ozat Watershed of Gujarat (India).’ *20th International Conference on Hydraulics, Water Resources and River Engineering*, IIT, Roorkee, 17-19 Dec., 2015.
2. Gundalia MJ, Dholakia MB, and Majumdar PK (2015) ‘Estimation of surface runoff with composite curve number in Ozat watershed of Gujarat (India).’ *20th International Conference on Hydraulics, Water Resources and River Engineering*, IIT, Roorkee, 17-19 Dec., 2015.

Appendices

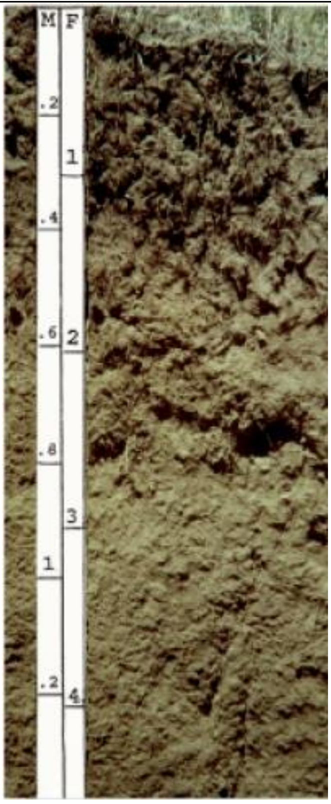
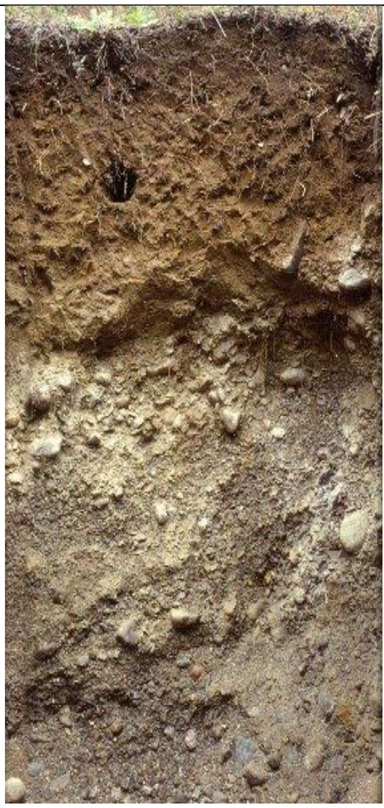
Appendix A-1 Physical characteristics and morphometric parameters of the test watersheds

Physical Characteristics	Ozat	Uben	Shetrunji
Total Area of catchment (*A*)	351.0633 Km^2	496.5448 Km^2	234.1213 Km^2
Total Length of Main Stream (*L*)	36.6255 Km	44.1366 Km	26.498 Km
Length from centroid (L_c)	15.9561 Km	22.3474 Km	13.552 Km
Axial Length (L_b)	27.4914 Km	36.8634	22.3245 Km
Axial Width (W_b)	26.40035 Km	20.5442	10.4580 Km
Perimeter (P_b)	99.6274 Km	105.1619 Km	72.5725Km
Higher Level (R. L.)	310 m	167 m	380 m
Lower Level (R. L.)	98 m	50 m	210 m
Slope %	0.5788	0.2651	0.6416
Runoff Coefficient (%)	0.33	0.19	0.10
Drainage Density (*DD*)	0.9131 Km/Km^2	0.8324 Km/Km^2	1.0699 Km/Km^2
Form Factor	0.2936	0.1881	0.3666
Elongation Ratio	0.6114	0.4894	0.6833
Shape Factor	5.0852	6.1886	4.4935
Circularity Ratio	0.6047	0.4705	0.5463

Appendix A-2 Soil Categories and its Characteristics based on Soil Taxonomy

Soil Categories	Recognized in Word	Characteristics:
Order	12	Presence or absence of diagnostic horizons that reflect soil forming processes.
Sub Order	64	It reflects diagnostic properties of the soil order
Great Group	300	It represents soil temperature and soil moisture regime of particular sub order.
Sub Group	>2400	It makes addition to the properties of great group. Sub group belongs to one great group but that have some properties of another order, sub order, great group or other kind of soil
Family	>50 Subclasses	It groups the soils within a sub group having similar physical and chemical properties (Texture, Mineralogy, Reactivity, Temperature Regime)
Series	>19000	Lowest Category, Acts as label, Named for Place where, first described

Appendix A-3 Soil profiles of Entisols, Inceptisols and Vertisols

		
Entisols	Inceptisols	Vertisols

Appendix A-4 Comparison of the observed runoff and computed runoff by different methods at daily time scale for selected sample month from validation period for Ozat watershed										
			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
01-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
02-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
03-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
04-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
05-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
06-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
07-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
08-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
09-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
14-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
15-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
16-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix A-4 Continue										
			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
17-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18-Jun-05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
19-Jun-05	18.5122	0.0000	0.0000	1.1549	0.3933	0.0000	0.0000	0.0000	0.0758	0.2136
20-Jun-05	13.8099	0.0000	0.0000	0.7013	0.3022	0.0000	0.0000	0.0000	0.0976	0.1090
21-Jun-05	24.4506	0.0000	0.0000	1.9340	0.5079	0.0000	0.0000	0.0000	0.3015	0.3393
22-Jun-05	39.2984	0.0000	19.8706	5.0644	0.8309	6.7013	0.0000	0.0000	0.8156	0.9354
23-Jun-05	27.2336	0.0000	10.4894	2.3870	0.5630	2.0966	0.0000	0.0000	0.7121	0.3588
24-Jun-05	58.3828	0.0000	36.3981	11.7610	1.4495	17.1968	0.0097	0.3229	2.2432	1.9864
25-Jun-05	41.7999	0.0000	21.9469	5.7708	0.8954	7.8863	0.0000	0.0327	1.9534	1.0428
26-Jun-05	26.3389	0.0000	9.8494	2.2349	0.5451	1.8421	0.0000	0.0000	1.3564	0.3804
27-Jun-05	53.4969	15.5595	32.0403	9.7658	1.2592	14.2249	0.0000	3.5474	3.3295	1.7914
28-Jun-05	170.0305	16.9123	143.3810	88.5515	19.5060	107.6504	32.3466	80.1639	16.6317	11.8261
29-Jun-05	126.1784	42.9561	100.5110	53.6516	8.5394	69.0261	13.6639	124.9862	15.6564	11.4937
30-Jun-05	46.6008	15.6230	26.0215	7.2737	1.0310	10.3402	0.0000	45.4219	6.1444	1.2051
Total	**646.1327**	**91.0510**	**400.5082**	**190.2510**	**35.8229**	**236.9646**	**46.0201**	**254.4751**	**49.3176**	**31.6819**

Appendix A-5 Comparison of the observed runoff and computed runoff by different methods at daily time scale for selected sample month from validation period for Uben watershed

			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
01-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
02-Jul-06	26.4653	0.0000	0.0000	0.5533	0.0100	0.0000	0.0000	0.0000	0.0369	0.0424
03-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
04-Jul-06	33.8293	13.0117	0.0295	1.5080	0.0047	0.0000	0.0000	0.0000	0.1072	0.0745
05-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
06-Jul-06	62.9801	0.0000	37.9991	10.6609	0.0012	16.5644	0.0000	0.0000	0.4084	0.2257
07-Jul-06	22.9240	0.0000	6.3828	0.2809	0.0132	0.4396	0.0000	0.0000	0.1751	0.0364
08-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
09-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
14-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
15-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
16-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix A-5 Continue										
			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
17-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
19-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
22-Jul-06	105.3932	0.0522	23.4355	34.7323	0.2486	0.4297	0.0000	0.3177	1.3311	0.9035
23-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
24-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
25-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
26-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
27-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
28-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
29-Jul-06	49.6428	8.1355	1.8357	5.4698	0.0005	0.0000	0.0000	0.0000	0.7536	0.1824
30-Jul-06	229.3771	2.6377	165.2459	133.1565	16.7233	95.4412	3.8476	47.6913	6.2550	6.0394
31-Jul-06	30.7686	6.5276	11.5866	1.0440	0.0067	2.0471	0.0000	0.0655	0.8887	0.0760
Total	**561.3804**	**30.3649**	**246.5151**	**187.4058**	**17.0081**	**114.9220**	**3.8476**	**48.0744**	**9.9561**	**7.5802**

Appendix A-6 Comparison of the observed runoff and computed runoff by different methods at daily time scale for selected sample month from validation period for Shetrunji watershed

			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
01-Aug-04	28.8101	26.2370	6.6472	0.2707	0.0000	0.5828	0.0000	0.0000	1.5808	1.6983
02-Aug-04	66.6995	22.9878	33.8227	8.2757	0.0000	14.1144	0.4126	0.0000	5.8938	7.6346
03-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
04-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
05-Aug-04	101.4790	0.0000	64.0544	24.6655	0.1339	35.3447	6.4391	0.5484	13.2153	20.7026
06-Aug-04	114.7330	0.0000	76.1361	32.4218	0.4406	44.6899	10.2939	6.1483	21.4628	17.9021
07-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
08-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
09-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
14-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
15-Aug-04	12.7674	0.0000	0.0000	0.0000	0.0012	0.0000	0.0000	0.0000	1.4309	0.2146
16-Aug-04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix A-6 Continue										
			Computed Runoff (Q_c) mm							
Date	**Rainfall (P) mm**	**Observed Runoff (Q_{obs}) mm**	**SCS-CN**	**AFM**	**CN_{asy}**	**HUANG**	**CN_{mor}**	**KANNAN**	**IHACRES**	**CN_{temp}**
17-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
19-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
22-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
23-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
24-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
25-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
26-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
27-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
28-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
29-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
30-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
31-Jul-06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**324.4890**	**49.2247**	**180.6604**	**65.6338**	**0.5757**	**94.7317**	**17.1456**	**6.6967**	**43.5836**	**48.1522**