ASSESSMENT OF DESIGN RUNOFF CURVE NUMBER FOR A WATERSHED

A DISSERTATION

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

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in this Dissertation entitled **"Assessment of Design Runoff Curve Number for a Watershed"** in partial fulfillment of the requirements for the award of the degree of MASTER OF TECHNOLOGY in Water Resources Development (Civil) and submitted to the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during the period from July 2010 to June 2011 under the supervision and guidance of **Dr. S. K. Mishra**, Associate Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, India.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

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Place: Roorkee

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

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ABSTRACT

Rainfall-runoff modeling is an integral part of water resources planning and management. The Soil Conservation Service-Curve Number (SCS-CN) method is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural watersheds. The method has been the focus of much discussion in agricultural, hydrologic literature and is also widely used in continuous modeling schemes. The main reason behind the method being adopted by most hydrologists lies in its simplicity and applicability to watersheds with minimum hydrologic information, viz., soil type, land use and treatment, surface condition, and antecedent moisture condition (AMC). CN-values are derived using limited values of rainfall-runoff events for a gauged watershed and using NEH-4 tables for an ungauged watershed for three AMCs. Of late, an approach based on the ordering of rainfall has also been suggested in literature.

In this study, employing the 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), a simple approach for CN derivation for three levels of AMC from long-term daily rainfall-runoff data has been suggested. It is of common experience that the SCS-CN method's parameter curve number decreases as the rain duration increases, and vice versa. It is because of the larger opportunity time available for water to loss in the watershed. In this study, this impact of rain duration on curve numbers is investigated in a rational manner, and a CN-rainfall duration relationship proposed for each watershed. In addition, there is no rational approach available in literature for derivation of curve numbers for design purposes associated with return periods. This study investigates this aspect and proposes a simple approach for design CN development and it is validated using the observed data.

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A = Catchment Area
AMC = Antecedent Moisture Condition
C = Runoff Coefficient
CN = Curve Number
F = Cumulative Infiltration
HSU = Hydrologically Similar Units
I_a = Initial Abstraction
λ = Initial Abstraction Coefficient
NEH = National Engineering Handbook
P = Precipitation,
P_o = Observed Rainfall
P_c = Adjusted Rainfall
P_5 = Antecedent 5-Day Precipitation Amount
Q = Direct Surface Runoff;
Q_p = Peak Discharge
Q_t = Total Daily Flow
$\overline{R}$ = Maximum Catchment Average Intensity of rainfall for duration equal to the time of concentration
S = Potential Maximum Retention
SCS = Soil Conservation Service
S_1 = Potential Maximum Retention for AMC I
S_r = Degree of Saturation
$\bar{t}_p$ = Mean Storm Duration
t_p = Storm Duration
USDA = United States Department of Agriculture
V_w = Volume of Water
CN_W = Temporally Weighted Average CN Value
$\propto$ = Temporal Weight
$CN_{t+\Delta t}$ = Function of the Retention Parameter $S_{t+\Delta t}$
S_o = Absolute Potential Maximum Retention

CHAPTER 1

INTRODUCTION

Rainfall-generated runoff is very important in various activities of water resources development and management such as flood control and its management, irrigation scheduling, design of irrigation and drainage works, design of hydraulic structures, and hydro-power generation etc. Determining a robust relationship between rainfall and runoff for a watershed has been one of the most important problems for hydrologists, engineers, and agriculturists since its first documentation by P. Perrault (In: Mishra and Singh 2003) about 330 years ago. The process of transformation of rainfall to runoff is highly complex, dynamic, non-linear, and exhibits temporal and spatial variability. It is further affected by many and often interrelated physical factors. Rain (precipitation) is the major object of hydrologic cycle and this is the primary cause of runoff.

The Soil Conservation Service-Curve Number (SCS-CN) method (SCS 1956, 1964, 1969, 1971, 1972, 1985, 1993) is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural watersheds. The method has been the focus of much discussion in agricultural hydrologic literature and is also widely used in continuous modeling schemes. Ponce and Hawkins (1996) critically examined this method; clarified its conceptual and empirical bases; delineated its capabilities, limitations, and uses; and identified areas of research in the SCS-CN methodology (Mishra and Singh, 2003). The main reason the method has been adopted by most hydrologists lies in its simplicity and applicability to watersheds with minimum hydrologic information: soil type, land use and treatment, surface condition, and antecedent moisture condition (AMC). The runoff curve number method is developed to estimate extreme or large event runoff volume. However, it is used in hydrologic simulation models such as CREAMS (Knisel, 1980) and AGNPS (Young et al., 1987) to estimate direct runoff from daily rainfall events.

Methods of selecting the runoff curve number (CN) for a watershed under various conditions are available in the National Engineering Handbook, Section 4, Hydrology or "NEH-4" (SCS, 1972). The CN values were originally defined from annual maximum rainfall and runoff data on small agricultural watersheds, where hydrologic soil group, land use/treatment, and surface condition were known. The CN values have also been documented for different tillage practices and surface mining and reclamation watersheds (Ritter and Gardner, 1991).

This SCS-CN method converts rainfall to surface runoff (or rainfall-excess) using curve number, derived from watershed characteristics and 5-days antecedent rainfall. This model is selected for predicting runoff as (1) it is a familiar procedure that has been used for many years around the world; (2) it is computationally efficient; (3) the required inputs are generally available; and (4) it relates runoff to soil type, land use, and management practices. To derive CN for an un-gauged watershed, SCS (1956) provided tables based on the soil type, land cover and practice, hydrologic condition, and AMC. Fairly accurate mathematical expressions (Ponce and Hawkins 1996) are also available for CN conversion from AMC I (dry) to AMC III (wet) or AMC II (normal) levels. Hjelmfelt et al. (1982) statistically related the AMC I through AMC III levels, respectively, to 90, 10, and 50% cumulative probability of the exceedance of runoff depth for a given rainfall. For gauged watersheds, Hawkins (1993) suggested the CN-computation from event rainfall-runoff data considering the median CN to correspond to AMC II and the upper and lower bounds of the scatter rainfall-runoff plot to AMC III and AMC I, respectively.

For hydrologic design purposes, Hawkins (1993) and Hawkins et al. (2001) derived CN from the ordered rainfall-runoff data, and McCuen (2002) developed confidence intervals for CNs (from 65 to 95) treating CN as a random variable. Mishra et al. (2004b) compared the existing SCS-CN and the modified Mishra and Singh (2003a,b,c) (MS) models using the data from small to large watersheds and found the latter to perform significantly better than the former. Jain et al. (2006b) quantitatively evaluated the existing SCS-CN model, its variants, and the modified Mishra and Singh (2003a) models for their suitability to particular land use, soil type and combination thereof using a large set of rainfall-runoff data from small to large watersheds of the U.S.A.

The above approaches, however, utilize discrete (generally annual extreme) storm events of varying time duration (less than or equal to 1-d) for computing curve numbers

(SCS, 1971; Hawkins et al., 2001). Consequently, the resulting curve numbers are applicable to only those high rain and short duration events from which they were derived, and not appropriate for events of low magnitude and/or long duration. It is of common experience that a given amount of rainfall on a watershed produces a high or low runoff depending on, besides others, the small or large time interval/duration, for the infiltration and evaporation losses depend significantly on how long the water remains in the watershed. Thus, it is in order to explore the application of the original SCS-CN method to long duration storm events by investigating the CN dependency on rain duration and, in turn, avoiding CN-variability due to varying event duration, which is otherwise accounted for in terms of AMC in the original procedure.

1.1 OBJECTIVES OF STUDY

The objectives of this study are to

(1) propose a simple approach for CN derivation for three levels of AMC and for different durations from long-term daily rainfall-runoff data of a watershed,
(2) investigate the impact of rain duration on curve numbers and develop a CN-rainfall duration relationship,
(3) determine the curve numbers for hydrologic design, and
(4) validate the derived design curve numbers.

1.2 ORGANIZATION OF DISSERTATION WORK

The present thesis has been divided into six chapters. CHAPTER 1 introduces the problem and defines the objectives of the study. CHAPTER 2 presents a review of the literature. CHAPTER 3 contains methodology. CHAPTER 4 presents the study area, the data and data preparation. CHAPTER 5 presents analysis and discussion of results. Finally, CHAPTER 6 concludes the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Rainfall - Runoff Modeling

Rainfall - runoff modeling is meant to model the hydrological processes of the land phase of the hydrological cycle which input the rainfall and other hydrologic, climatic and basin parameters and produces the desired output such as runoff, peak discharge etc. Its description requires a little understanding of the hydrological cycle. The hydrological cycle is a continuous process in which water circulates from the oceans through the atmosphere and rivers back to the oceans. Among the various components of hydrological cycle, the term precipitation denotes all forms of water that reach the earth from the atmosphere. Rain (precipitation) is the major object of hydrologic cycle and this is the primary cause of runoff. The rainfall is subjected to the physical processes which depend on climatological factors like temperature, humidity, wind velocity, cloud cover, evaporation and evapotranspiration, topographical features like depressions, slope of the catchments, vegetation and land use pattern, the soil characteristics like permeability, antecedent moisture content and irrigability characteristics; and the hydrological condition like rock formation, elevation of water table and sub-surface channels too affect this process considerably. Runoff is defined as the portion of the precipitation that makes its way towards river or ocean etc. as surface and subsurface flow. Runoff, representing the response of a catchment to precipitation, reflects the integrated effect of a catchment, climate & precipitation characteristics. Under these influencing parameters, it is extremely difficult to estimate accurately the runoff to be generated by a particular storm. Precipitation (rain) falling on the land surface has several pathways as shown in Figure 2.1.

The precipitation responsible for runoff generation is known as effective precipitation or rainfall-excess. For a given precipitation the evapotranspiration, initial loss, infiltration and detention storage requirements will have to be first satisfied before the commencement of runoff. When these are satisfied the excess precipitation moves over the land surface to reach smaller channels. The portion of the runoff is called as overland flow and involves building up of storage over the surface and draining the same. Flows from several small channels join bigger channels and flows from there and, in turn, combine to form a large stream and so on till the flow reaches the catchment's outlet.

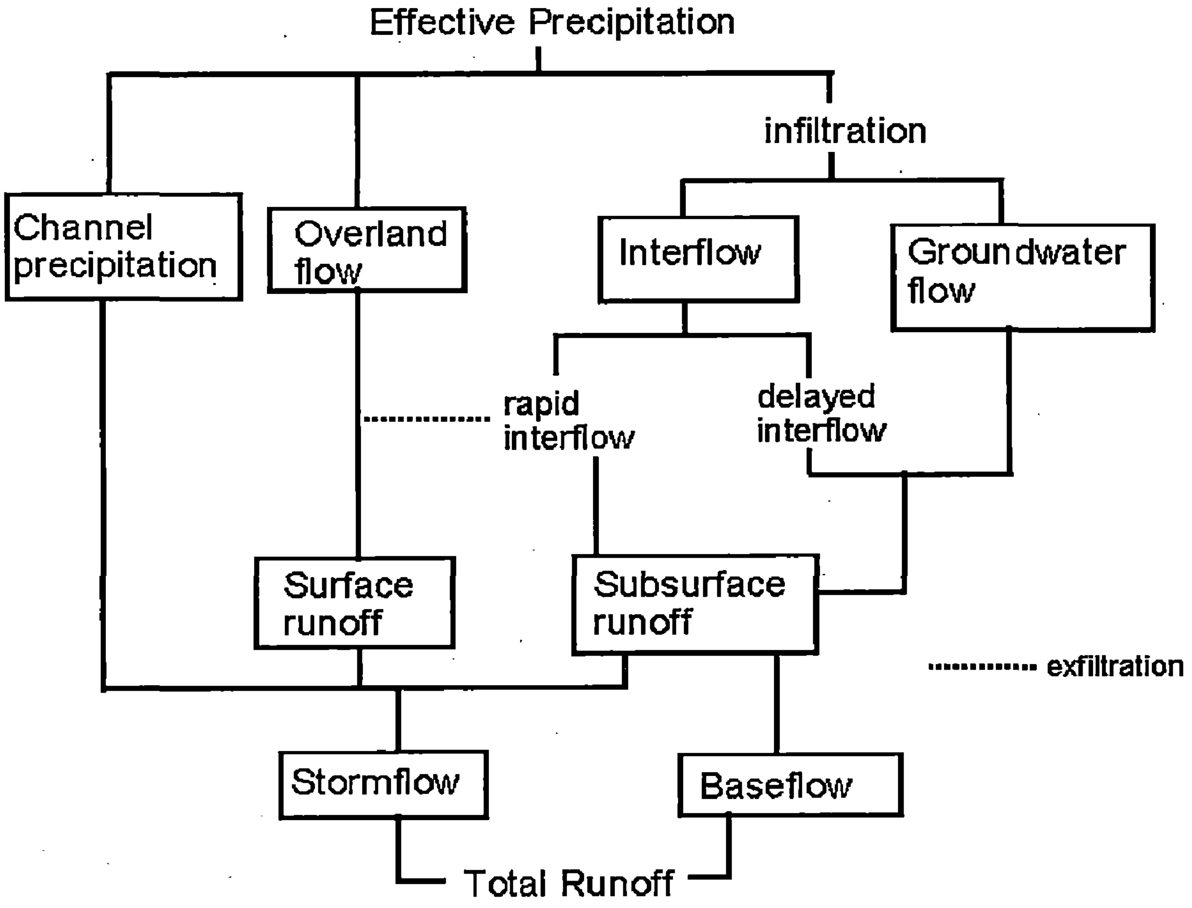


Figure 2.1: Generation of runoff from effective rainfall in a catchment
(Source :- www.cartage.org.lb/.....sourcesofrunoff.htm)

The flow in this mode where it travels all the time over the surface as overland flow and through the channels as open channel flow and reaches the catchment's outlet is called surface runoff. A part of precipitation that infiltrates moves laterally through upper crust of the soil and returns to the surface at some location away from the point of entry into the soil. This component of runoff is known as interflow. The amount of interflow depends on the geological condition of the soil. Depending on the time delay between infiltration and outflow, the interflow is sometimes classified into prompt interflow or rapid interflow i.e. the interflow with the least time lag and delayed interflow. Another route for the infiltrated water is to undergo deep percolation and reach the ground water storage in the soil. The time lag i.e. difference in time between the entry into the soil and outflow from it is very large, being of the order of months and years. This part of runoff is called groundwater runoff or groundwater flow.

Based on the time delay between the precipitation and the runoff, runoff is classified into two categories as direct runoff or storm runoff and base flow. Direct runoff is the part of runoff which enters the stream immediately after the precipitation. It includes surface runoff, prompt interflows and precipitation on channel surface. The delayed flow that reaches stream essentially as groundwater flow is called as base flow. Rainfall-runoff models may be grouped into two general classifications. The first approach uses the concept of effective rainfall in which a loss model is assumed which divides the rainfall intensity into losses and an effective rainfall hyetograph. The effective rainfall is then used as input to a catchment model to produce the runoff hydrograph. It follows from this approach that the infiltration process ceases at the end of the storm duration.

An alternative approach that might be termed as surface water budget model incorporates the loss mechanism into the catchment model. In this way, the incident rainfall hyetograph is used as input and the estimation of infiltration and other losses is made as an integral part of the calculation of runoff. This approach implies that infiltration will continue to occur as long as the average depth of excess water on the surface is finite. Clearly, this may continue after the cessation of rainfall.

The origin of rainfall- runoff modeling, widely used for flow simulation, can be found in the second half of the 19th century when engineers faced the problems of urban drainage and river training networks. During the last part of 19th century and early part of 20th century, the empirical formulae were in wide use (Dooge, 1957, 1973). The approaches were mainly confined to small and mountainous watersheds. Later attempts were mainly confined to their application to larger catchments. In 1930's the popular unit hydrograph techniques were developed. With the advent of computers in 1950's, sophistication to models through mathematical jugglery was introduced with the objective of providing the generality of available approaches. The subsequent era saw the development of a number of models and evoked the problem of classification.

The relation between precipitation (rainfall) and runoff is influenced by various storm and basin characteristics. Because of the complexities and frequent paucity of adequate runoff data, many approximate formulae have been developed to relate runoff with rainfall. The earliest of these were usually crude empirical statements, whereas the trend now is to develop descriptive equations based on physical processes.

2.2 Classification of Hydrological Models

The rainfall-runoff (R-R) simulation has been an unavoidable issue of hydrological research for several decades and has resulted in plenty of models proposed in literature. In recent decades the science of computer simulation of groundwater and surface water resources systems has passed from scattered academic interest to a practical engineering procedure. A few of the most descriptive classifications are presented. The available hydrological models can be broadly classified into Deterministic vs. Stochastic / Probabilistic, Conceptual vs. Physically Based Models, Lumped Models vs. Spatially Distributed Models, a brief description of which is provided as follows:

- **Deterministic vs. Stochastic / Probabilistic Models**

Water balance models can be referred to as "deterministic" if the statistical properties of input and output parameters are not considered. On the other hand, probabilistic models include random variations in input parameters, whereby known probability distributions are used to determine statistical probabilities of output parameters; i.e. *deterministic models permit only one outcome from a simulation with* one set of input and parameter values. Stochastic models allow for some randomness or uncertainty in the possible outcomes due to uncertainty in input variables.

- **Conceptual vs. Physically Based Models**

Conceptual models rely primarily on empirical relationships between input and output parameters. These are based on overall observations of system behaviour (sometimes called "black box" models). The modeling systems may or may not have clearly defined physical, chemical or hydraulic relationships. Physically based models seek to describe water movement based on physical laws and principles. This may result in more reliable descriptions of water balance relationships. This type of model demands appropriate data for input and requires documentation of processes and assumptions.

- **Lumped Models vs. Spatially Distributed Models**

Lumped models treat a sub-watershed as a single system and use the basin- wide averaged data as input parameters. This method assumes that the hydrologic characteristics of sub-watersheds are homogeneous. A spatially distributed model accounts for variations in water budget characteristics. Various methods are available, such asdivision of the watershed into grid cells or use of Hydrological Similar Units (HSU). For example, a grid cell model uses data for each grid cell inside the basin to compute flow from cell to cell. By this method, the spatial variation in hydrologic characteristics can be handled individually (i.e. assuming homogeneity for each cell), and therefore, may be a more appropriate treatment. Spatially distributed models are suitable for GIS applications.

2.3 Early Rainfall-Runoff Models

A number of methods/models to estimate runoff from a rainfall event have been developed since the first widely used rainfall- runoff model developed nearly 160 years back by the Irish engineer Thomas James Mulvaney (1822-1892) and published in 1851. The model was a single simple equation but, even so, manages to illustrate most of the problems that have made life difficult for hydrological modelers ever since. The Mulvaney equation in FPS unit is as follows:

$$Q_P = C A \bar{R} \qquad (2.1)$$

where Q_P = peak discharge in cubic feet per second (cfs), C= runoff coefficient, depending on the characteristics of the catchment, A= catchment area in acres, and $\bar{R}$ = a maximum catchment average intensity of rainfall (in inches per hour) for duration equal to the time of concentration. Equation 2.1 does not attempt to predict the whole hydrograph but only the hydrograph peak Q_p. This is often all an engineering hydrologist might need to design a bridge or culvert capable of carrying the estimated peak discharge. The input variables are the catchment area, A, a maximum catchment average rainfall intensity, $\bar{R}$, and an empirical coefficient or parameter, C. Thus, this model reflects the way in which discharges are expected to increase with area and rainfall intensity in a rational way. It has become known as the rational method. In the rational equation, the most difficult part is predicting the correct value of C, which takes account of the nonlinear relationship between antecedent conditions and the profile of the storm rainfall and the resulting runoff production, and varies from storm to storm on the same catchment, and catchment to catchment for similar storms. It is further difficult for a different set of conditions, perhaps more extreme than those that have occurred before, or for a catchment that has no observations.

Similar difficulties persist to the present day, even in the most sophisticated computer models. It is still more difficult to take proper account of the nonlinearities of the runoff production process, particularly in situations where data are very limited. It is still easiest to obtain effective parameter values by back-calculation or calibration where observations are available; it is much more difficult to predict the effective values for a more extreme storm on ungauged catchment. Thus, not only in the past but even today, more difficult problem remains how to determine the amount of effective rainfall. This is definitely a nonlinear problem that involves a variety of hydrological processes and the heterogeneity of rainfall intensities, soil characteristics and antecedent conditions in the same way as the coefficient C of the rational formula. Thinking about the problem of estimating effective rainfalls was the start of thinking about the modeling- the rainfall-runoff process on the basis of an understanding of hydrological process. It is not yet, however, a solved problem and there remain a number of competing models for estimating effective rainfalls based on different assumptions about the nature of the process involved. The USDA Soil Conservation Service Curve Number (SCS-CN) method is one of them, which is simple, lumped, conceptual, and empirical.

2.4 Soil Conservation Service-Curve Number (SCS-CN) Method

The Soil Conservation Service Curve Number (SCS-CN) method is widely used for predicting direct runoff volume for a given rainfall event. This method was originally developed by the US Department of Agriculture (USDA), Soil Conservation Service and documented in detail in the National Engineering Handbook, Sect. 4: Hydrology (NEH-4) (SCS 1956, 1964, 1971, 1985, 1993). Due to its simplicity, it soon became one of the most popular techniques among the engineers and the practitioners, mainly for small catchment hydrology. The SCS-CN method arose out of the empirical analysis of runoff from small catchments and hill slope plot monitored by the USDA. Mockus (1949) proposed that such data could be represented by an equation of the following form:

$$\frac{Q}{P-I_a} = [1-(10)^{-b(P-I_a)} \tag{2.2}$$

or

$$\frac{Q}{P-I_a} = [1-exp\{-B(P-I_a)\}] \tag{2.3}$$

where Q is the volume of storm runoff; P is the volume of precipitation, I_a is an initial retention of rainfall in the soil; and b and B are coefficients. Mockus (1949) suggested the coefficient b was related to antecedent rainfall, a soil and cover management index, a seasonal index, and storm duration.

Mishra and Singh (1999b) showed how this equation could be derived from water balance equation with the assumption that the rate of change of retention with effective precipitation is a linear function of retention and with the constraint that B (P - Ia)<1. Approximating the right hand side of equation (2.3) as a series expansion results into an equation equivalent to standard SCS-CN formulation

$$\frac{Q}{P-I_a} = \frac{P-I_a}{S+P-I_a} \tag{2.4}$$

where S (= 1/B) is the maximum volume of retention. Mishra and Singh (1999b) proposed a further generalization resulting from a more accurate series representation of equation (2.4) (and giving better fits to data from five catchments) as:

$$\frac{Q}{P-I_a} = \frac{P-I_a}{S+a(P-I_{a)}} \tag{2.5}$$

This is equivalent to assuming that the cumulative volume of retention F can be predicted as:

$$\frac{F}{S} = \frac{Q}{P - I_a} \tag{2.6}$$

F is often interpreted as a cumulative volume of infiltration, but it is not necessary to assume that the predicted storm flow is all overland flow, since it may not have been In original small catchment data on which the method is based (application of the method to one of the permeable, forested, Coweeta catchments in Hjelmfelt et al. (1982) is such an example).

A further assumption is usually made in the SCS-CN method that $I_a = \lambda S$ with A commonly assumed to be ≈ 0.2. Thus, with this assumption, the volume of storm runoff may be predicted from a general form of the SCS-CN equation:

$$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \tag{2.7}$$

With the usual assumption of $\lambda = 0.2$, Equation (2.7) can be re-written as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2.8}$$

which is the existing SCS-CN method.

2.4.1 Estimation of Potential Maximum Retention

The parameter S is called the potential maximum retention or maximum potential infiltration. This is also called watershed/catchment storage factor. Its value depends on characteristics of the soil-vegetation-land use (SVL) complex and antecedent soil–moisture conditions in a watershed. For each SVL complex, there is a lower limit and upper limit of S. The parameter S can vary in the range of $0 \leq S \leq \infty$. It is mapped onto a dimensionless curve number CN, varying in a more appealing range 0 ≤ CN ≤ 100,as:

$$S = \frac{25400}{CN} - 254 \tag{2.9}$$

where S is in mm. When S is in inches the equation is:

$$S = \frac{1000}{CN} - 10 \tag{2.10}$$

The difference between S and CN is that the former is a dimensional quantity (L) whereas the later is non-dimensional. CN = 100 represents a condition of zero potential maximum retention (S = 0), that is, an impermeable watershed. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention (S = ∞), that is an infinitely abstracting watershed. However, the practical design values validated by experience lie in the range (40, 98) (Van and Mullem, 1989). It is to explicitly mention here that CN has no intrinsic meaning; it is only a convenient transformation of S to establish a 0-100 scale (Hawkins,1978).Obviously, higher is the S, lower will be the CN and vice-versa. It infers that the runoff potential increases with increase in CN and decreases with decrease in CN.

Thus, the SCS-CN method relies on only one parameter, the curve number CN, which is a function of the runoff producing watershed characteristics. The method of selecting a curve number (CN) value for a watershed under various hydrologic conditions is available in the National Engineering Handbook, Section 4 as well as in subsequent publications (McCuen, 1982, 1989; Ponce, 1989; Singh, 1992; Mishra and Singh, 2003a).

A significant research dealing with several issues (Ponce and Hawkins 1996; Mishra and Singh 2003a) related with the SCS-CN method's capabilities, limitations, uses, and possible advancements have been published in the recent past. Specific to the subject matter, Hjelmfelt (1991), Hawkins (1993), Bonta (1997), and Bhunya et al. (2003) suggested procedures for determining curve numbers for a watershed using field data. Neitsch et al. (2002) provided an empirical relation to account for the effect of watershed slope on CN. Hjelmfelt (1991), Svoboda (1991), and Mishra and Singh (1999a, b; 2002a; 2003a, b) provided analytical treatments of the SCS-CN methodology. Jain et al. (2006a) incorporated the storm duration and a nonlinear relation for initial abstraction (I_a), to enhance the SCS-CN-based Mishra and Singh (2003a) model.

Using the volumetric concept of soil-water-air, Mishra et al. (2004a) described CN as the percent degree of saturation of the watershed at 10 in. of rainfall and its efficacy to distinguish the hydrological activeness of watersheds. This concept is consistent with the work of Neitsch et al. (2002) relating the curve number with the available soil water content, wilting point, and field capacity. Such a description, however, is not in conformity with the works of Hjelmfelt (1982), McCuen (2002), and Bhunya et al. (2003) describing CN as a stochastic variable. Furthermore, since the basic structure of the original SCS-CN method with 5 day AMC (SCS, 1956) yields runoff for any value of the potential maximum retention (S) ranging from 0 to (less than) oo in contrast to that from only saturated portions of the watershed for which S=0, both the volumetric concept and the concept of Schaake et al. (1996) are in disagreement with the partial area concept (Hewlett and Hibbert 1967; Dunne and Black 1970). Mishra and Singh (2003a, c) further extended the physical description of CN using dynamical concept of infiltration and attributed its dependence on soil sorptivity and hydraulic conductivity besides others. The CN value for estimating watershed runoff potential for design purposes is often a policy decision. The available approaches utilize either extreme annual high events or average physical characteristics of watersheds. To derive CN for an ungauged watershed, SCS (1956) provided tables based on the soil type, land cover and practice, hydrologic condition, and AMC.

2.4.2 Hydrological Soil Group

The Soil Conservation Service identified four hydrological groups of soils A, B, C, and D, based on their infiltration and transmission rates. The former is measured by the infiltration capacity of the soil whereas the latter refers to the hydraulic conductivity of the soil. The characteristics of various soil groups classified above have been described by Mishra and Singh (2003). The soil type of a watershed significantly affects the runoff potential of the watershed. The runoff potential increases (and hence curve number increases) as the soil type changes from Group A to Group D. This classification is based on the fact that the soils that are similar in depth, organic matter content, structure, and the degree of swelling when saturated will respond in an essentially similar fashion during a storm of excessively high rainfall intensities.

2.4.3 Antecedent Moisture Condition

Surface runoff is directly related to the effective rainfall, and the effective rainfall is inversely related to the hydrologic abstractions including interception, surface detention, evaporation, evapotranspiration, and infiltration. Actual infiltration rates and amounts vary widely, for they are heavily dependent on the initial soil moisture or antecedent moisture condition. The Soil Conservation Service Curve Number (SCS-CN) method uses the concept of Antecedent Moisture Condition (AMC). AMC here refers to the water content of the soil, or alternatively, the degree of saturation of the soil before the start of the storm. The AMC value is intended to reflect the effect of infiltration on both the volume and rate of runoff, according to the infiltration curve. The Soil Conservation Service developed three antecedent moisture conditions and labelled them as AMC I, AMC II and AMC III where AMC III yields highest runoff while AMC I the lowest. The term antecedent is taken to vary from previous 5 to 30 days. However, there is no explicit guideline available to vary the soil moisture with the antecedent rainfall of certain duration. The National Engineering Handbook (SCS, 1971) uses the antecedent 5-day rainfall for AMC and it is generally used in practice.

Fairly accurate mathematical expressions (Ponce and Hawkins, 1996) are also available for CN conversion from AMC I (dry) to AMC III (wet) or AMC II (normal) levels. Hjelmfelt et al. (1982) statistically related the AMC I through AMC III levels, respectively, to 90, 10, and 50% cumulative probability of the exceedance of runoff depth for a given rainfall. For gauged watersheds, Hawkins (1993) suggested the CN-computation from event rainfall-runoff data considering the median CN to correspond to AMC II and the upper and lower bounds of the scatter rainfall-runoff plot to AMC III and AMC I, respectively. For hydrologic design purposes, Hawkins (1993) and Hawkins et al. (2001) derived CN from the ordered rainfall-runoff data, and McCuen (2002) developed confidence intervals for CNs (from 65 to 95) treating CN as a random variable. Mishra et al. (2004b) compared the existing SCS-CN and the modified Mishra and Singh (2003a, b, c)(MS) models using the data from 234 small to large watersheds and found the latter to perform significantly better than the former. Jain et al. (2006b) quantitatively evaluated the existing SCS-CN model, its variants, and the modified Mishra and Singh (2003a) models for their suitability to particular land use, soil type and combination thereof using a large set of rainfall- runoff data from small to large watersheds of the U.S.A.

2.4.4 Hydrologic Condition

The hydrologic condition refers to the state of the vegetation growth. For an agricultural watershed it is defined in terms of the percent area of grass cover. The larger the area of grass cover in a watershed, the lesser will be the runoff potential of the watershed and more will be infiltration. Such a situation describes the watershed to be in a good condition. The curve number will be the highest for poor, average for fair, and the lowest for good condition, leading to categorizing the hydrologic condition into three groups: good, fair, and poor, depending upon the areal extent of grasslands or native pasture or range.

2.4.5 Land Use

The land use characterizes the uppermost surface of the soil system and has a definite bearing on infiltration. It describes the watershed cover and includes every kind of vegetation, litter and mulch, and fallow as well as non agricultural uses, such as water surfaces, roads, roofs, etc. It affects infiltration. A forest soil, rich in organic matter, allows greater infiltration than a paved one in urban areas. On agriculture land or a land surface with loose soil whose particles are easily detached by the impact of rainfall, infiltration is affected by the process of rearrangement of these particles in the upper layers such that the pores are clogged leading to reduction in the infiltration rate. The land use and treatment classes can be broadly classified into urban land, cultivated land, and woods and forest.

The agriculture land uses are classified as fallow land, row crops, small grain crops, close-seeded legumes or rotation meadow, pasture or range and meadow. Fallow refers to bare agricultural land having the highest runoff potential. Planting the crops in rows on contours increases infiltration and hence decreases runoff. Woods are usually small isolated grooves of trees raised for farm use. Forests generally cover a considerable part of a watershed. Humus increases with age of forest. Because of porous nature, it increases infiltration and hence decreases runoff.

2.4.6 Land Cover

The type and quality of vegetative cover on the land is called land cover. The most cover types are vegetation, bare soil and impervious surface. There are a number of methods for determining cover types, the most common are field reconnaissance, aerial photograph and land use map. A dense cover of vegetation is a most powerful weapon for reducing erosion.

2.4.7 Land Treatment

Land treatment applies mainly to agricultural land uses and includes management practices, such as contouring and terracing and other management practices, such as grazing control or rotation of crops.

2.5 Advantages and Limitations

Following are the main advantages (Ponce and Hawkins, 1996; Mishra and Singh, 2003a) of the SCS-CN method:

(i) It is simple conceptual method for predicting direct surface runoff from a storm rainfall amount, and is well supported by empirical data and wide experience.
(ii) It is easy to apply and useful for ungauged watersheds.
(iii) The method relies on only one parameter-CN.
(iv) The parameter CN is a function of the watershed characteristics and hence, the method exhibits responsiveness to major runoff- producing watershed characteristics.

The main limitations of the method can be summarized as below:

(i) Following are the main advantages (Ponce and Hawkins, 1996; Mishra and Singh, 2003a) of the SCS-CN method:
(ii) It is simple conceptual method for predicting direct surface runoff from a storm rainfall amount, and is well supported by empirical data and wide experience.
(iii) It is easy to apply and useful for ungauged watersheds.
(iv) The method relies on only one parameter-CN.

(v) The parameter CN is a function of the watershed characteristics and hence, the method exhibits responsiveness to major runoff- producing watershed characteristics.

(vi) This method does not contain any expression for time and ignores the impact of rainfall intensity and its temporal distribution.

(vii) The method does not consider effect of watershed slope/relief on runoff.

(viii) There is no explicit provision for spatial scale effects.

(ix) This method performs poorly on forest sites (Hawkins, 1984, 1993; Mishra and Singh, 2003a)

(x) The method is applicable to only small watersheds. Ponce and Hawkins (1996) cautioned against its use to watersheds larger than 250 Sq. km.

2.6 Applications

The SCS-CN method has been widely used in the United States and across the world, and has more recently been integrated into several rainfall-runoff models. It computes volume of surface runoff for a given rainfall event from small agricultural, forest, and urban watersheds (SCS, 1986). The main reasons for its wide applicability and acceptability lie in the fact that it accounts for most runoff producing watershed characteristics: soil type, land use, surface condition and antecedent moisture condition (Ponce and Hawkins, 1996; Mishra and Singh, 2003a). Shrivastava and Bhatia (1992), Schroeder (1994), Silveira et al. (2000), Thomas and Jaiswal (2002) are but a few examples among many others who used the SCS-CN method for their field study and found a good correlation between measured and predicted values of runoff. However, Hussein (1996), Manivannam et al. (2001), and many others felt a need of modification in the methodology. The SCS-CN method has been recently integrated with remote sensing and geographical information system (Jacobs et al., 2003). Though the SCS-CN method was originally developed for computation of direct surface runoff from the storm rainfall, it has since been applied to other areas, such as long-term hydrologic simulation, prediction of infiltration and rainfall-excess rates, hydrograph simulation, sediment yield modeling, partitioning of heavy metals and determination of sub-surface flow. The method has also been successfully applied to distributed watershed modeling (White, 1988; Moglen, 2000; and Mishra and Singh, 2003a).

2.7 SCS-CN Inspired Methods

2.7.1 Mishra et al. Model

The Mishra et al. (1998) model assumes CN variation with time t dependent on AMC (Ponce and Hawkins, 1996) only. The computed rainfall-excess Q (equation 2.5) is transformed to direct runoff amount using a linear regression approach, analogous to the unit hydrograph scheme. Taking base flow as a fraction of cumulative infiltration along with the time lag, the total daily flow is computed as the sum of direct runoff and base flow. The model parameters are optimized utilizing the objective function of minimizing the errors between the computed and observed data.

The advantage of the Mishra et al. (1998) model is that it allows the transformation of rainfall-excess to direct runoff and takes into account the base flow, enabling its application to even large basins. The model, however, has the following limitations.

1. It does not distinguish between dynamic and static infiltration, similar to the Williams-Laseur and Hawkins models.
2. It allows sudden jumps in CN values when changing from one AMC to another AMC level.
3. The use of a linear regression equation invokes the problem of mass balance, for the sum of the regression coefficients is seldom equal to 1.0 in long-term hydrological simulation.
4. The base flow is taken as a fraction of cumulative infiltration, which is not rational. The water retained in the soil pores may not be available for base flow, rather the water that percolates down to meet the water table may appear at the outlet as base flow.

2.7.2 Mishra-Singh Model

Due to the major weakness of discrete relationship of existing AMC approach, Mishra and Singh (2002a) proposed a continuous variation of antecedent moisture (M) directly within the runoff equation itself. In the basic SCS-CN hypothesis (Equation 2.6), F represents the infiltrated amount of water (=V_W, volume of water), and S is equal to the maximum possible amount of infiltration equal to the maximum (P-Q) difference, which in turn, is equal to the maximum (P-Q) difference, or equal to the volume of void, Vv. Therefore, Mishra and Singh (2002a) represented F/S ratio as degree of saturation (Sr) of the soil, and finally arrived C=Sr from Equation (2.6), where C is the runoff coefficient (=Q/ (P- I_a)). Using this C=Sr concept, Mishra and Singh (2002a) modified Equation (2.6) for antecedent moisture M as:

$$\frac{Q}{P_a} = \frac{F+M}{S+M} \tag{2.11}$$

which is termed as 'Mishra-Singh proportionality concept'. A further substitution into Equation (3.1) leads to

$$Q = \frac{(P-I_a)(P-I_a+M)}{P-I_a+M+S} \tag{2.12}$$

when P >I_a,

$$M = \frac{S_1(P_5-\lambda S_1)}{P_5+(1-\lambda)S_1} \qquad \text{Q=0 otherwise} \tag{2.13}$$

Here, P_5=antecedent 5-day precipitation amount and S_1 is the potential maximum retention corresponding to AMC I. Equation (2.13) can be further simplified as:

$$\mathrm{M} = \gamma P_5 \tag{2.14}$$

Where γ = proportionality coefficient which can be determined using regression analysts.

2.7.3 Jain et al. Model

Jain et al. (2006) identified the existence of following issues in the conventional SCS-CN model: (1) Implementation of AMC procedure; (2) I_a-S relationship; and (3) Effect of storm intensity or duration in the runoff estimation. Based on these identified issues, Jain et al. (2006) suggested a new model formulation to enhance the SCS-CN model. This is expressed as follows:

$$Q = \frac{(P_c-I_{ad})(P_c-I_{ad}+M)}{P_c-I_{ad}+M+S} \tag{2.15}$$

where Pc $> I_{ad}$, otherwise Q = 0. A non-linear I_a- S relation has also been given as below:

$$I_{ad} = \lambda S\left(\frac{P_c}{P_c + S}\right)^{\alpha} \qquad (2.16)$$

M, the 5-day antecedent moisture is computed using the Equation (2.14), as in Mishra and Singh model; and P_c and S are calculated as follows:

$$P_c = P_0\left(\frac{t_p}{\bar{t}_p}\right)^{\beta} \qquad (2.17)$$

$$S = \frac{25400}{CN} - 254 \qquad (2.18)$$

In these equations, P_o = observed rainfall; P_c = adjusted rainfall; $\bar{t}_p$ = mean storm duration; t_p = storm duration; and P_5 = antecedent 5-day precipitation amount. The above equations represents an enhanced form of the runoff curve number model (Jain et al., 2006), which incorporates storm duration, a non-linear I_a-S relation and a simple continuous moisture content in runoff estimation. This model has five parameters.

2.7.4 Geetha et al. Model

Geetha et al. (2007) model has proposed two methods to modify the existing SCN-CN model. They tried by varying the CN using antecedent moisture condition (AMC) (designated as Model I), and by using antecedent moisture amount (AMA) (designated as Model II). These two different models are constructed to compute stream flow components: Direct surface runoff, base flow, and hydrological abstractions. Their methodology was successfully applied to daily data of catchment of Cauvery, Narmada, Ganga, and Ulhas Rivers, lying in different climatic regions of India.

The above two models are capable of simulating Stream flow and also help to understand and identify various processes involved in the runoff generation mechanisms with reasonable accuracy in wet catchments. Both models account for marked sensitivity of variability of curve number with respect to variations in moisture availability prior to the storm. Better and satisfactory performance of Model II is attributed to the CN variation that varies with antecedent moisture amount(AMA) than Model I in which CN is varied with antecedent moisture conditions(AMC). Model II advantageously obviates the sudden jumps in the curve number values with antecedent moisture conditions, as in Model I.

2.7.5 Kim and Lee Model

Kim and Lee (2008) proposed a method that uses the temporally weighted average curve number (TWA-CN) to estimate daily surface runoff, while considering the effect of rainfall during a given day as well as the antecedent soil moisture condition. They employed their model to the data of Mino River watershed located in the middle of South Korea. The essential idea of the TWA-CN method is that the introduction of weighted averaging concept, and hence given as follows:

$$CN_W = \propto CN_t + (1 - \propto) CN_{t+\Delta t} \tag{2.19}$$

where CN_W is the temporally weighted average CN value, and $\propto$ is temporal weight varying from 0 to 1, which represents the degree of effect of increase in soil moisture on the current rainy day. Here, 'temporal' means two points of time, namely, at the beginning of the day and at the end of the day.

In the above Equation $CN_{t+\Delta t}$ is a function of the retention parameter $S_{t+\Delta t}$ which is related to soil moisture content $SW_{t+\Delta t}$ at the end of the time interval. This is expressed as:

$$CN_{t+\Delta t} = f(S_{t+\Delta t}) \tag{2.20}$$

$$S_{t+\Delta t} = f(SW_{t+\Delta t}) = f(SW_t + F_{t,t+\Delta t}) \tag{2.21}$$

Unknown values $CN_{t+\Delta t}$ and $F_{t,t+\Delta t}$ are computed by an iterative procedure.

2.7.6 Sahu et al. Model

Sahu et al. (2010) model is the refinement of the earlier method proposed by Mishra and Singh (2002), i.e. a better expression of M (antecedent moisture in mm) coupled in the above model to produce improved version as follows:

$$Q = \frac{(P - I_a)(P - I_a + M)}{P - I_a + M}, \quad if\ P > I_a \tag{2.22}$$

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

$$I_a = \lambda(S_o - M) \tag{2.23}$$

M is determined by the following expression:

$$M = \beta\left[\frac{(P_5 - \lambda S_o)S_o}{P_5 + (1-\lambda)S_o}\right], \quad for\ P_5 > \lambda S_o \tag{2.24}$$

and

$$M = 0, \quad for\ P_5 \le \lambda S_o \tag{2.25}$$

The proposed SME model has the following advantages over the MS model:

(i) The proposed SME model uses more rational continuous expression for estimating antecedent moisture M. It restricts the validity of M being equal to zero for $P_5 \le \lambda S_o$, and therefore, M is never negative.

(ii) The SME model explicitly relates I_a with M while MS model and SCS-CN model do not.

(iii) The proposed SME model allows optimization of S_o, an intrinsic parameter, and thus, a constant quantity for a given watershed. S_o can be more rationally linked with watershed characteristics while the MS model allows optimizing S, a varying parameter for a given watershed.

Summary

It is evident from the above review that the curve numbers for the SCS-CN method have been largely derived from short-term rainfall-runoff events. Only a few studies attempted to use the daily series of available rainfall-runoff data for a watershed. This study therefore proposes a simple approach for CN derivation for three levels of AMC from long-term daily rainfall-runoff data of three hydro-meteorologically different watersheds. It is of common experience that the curve number decreases as the rain duration increases, and vice versa. In this study, the impact of rain duration on curve numbers is investigated in a rational manner, and a CN-rainfall duration relationship developed. There is however no rational approach suggested for derivation of curve numbers for design purpose associated with return periods. This study investigates it and proposes a suitable method for design CN development.

METHODOLOGY

In order to achieve more accurate prediction of runoff from rainfall data, deriving improved rainfall-runoff model(s) has always been one of the important objectives for most of the hydrologists. The main objective here is to develop a relationship between curve number and rain duration and finally propose a procedure for derivation of the design curve number for a watershed.

3.1 Existing SCS-CN Equation

The existing SCS-CN equation can be derived from water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of actual amount of direct surface runoff Q to the total rainfall P to the ratio of actual infiltration (F) to the amount of the potential maximum retention S. The second hypothesis relates the initial abstraction (I_a) to the potential maximum retention (S), also described as the potential post initial abstraction retention (McCuen, 2002). Expressed mathematically,

(a) Water balance equation

$$P = I_a + F + Q \tag{3.1}$$

(b) Proportional equality (First hypothesis)

$$\frac{Q}{P-I_a} = \frac{F}{S} \tag{3.2}$$

(c) I_a-S relationship (Second hypothesis)

$$I_a = \lambda S \tag{3.3}$$

The values of P, Q, and S are given in depth dimensions, while the initial abstraction coefficient λ is dimensionless. Though the original method was developed in U.S. customary units (in.), an appropriate conversion to SI units (cm) is possible (Ponce, 1989). In a typical case, a certain amount of rainfall is initially abstracted as interception, infiltration, and surface storage before runoff begins, and a sum of these is termed as 'initial abstraction'. The first (or fundamental) hypothesis, Eq. (3.2), is primarily a proportionality concept (Mishra and Singh, 2003a). Figure 3.1graphically represents this proportionality concept. Apparently, as Q = ($P-I_a$), F=S. This proportionality enables dividing (P-I_a) into two components: surface water Q and subsurface water F for given watershed characteristics.

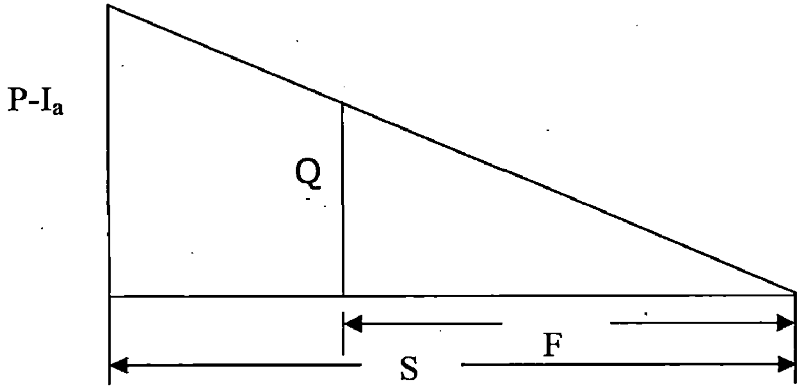


Figure 3.1: Proportionality concept of the existing SCS-CN method.

The parameter S of the SCS-CN method depends on soil type, land use, hydrologic condition, and antecedent moisture condition (AMC). The initial abstraction coefficient λ is frequently viewed as a regional parameter depending on geologic and climatic factors (McCuen, 1982, 1989; Boszany, 1989; Mishra and Singh, 2003a). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries (SCD, 1972; Springer et al., 1980; Cazier and Hawkins, 1984; Ramasastri and Seth, 1985; Bosznay, 1989) report λ to vary in the range of (0, 0.3). However, as the initial abstraction component accounts for the short-term losses such as interception, surface storage, and infiltration before runoff begins λ can take any value ranging from 0 to ∞ (Mishra and Singh, 1999a, b). A study of Hawkins et al. (2001) suggested that value of $\lambda = 0.05$ gives a better fit to data and would be more appropriate for use in runoff calculations.

The second hypothesis, Eq. (3.3) is a linear relationship between initial abstraction I_a and potential maximum retention S. By combining Eq. (3) and (4), the expression for Q can be given as:

$$Q = \frac{(P-I_a)^2}{P-I_a+S} = \frac{(P-\lambda S)^2}{P-\lambda S+S} \tag{3.4}$$

Eq. (3.4) is the general form of the popular SCS-CN method and is valid for $P \geq I_a$; Q= 0 otherwise. For $\lambda = 0.2$, the coupling of Eq. (3.3) and (3.4) results

$$Q=\frac{(P-0.2S)^2}{P+0.8S} \qquad (3.5)$$

Eq. (3.5) is the popular form of existing SCS-CN method. Thus, the existing SCS-CN method with λ = 0.2 is a one-parameter model for computing surface runoff from a storm rainfall event.

3.2 Estimation of Design Curve Number

In the existing SCS-CN methodology with λ = 0.2, curve number (CN) forms to be the most important and only parameter that requires to be determined for runoff estimation. The available text-book methodology however describes the derivation of CN-values from physical characteristics of the watershed, such as soil type, land use, hydrologic condition, and antecedent moisture condition. Thus, for a watershed, CN can be derived for three AMC conditions, viz., AMC I, AMC II, and AMC III. The method is found to work satisfactorily under normal circumstances. The need of a CN-value that is applicable to design storms has been experienced since long. The curve number (CN) method for estimating direct runoff response from rainstorms was developed to fill a technological niche in the 1950s. Since then, use of the CN method has been extended to other applications, and user experience and analysis have redefined numerous features of the original technology. In "Curve Number Hydrology: State of the Practice", an ASCE/EWRI Task Committee investigates the origin, development, role, application, and current status of the CN method. One of the Committee's recommendations is assigning a keeper to serve as the central source for responsible information and updates. Additional suggestions cover the hydrologic soil groups, the initial abstraction ratio, CN roles in continuous modeling systems, local calibrations, the limits of applicability, the need for an alternative method on forested watersheds, and the potential for application to land management decision making. This is valuable to water and environmental engineers involved in hydrology, especially the analysis of rainwater runoff problems. A suitable procedure has however yet to be evolved. In this dissertation work, a procedure has been proposed and it is employed to the data of three watersheds.

3.3 Procedure in Steps

The procedure followed in this dissertation work is described in steps as follows:

1. Derivation of CN-Values for Various AMCs
    a. Prepare a series of available daily rainfall (P) and runoff (Q) data in same units (for example, mm/day) for the period the data are available.
    b. Filter the rainfall and runoff data by removing the pairs of P-Q data showing the runoff factor ($C = Q/P$) > 1.
    c. Sort the P-Q data in the descending order of P and assign the probability to P using Weibull's plotting position formula and plot this data.
    d. Assume a suitable value of CN (or S) and compute Q-values for all P-values using Eq. 3.5.
    e. Try to fit the upper bound of the whole data on the chart by the line representing the Q-values computed from P at step 1(d) for different CN-values assumed. Adopt a CN-value that closely fits the upper bound of the whole P-Q data set.
    f. Similar to steps 1(d & e), derive a Q-line for a suitable CN-value representing the mid of whole data.
    g. Similar to step 1(f), derive a Q-line for a suitable CN-value representing the lower bound of whole data.
    h. The CN-values corresponding to those at steps 1(e, f, and g) may be taken to correspond to AMC III, AMC II, and AMC I, respectively. Note, since these values are derived from daily P-Q data, the derived CN-values correspond to 1-d rain duration.

2. Derivation of CN-Values for Various AMCs and Different Durations
    a. From the above daily P-Q data, derive two-daily, three-daily, four-daily and so on P-Q series derived by summing the rainfall and corresponding runoff values for respective durations. Note, both P & Q are in depth units.
    b. Repeat steps 1(b) through 1(h) for deriving CN values for different AMCs and all P-Q series developed for all durations separately.

3. Derivation of CN-Rain Duration Relationship
    a. For a particular AMC, plot CN values (ordinate) against rain duration (abscissa).

   b. Fit a relationship using a suitable least squares approach for the above particular AMC.
   c. Repeat steps 3 (a) and 3(b) for other AMCs.

4. Estimation of Design CN
   a. The above steps 1-3 are based on consideration of whole P-Q data for all the years. However, for determination of design CN, daily, 2-daily, and 3-daily P-Q data series are developed for each year, similar to that described at Step 2.
   b. For each yearly P-Q series, CN values are derived for three AMCs. Thus, for a given AMC and duration, there is one CN-value available for each AMC for a year. It leads to the development of an annual CN-series for each of three AMCs and each of the considered durations. Each of the CN-series can be assumed to be a random series as there exists no correlation between the two consecutive annual CN-values.
   c. For a given AMC and duration, fit a suitable frequency distribution in the annual CN-series and derive CN-values corresponding to different return periods.
   d. Repeat steps 4(a) to 4(c) for determination of quantum CN-values for other AMCs and rain durations.
   e. Plot the available CN-values for different return periods, different AMCs, and different durations for their field use.

5. Validation of Design CN Estimates
   a. For a duration, develop an annual P-series to determine P-values corresponding to different return periods using a suitable distribution.
   b. From the same distribution and return period values of P and CN compute the runoff which corresponds to the used duration and return period. Assume these are computed Q-values.
   c. Similar to step 5(a), develop a Q-series for a duration and estimate Q-values corresponding to different return periods. Treat these values as observed for comparing with those at step 5(b). Here match has to be evaluated w.r.t. AMC.
   d. Following steps 5(a) to 5(c), compare the estimated Q-values for different durations and AMCs with the observed ones, but for the same duration.

STUDY AREA AND DATA AVAILABILITY

This chapter describes the study area and data availability. The study areas chosen for the present work are Ramganga and Maithon catchments of India and a sub-watershed of Rapti catchment located in Nepal, and thus, representing significantly different geo-climatic settings for application and testing of the proposed methodology. A brief of these catchments is given as follows.

4.1 Maithon Catchment

The Barakar River is the main tributary of Damodar River in eastern India. Originating near Padma in Hazaribagh district of Jharkhand it flows for 225 km across the northern part of the Chota Nagpur plateau, mostly in a west to east direction, before joining the Damodar near Dishergarh in Bardhaman district of West Bengal. The study area falls within latitude 23°44'N to 24°0'N and longitude 86°44'E to 86°52'E. It has a catchment area of 6294 km^2 and has an average altitude of approximately 110.0 m. The main tributaries, Barsoti and Usri, flow from the south and north respectively. Apart from the two main tributaries some fifteen medium/small streams also join it. Six sub-types of soils have been identified under the main alluvium, either the Ganga alluvium or the Damodar alluvium in the delta area. Open Sal forests (Shorearobusta) thrive mainly on laterite and dense Sal forest on red and yellow loams in the upper valley. The climate of the area is characterized by moderate winters and hot & humid summers. Like the rest of India, the region experiences two principal rainy seasons. In the winters from December to March there is little rain. In the summer months, June to September, the flow of air is from sea to land and the season is characterized by high humidity, clouds and rain. The direction of winds being south-westerly, the season is named South-West Monsoon which is the main season producing rains. Between these two principal seasons are the transition seasons of the hot weather months of April & May and the retreating monsoon months of October & November. The annual rainfall over the valley ranges between 1,000 mm and 1,800 mm. Distribution of rainfall varies widely owing to differences of terrain and atmospheric conditions in the different parts of the valley. Within the command area, the upper and the middle parts of the Damodar basin receive 1,209 mm rainfall annually and the lower valley 1,329 mm above the main plateau escarpment rainfall increases to over 1,500 mm a year. Mean annual rainfall in the basin is of the order of 1,300 mm and about 80% of rain precipitates during the summer monsoon (June to September). The highest maximum temperature exceeding 46 °C was recorded over a larger part of the valley. Normal temperature swings between 40 to 42 degrees Celsius in the summers (May & June) to 23 to 26 degrees Celsius in the cold months (December & January).Mean relative humidity varies from 80% during July to September to 40% in March., April & May. Fig. 4.1 shows the index map of Maithon catchment.

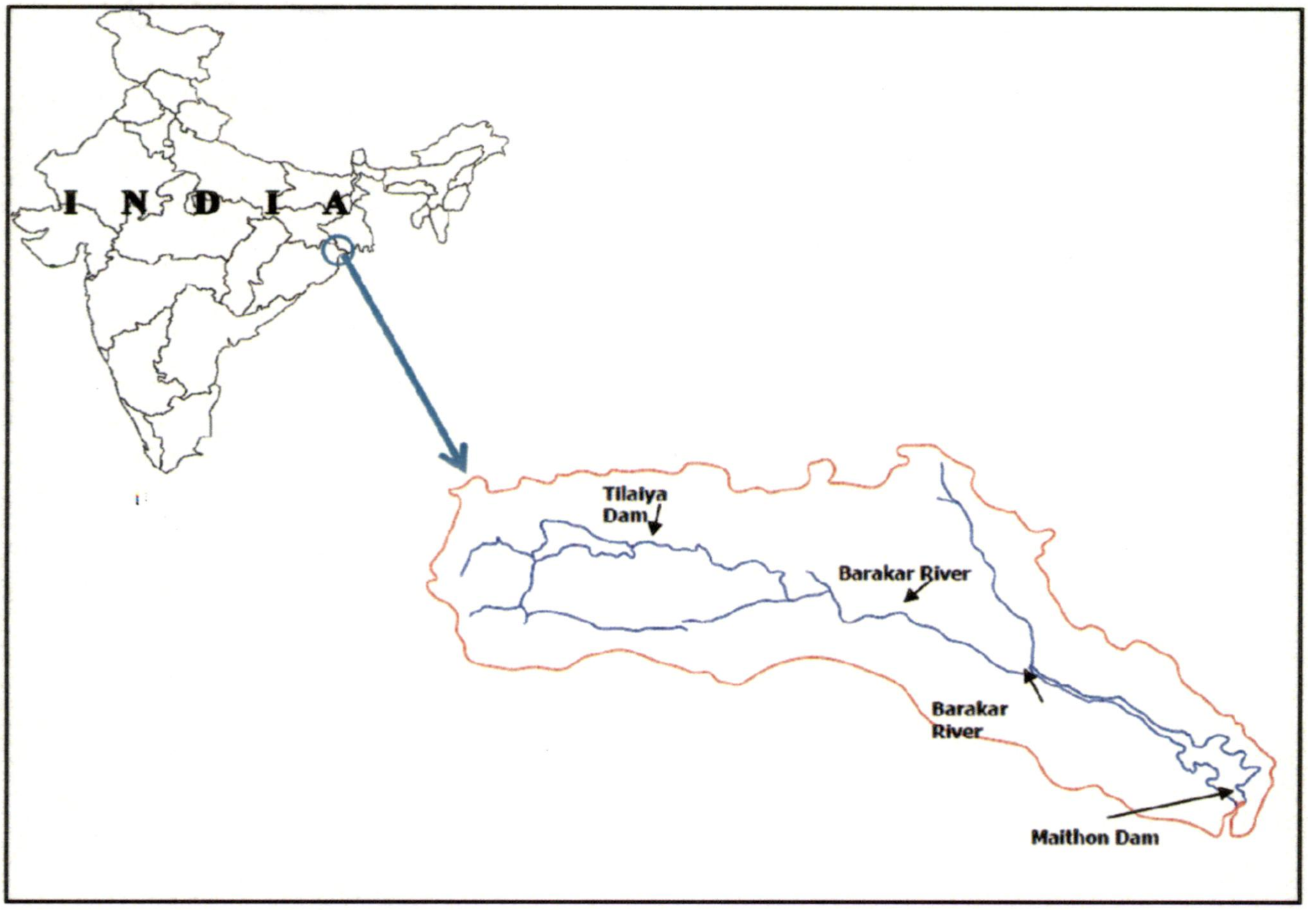


Figure 4.1: Index map of Maithon Catchment (India).

4.2 Ramganga Catchment

The Ramganga river is a major tributary of Ganga and drains a catchment area of 3,134 sq. km. Its catchment lies in the Shivalik ranges of Himalayas and the valley is known as Patlei Dun. River Ramganga originating at Diwali Khel. It emerges out of the hills at Kalagarh (District Almora) where a major multipurpose Ramganga dam is situated. Its catchments lies between elevation 262 and 2,926 m above mean sea level, and it is considerably below the perpetual snow line of the Himalayas. The river traverses approximately 158 km before it meets the reservoir and then continues its journey in the downstream plains for 370 km before joining River Ganga at Farrukhabad. Fig. 4.2 shows the index map of Ramganga catchment.

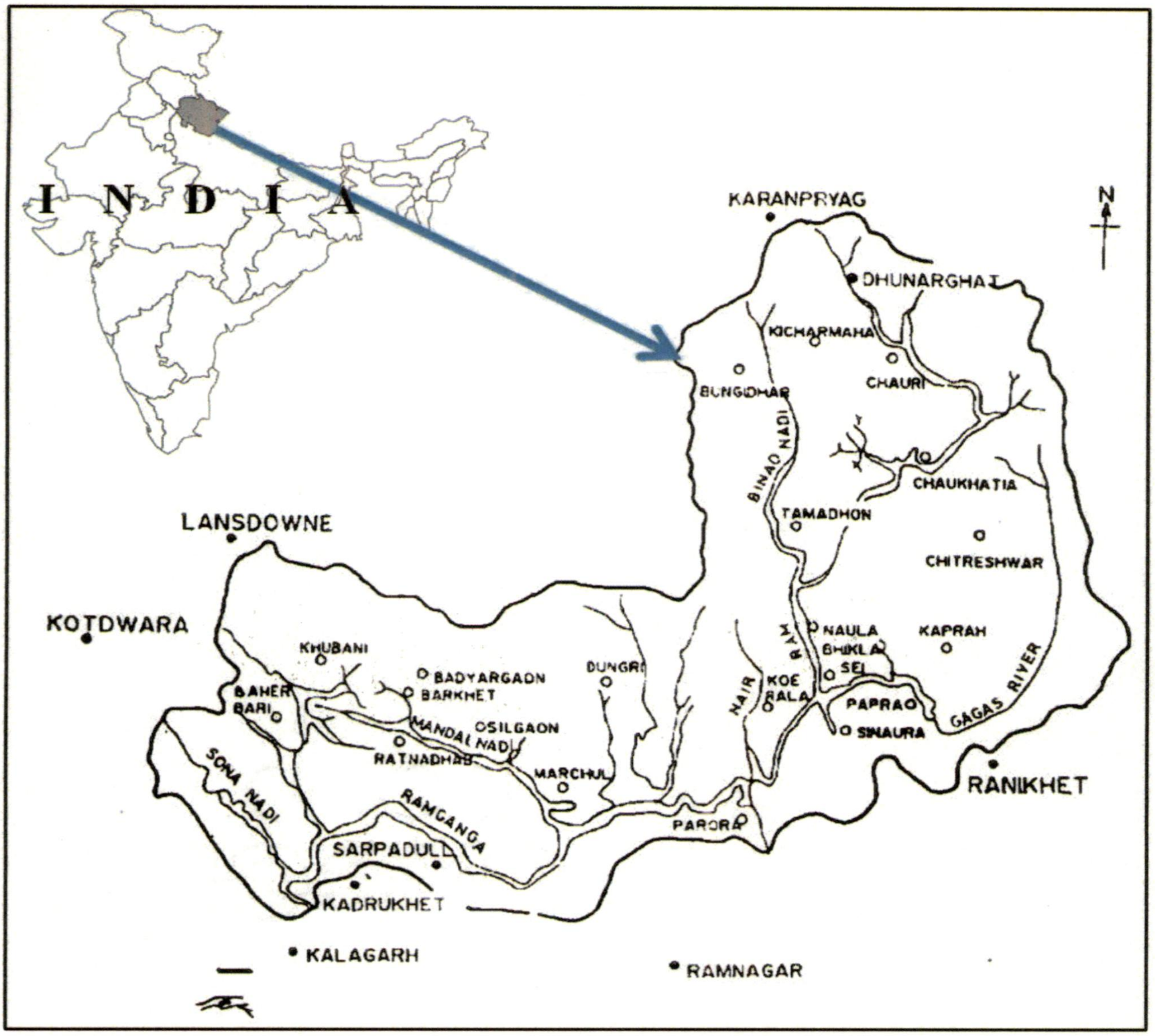


Figure 4.2: Index map of Ramganga Catchment(India).

During its travel up to Ramganga dam, the river is joined by main tributaries: Ganges, Binoo, Khatraun, Nair, Badangad, Mandal, Helgad, and SonaNadi. About 50% of the drainage basin is covered with forest, 30% is under cultivation on terraced fields, and the remaining 20% is urban/barren land. Specific features of the area are as follows:

- Located in the foothills of Himalayas in the Uttarakhand.

ga originates at Diwali Khel.

ary of River Ganga.

of the hills at Kalagarh (District Almora)

major multi-purpose Ramganga dam.

s approx. 158 km before it joins the reservoir and finally joins Ganga d, 370 km d/s.

es: Ganges, Binoo, Khatraun, Nair, Badangad, Mandal, Helgad, and Sona Nadi.

- Its catchment area = 3134 sq. km.
- Elevation difference: 262 to 2926 m above msl
- Snow contribution: Almost nil.
- Land use: About 50% forest, 30% cultivated on terraced fields, and 20% is urban/barren land.
- Annual rainfall = 1550 mm.
- Rain gauges: Ranikhet, Chaukhatia, Naula, Marchulla, Lansdowne and Kalagarh.
- Stream flow measurement: records of river stages, instantaneous as well as monthly, are available at Kalagarh since 1958.

At the outlet of the Upper Ramganga catchment, i.e. Kalagarh, there exists a multi-purpose Ramganga dam.

4.3 Rapti Catchment

Nepal is a land-locked Himalayan Kingdom located between People's Republic of China and India. Its elevation varies from 60m (msl) at the lowest point to 8848m (msl) (Mt. Everest). The country is divided into three more or less parallel ecological regions namely the Mountains, the Hills and the Terai. The study area, i.e., the Rapti sub-watershed geographically lies between 27°51' N & 82°26' E and 28°32' N & 82°64' E. Its area is 3380 km^2.The climate prevailing in this catchment area is characterized by the monsoon regime with rainfall occurring mainly between July and September (85% of annual rainfall). Winds are strong and maximum temperature averages above 32 °C during the remaining months leading to intense average

Evapotranspiration 5.6 mm/day. Analysis of the last 30 years of climatic records, established the annual average rainfall at 1401mm. Winds are usually mild. The average minimum temperature for the coldest month is 5.2 °C during December-January. Average maximum during that month reaches 21.8 °C. Air moisture is high during the monsoon months (July to September) with an average of 85 %. It drops sharply during April and May to reach 60%. Extreme monthly averages, as low as 27%, have been recorded. The major landscape of the catchment area comprise of the foothills of the Churia Muria (Siwalik) ranges and the main Terai plain in the Mid Western Region. Its elevation ranges from 300m (msl) to 1250m (msl). Most of this area is covered by forest and it can be categorized as a Terai Mixed Hardwood forest type. Fig. 4.3 shows the index map of Rapti catchment.

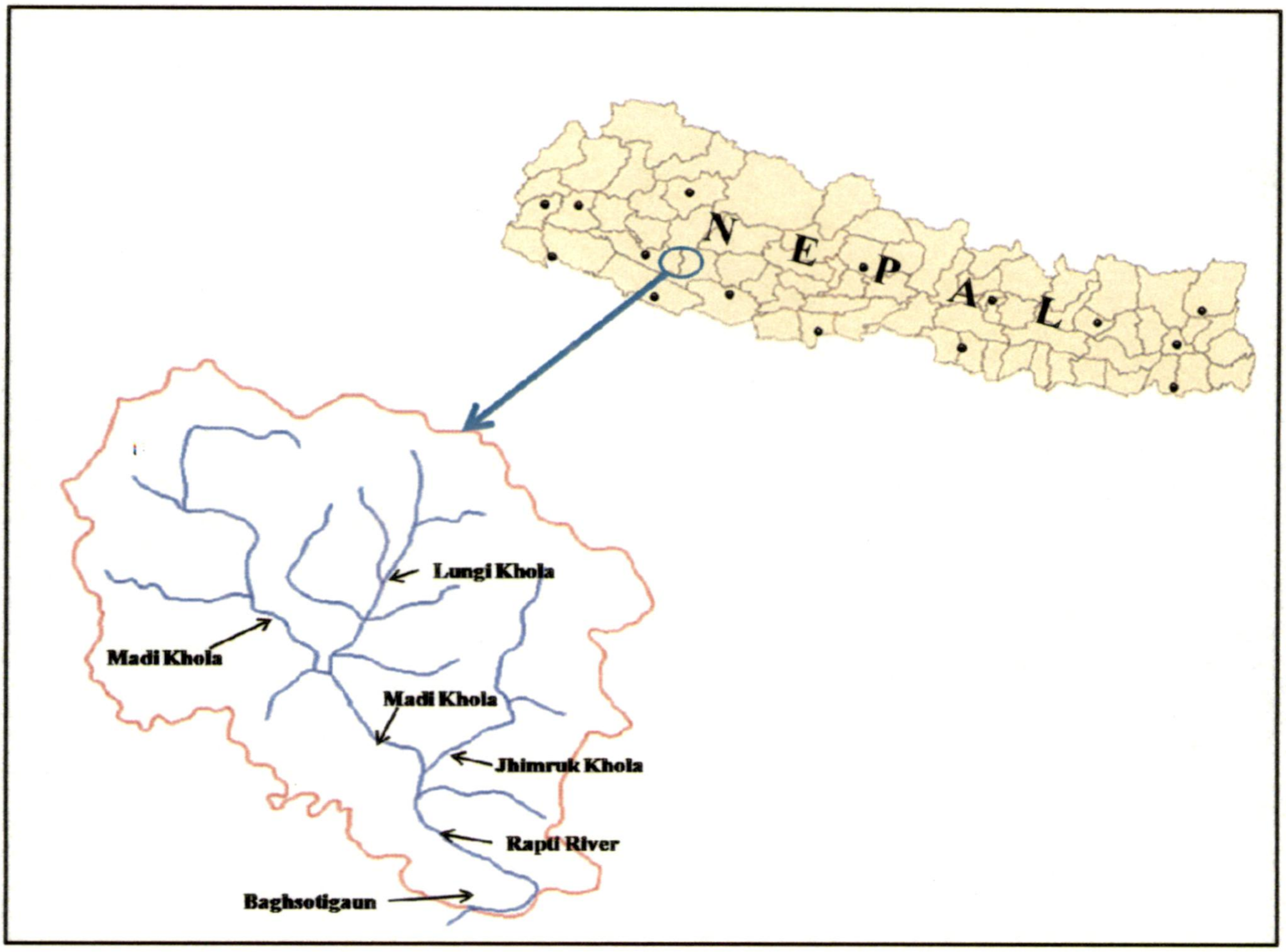


Figure 4.3: Index map of Rapti Catchment (Nepal).

4.4 Data Acquisition

The details of collection of daily rainfall and runoff data used in this study are summarized as below.

4.4.1 Maithon Catchment Data

Rainfall Data

Available rainfall data in mm at different raingauge stations along with their Theissen Weight are summarized in Table 4.1.

Table 4.1 Rainfall data availability at different raingauge stations of Maithon Catchment

	Raingauge Stations			
	Maithon Dam Site	Nandadih	Barkisurya	Tilaiya
Data availability	01.01.2000- 02.03.2010	01.01.2000- 02.03.2010	01.01.2000- 02.03.2010	01.01.2000- 02.03.2010
Theissen Weight	0.0563	0.3662	0.2817	0.2958

Runoff Data

Runoff data at Maithon were available from 01.01.2000 to 02.03.2010 in ha-m units and these are used in the present study.

4.4.2 Ramganga Catchment Data

Rainfall Data

Available rainfall data in mm at different raingauge stations along with their Theissen Weight are summarized in Table 4.2.

Table 4.2 Rainfall data availability at different raingauge stations of Ramganga Catchment

	Rain gauge Stations					
	Chaukhutia	Marchula	Naula	Kalagarh	Ranikhet	Lansdown
Data availability	01.06.78- 31.12.09	01.06.78- 31.12.09	01.06.78- 31.12.09	01.06.78- 31.12.09	01.06.78- 31.12.09	01.06.78- 31.12.09
Theissen Weight	0.298	0.251	0.19	0.081	0.088	0.092

Runoff Data

Runoff data in MM^3 at Kalagarh were available from 01.06.78-31.12.09 and these are used in the present study.

4.4.3 Rapti Catchment Data

Rainfall Data

Available rainfall data in mm at different raingauge stations along with their Theissen Weight are summarized in Table 4.3.

Table 4.3 Rainfall data availability at different raingauge stations of Rapti Catchment

	Rain gauge Stations		
	SheraGaun	LibangGaun	Bijuwar Tar
Data availability	01.01.1977-31.12.2008	01.01.1977-31.12.2008	01.01.1977-31.12.2008
Theissen Weight	0.0933	0.4901	0.4165

Runoff Data (m^3/s)

Runoff data in m^3/s at Baghsutigaun (27°51'12"N; 82°47'34"E) were available from 01.01.1977 to 31.12.2008and these are used in the present study.

To show the adequacy of rainfall data stations, it is in order to present here the World Meteorological Organisation (WMO) recommendations for densities of raingauge stations depending on several feasibilities:

1. In flat regions of temperate, Mediterranean and tropical zones:

Ideal	one station for 600-900 km^2,
Acceptable	one station for 900-3000 km^2;

2. In mountainous regions of temperate, Mediterranean and tropical zones:

Ideal	one station for 100-250 km^2,
Acceptable	one station for 250-1500 km2;

3. In arid and polar zones: one station for 1500-10000 km2.

The above indicates the density of rainfall stations in the above catchments was sufficient to describe the data.

4.5 Data Processing

The available data were processed for different catchments as follows:

a. The daily data (i.e. the rainfall and runoff) available from various sources were computerized. These were checked for missing data, if any, and wherever found to be missing; it was replaced by the average value for that day of a particular month.

b. Date-wise weighted average rainfall (mm) values were computed for each catchment.

c. The daily runoff data available in either MM^3, ha-m or in m^3/s units were converted to mm unit.

CHAPTER 5

RESULTS AND DISCUSSION

The proposed methodology (Chapter 3) was employed to the data of Maithon (India), Ramganga (India) and Rapti (Nepal) catchments and the results are discussed in sequence of steps suggested in Chapter 3.

5.1 Data Processing

The daily rainfall (P)-runoff (Q) data series for 10 years of Maithon, 32 years of Ramganga and Rapti were first arranged in chronological order, separately for each watershed. Each of these series was then processed for exclusion of those pairs exhibiting daily runoff coefficient (i.e. Q/P) to be greater than 1.0. Here, it is noted that the dimensions of both P and Q were kept as mm.

5.2 Determination of CN

The processed data series was sorted in the descending order of P, and probability assigned to P using Weibull's plotting position formula. Then assuming a suitable value of CN (or S), Q-values were computed for all P-values using Eq. 3.5 and these were plotted in Figs. 5.1a, 5.1b & 5.1c, respectively. Trial values of CN were so selected that the Q-line represented the upper bound, lower bound, and mid of the whole data. The upper bound CN-value was taken such as to correspond to AMC III, the lower bound to AMC I, and the mid to normal AMC II. Since these CN-values were derived from daily P-Q data series, these were taken to correspond to 1 day. Figs. 5.1a, 5.1b & 5.1c, respectively, show the fits for AMC-I through AMC III for 1-day duration for Maithon, Ramganga, and Rapti watersheds. Similarly, CN-values for 2 days, 3 days, 4 days etc. were derived from 2 daily, 3 daily, 4 daily etc. P-Q series, respectively.

5.3 Development of CN-Duration-AMC Relationship

Following the above, CN values were derived for different AMCs and durations as shown in Tables 5.1a, 5.1b & 5.1c and plotted in Figs. 5.2a, 5.2b & 5.2c, respectively for Maithon, Ramganga, and Rapti watersheds. As shown in these figures and tables, CN decays almost exponentially as duration increases. The derived pattern is consistent with the notion that as rain duration increases, CN decreases because of larger opportunity time available for water loss in the watershed; and vice versa. Since whole data, which forms to be quite a large data set, is used in this study, these curve number values are representative of the respective watershed characteristic. The derived best fit relations for various AMCs are shown in Tables 5.2 for Maithon, Ramganga, and Rapti, respectively. In these tables, y on the ordinate is the curve number (CN) (non-dimensional), x is the rainfall duration (day) on abscissa, and R^2 is the coefficient of determination. High values of R^2 indicate a reasonable and satisfactory fit.

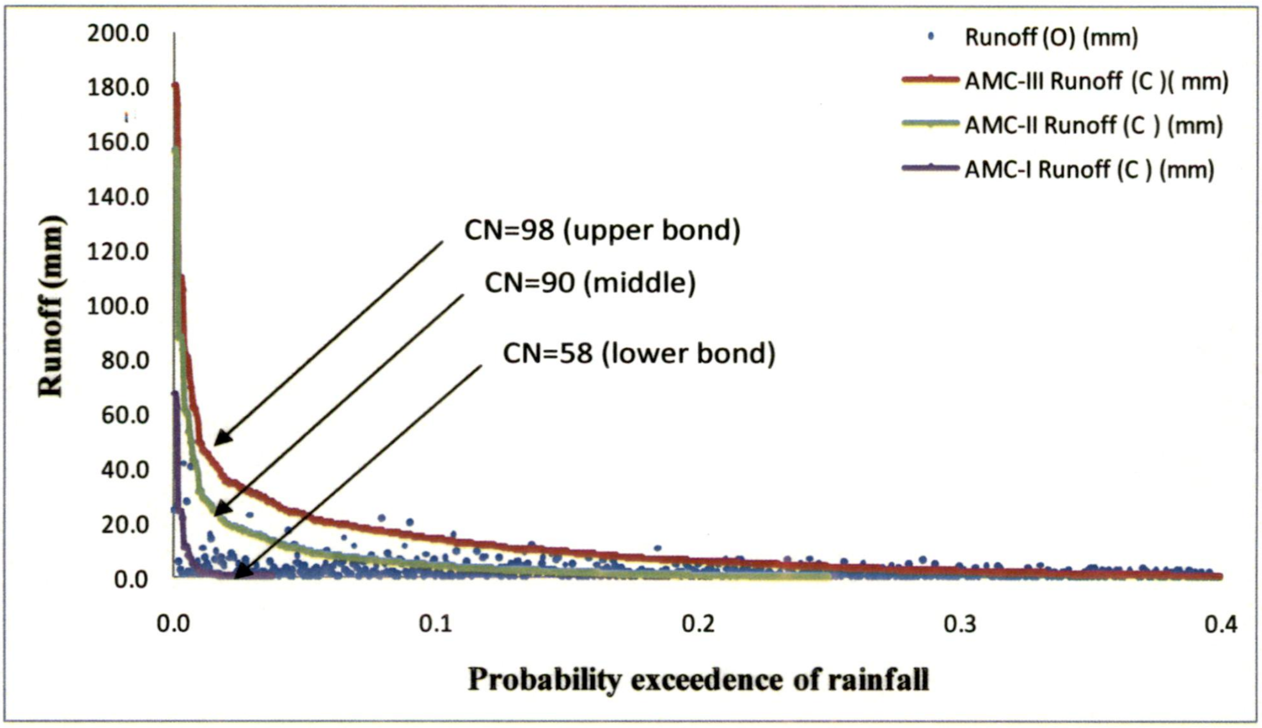


Fig. 5.1a: Ordered daily runoff data of Maithon watershed for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively, and the middle one to AMC-II (Complete data of 10 years used).

Table 5.1 a: CN values for different AMCs and duration for Maithon watershed (India)

Duration Day(s)	CN			Potential Maximum Retention S (mm)		
	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
1	98	90	58	5.18	28.22	183.93
2	96	88	56	10.58	34.64	199.57
3	94	83	54	16.21	52.02	216.37
4	92	79	51	22.09	67.52	244.04
5	90	76	49	28.22	80.21	264.37
6	88	73	47	34.64	93.95	286.43
7	86	70	45	41.35	108.86	310.44
8	84	67	43	48.38	125.10	336.70
9	82	65	41	55.76	136.77	365.51
10	80	63	39	63.50	149.17	397.28
15	78	61	37	71.64	162.39	432.49
20	76	57	35	80.21	191.61	471.71
25	74	54	32	89.24	216.37	539.75
30	72	52	30	98.78	234.46	592.67

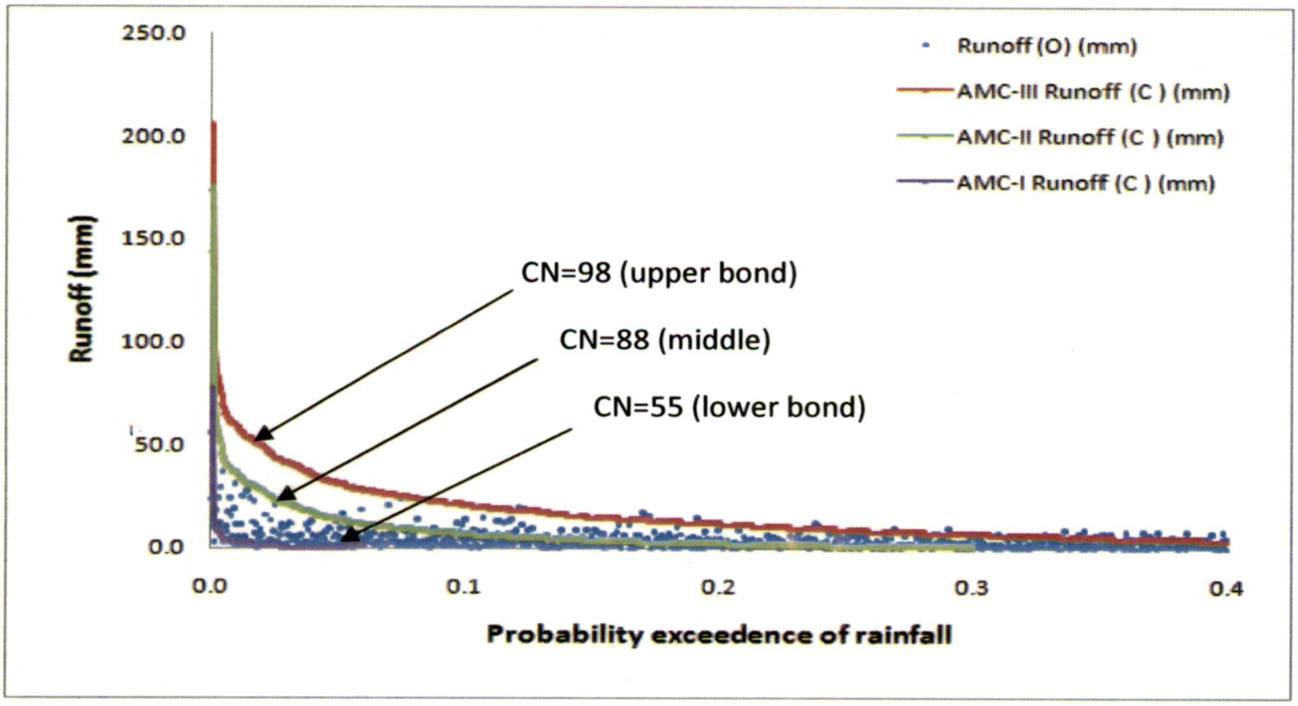


Figure 5.1b: Ordered daily runoff data of Ramganga watershed for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively, and the middle one to AMC-II (Complete data of 32 years used).

Table 5.1b: CN values for different AMCs and duration for Ramganga watershed (India)

Duration Day(s)	**CN**			**Potential Maximum Retention S (mm)**		
	AMC-III	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**
1	98	88	55	5.18	34.64	207.82
2	96	84	52	10.58	48.38	234.46
3	94	80	50	16.21	63.50	254.00
4	94	78	48	16.21	71.64	275.17
5	93	76	46	19.12	80.21	298.17
6	92	72	40	22.09	98.78	381.00
7	90	70	40	28.22	108.86	381.00
8	89	68	38	31.39	119.53	414.42
9	86	65	36	41.35	136.77	451.56
10	84	62	34	48.38	155.68	493.06
15	77	54	32	75.87	216.37	539.75
20	68	47	28	119.53	286.43	653.14
25	62	42	25	155.68	350.76	762.00
30	58	38	24	183.93	414.42	804.33

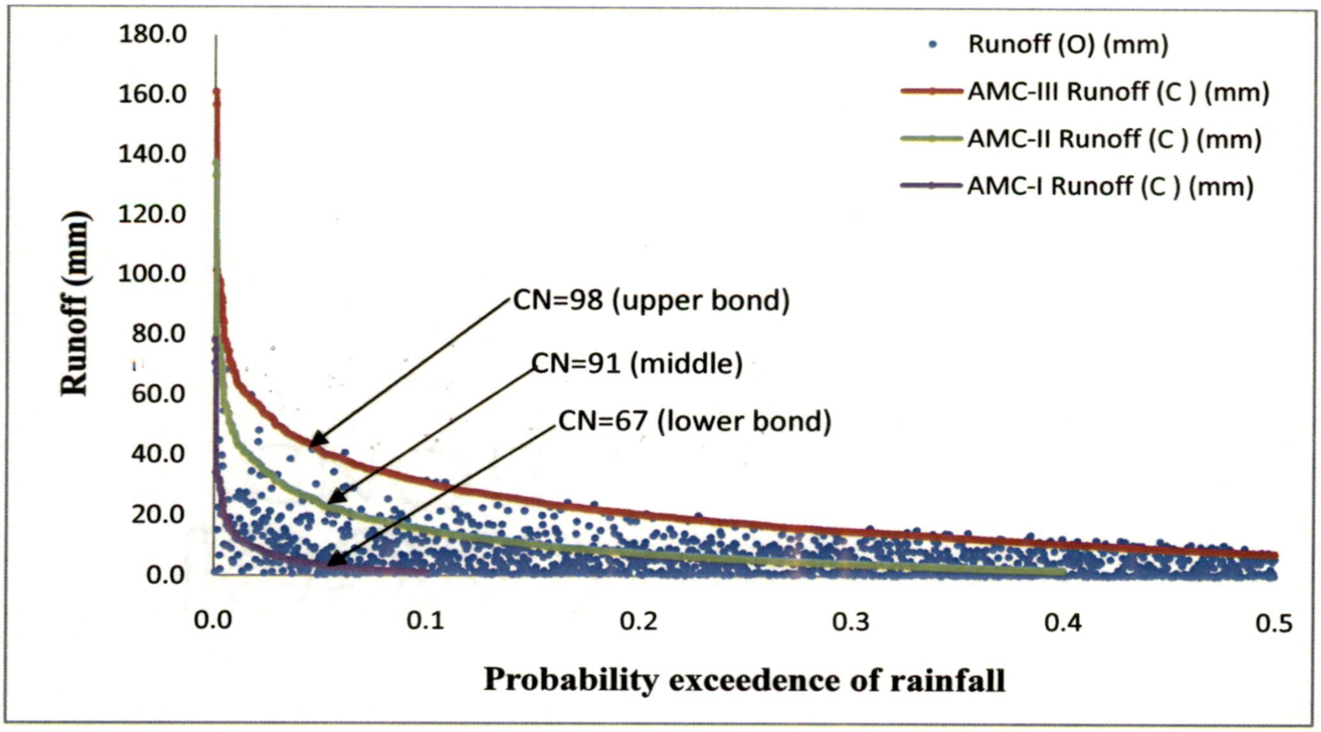
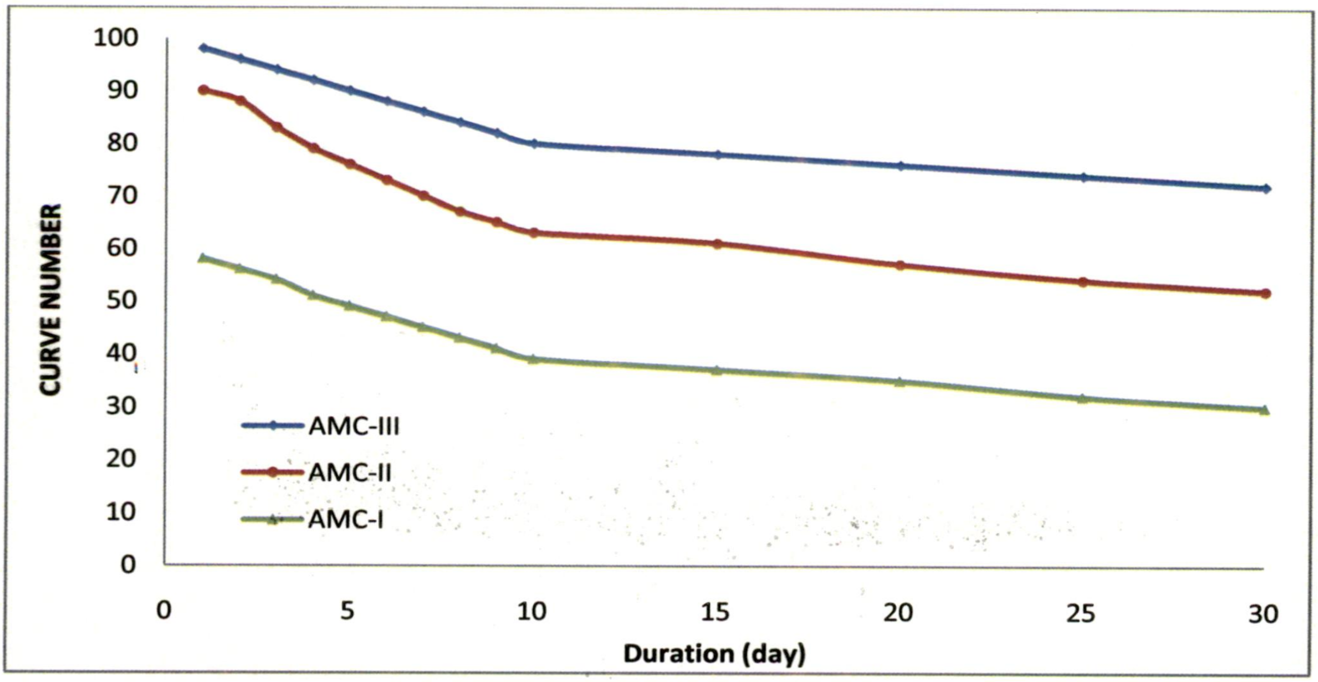


Figure 5.1c: Ordered daily runoff data of Rapti watershed for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively, and the middle one to AMC-II (Complete data of 32 years used).

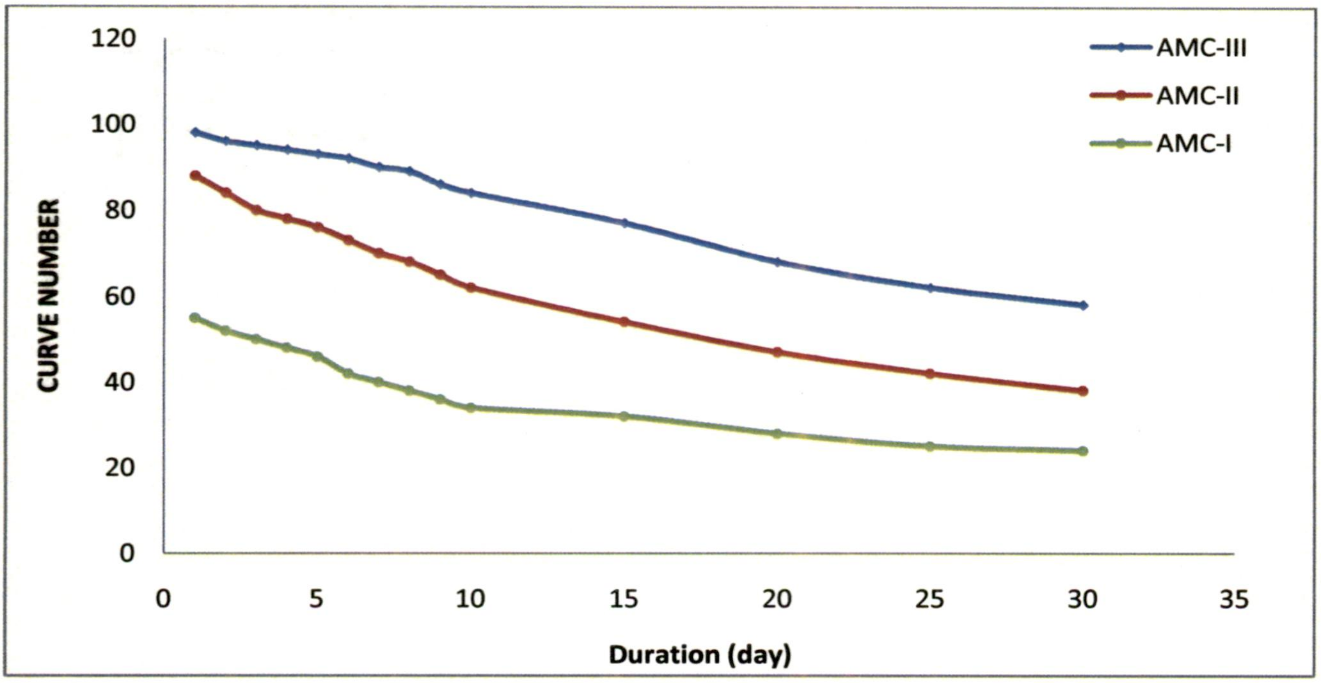
Table 5.1c: CN values for different AMCs and duration for Rapti watersheds (Nepal)

Duration Day(s)	CN			Potential Maximum Retention S (mm)		
	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
1	98	91	67	5.18	25.12	125.10
2	98	88	59	5.18	34.64	176.51
3	98	86	56	5.18	41.35	199.57
4	97	84	54	7.86	48.38	216.37
5	96	82	52	10.58	55.76	234.46
6	94	80	50	16.21	63.50	254.00
7	93	78	48	19.12	71.64	275.17
8	92	76	46	22.09	80.21	298.17
9	91	74	44	25.12	89.24	323.27
10	89	72	42	31.39	98.78	350.76
15	87	69	40	37.95	114.12	381.00
20	85	66	38	44.82	130.85	414.42
25	83	62	35	52.02	155.68	471.71
30	81	57	32	59.58	191.61	539.75



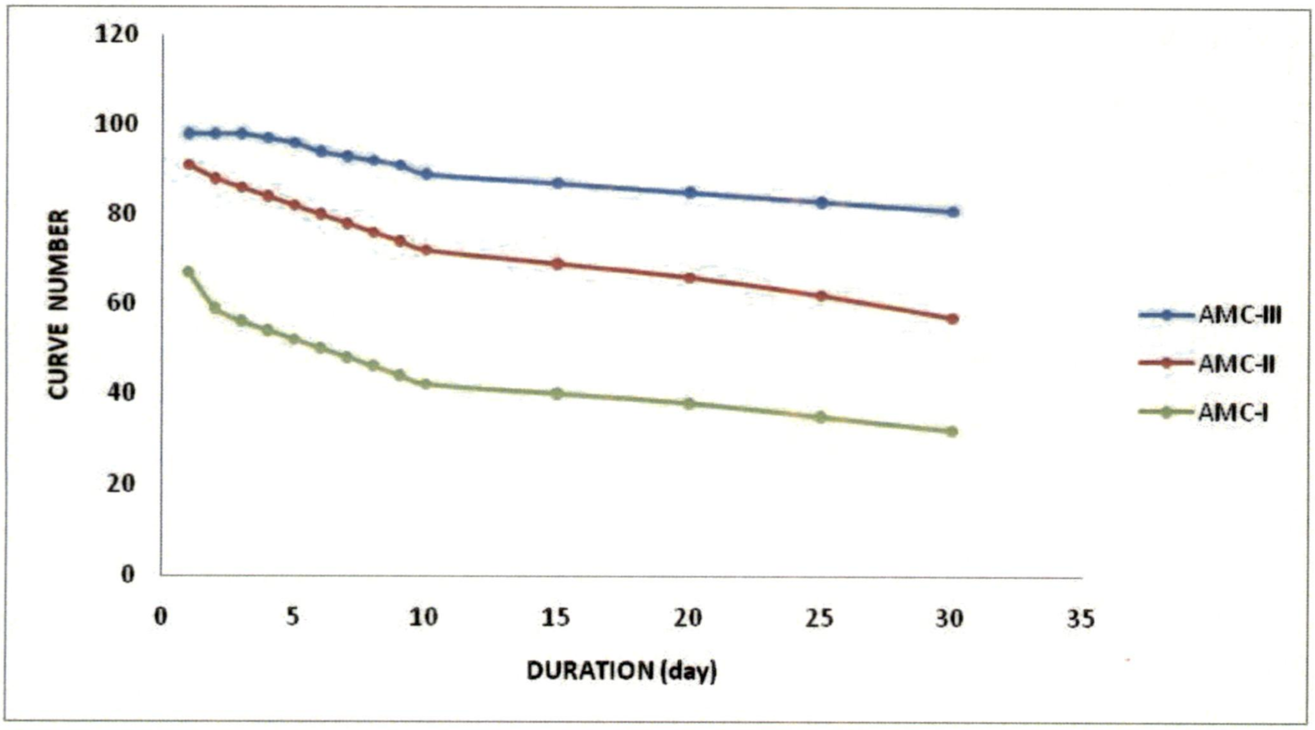
100
90
80
70
60
50
40
30
20
10
0
CURVE NUMBER
AMC-III
AMC-II
AMC-I
0
5
10
15
20
25
30
Duration (day)

(a)



120
100
80
60
40
20
0
CURVE NUMBER
AMC-III
AMC-II
AMC-I
0
5
10
15
20
25
30
35
Duration (day)

(b)



(c)

Figure 5.2: CN Variation with rainfall duration (greater than or equal to 1 day) for (a) Maithon, (b) Ramganga, and (c) Rapti.

Table 5.2: Relationship between CN rainfall and duration for AMC III, II and I condition for Maithon, Ramganga, and Rapti watersheds

AMC	Relation	R^2
	Maithon watershed	
I	$y = -9.047\ln(x) + 61.796$	0.97
II	$y = -12.44\ln(x) + 94.235$	0.97
III	$y = -8.488\ln(x) + 101.63$	0.96
	Ramganga watershed	
I	$y = -10.17\ln(x) + 59.058$	0.96
II	$y = 86.724e^{-0.029x}$	0.99
III	$y = 101.39e^{-0.019x}$	0.99
	Rapti watershed	
I	$y = -10.38\ln(x) + 67.845$	0.99
II	$y = 88.158e^{-0.015x}$	0.96
III	$y = 98.484e^{-0.007x}$	0.95

5.4 Determination of Design Curve Numbers

To enhance the field utility, the above work is further extended to the derivation of design curve numbers for different return periods. For this, annual P-Q data series were prepared for each year of the dataset following the above procedure. CN values for three AMCs were derived for different durations (viz., 1 day, 2 day & 3 day) for each of the years. The results are shown in Tables 5.3 a, b & c for AMC III, AMC II, and AMC I for the Maithon, Ramganga, and Rapti watersheds, respectively.

Table 5.3 a: Annual Curve Number (CN) values for different rain durations and AMCs for Maithon watershed

Year	**Duration**								
	1-day			**2-day**			**3-day**		
	AMC-III	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**
2000	97	88	68	96	86	65	94	82	60
2001	96	86	65	95	82	56	92	79	53
2002	98	91	60	96	85	55	94	80	50
2003	97	89	59	96	86	53	94	81	50
2004	96	84	54	95	81	52	92	78	49
2005	98	88	64	96	80	55	93	75	50
2006	97	87	49	95	83	46	93	82	43
2007	97	86	53	96	81	53	92	78	51
2008	97	88	56	95	82	55	93	80	46
2009	95	84	62	93	80	60	92	77	58
Average	96.80	87.10	59.00	95.30	82.60	55.00	92.90	79.20	51.00

Table 5.3 b: Annual Curve Number (CN) values for different rain durations and AMCs for Ramganga watershed

Year	**Duration**								
	1-day			**2-day**			**3-day**		
	AMC-III	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**
1978	98	88	62	97	84	60	94	78	58
1979	97	88	68	95	83	61	94	82	53
1980	96	88	65	95	86	58	94	82	55
1981	98	89	60	96	85	56	95	79	53
1982	98	88	65	97	81	60	94	79	55
1983	98	86	54	96	79	52	95	75	47
1984	98	90	62	97	84	52	96	84	48
1985	97	86	58	95	82	56	93	80	55
1986	98	86	55	97	84	51	95	81	48
1987	98	84	57	95	81	54	94	79	54
1988	98	89	57	97	85	54	95	78	53
1989	98	89	63	96	84	58	94	81	56
1990	98	87	55	97	85	52	95	80	51
1991	97	88	62	96	87	60	94	83	59
1992	97	89	62	96	86	55	94	84	54
1993	96	84	53	94	80	45	92	77	42
1994	98	90	65	97	89	65	96	87	65
1995	98	93	73	96	89	70	95	87	68
1996	98	90	60	97	87	58	95	86	55
1997	98	91	64	97	87	57	95	85	57
1998	96	84	46	94	78	41	91	71	39
1999	98	89	59	97	85	56	92	82	54
2000	97	85	58	96	82	55	95	80	52
2001	98	92	76	96	88	68	94	85	65
2002	98	90	65	96	83	58	93	78	51
2003	98	90	60	97	85	55	96	84	50
2004	98	91	72	97	86	63	95	83	62
2005	98	90	71	97	87	69	95	83	64
2006	98	91	69	96	86	63	95	83	59
2007	98	88	53	97	85	54	95	82	53
2008	97	91	77	96	87	70	95	85	68
2009	98	90	74	97	88	68	95	85	66
Average	97.63	88.56	62.50	96.22	84.63	57.94	94.38	81.50	55.28

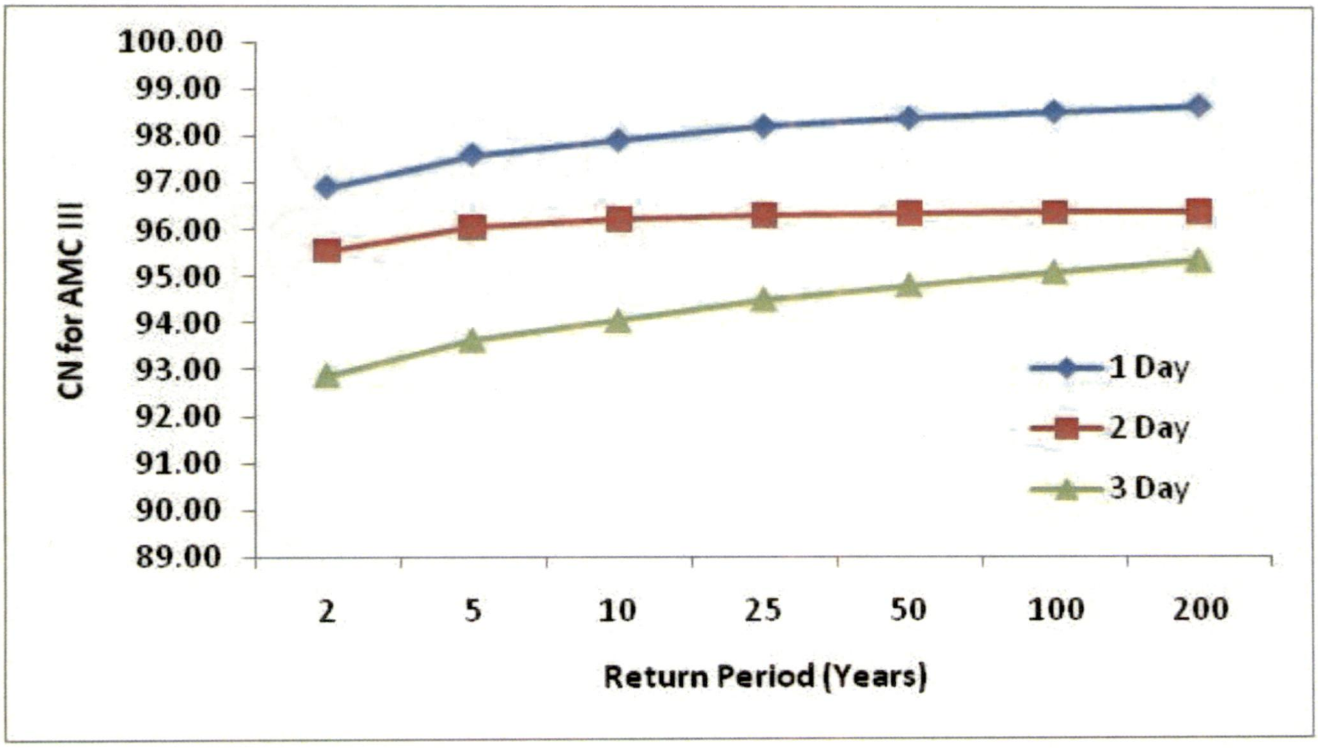
Table 5.3 c: Annual Curve Number (CN) values for different rain durations and AMCs for Rapti watershed

Year	Duration								
	1-day			2-day			3-day		
	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
1977	96	90	69	95	87	66	93	83	59
1978	98	90	70	96	87	70	95	83	62
1979	96	83	61	95	81	60	91	76	59
1980	97	85	63	95	81	60	94	79	55
1981	97	88	60	96	84	59	96	82	53
1982	98	90	65	97	86	63	96	83	62
1983	97	88	68	97	86	67	96	82	61
1984	98	89	70	97	86	70	96	83	68
1985	98	89	67	97	85	59	96	82	55
1986	97	86	63	96	82	58	96	78	50
1987	97	86	54	96	82	53	95	78	52
1988	98	88	62	97	86	61	96	82	55
1989	98	86	58	95	82	54	89	73	50
1990	98	91	71	97	87	66	96	82	61
1991	97	87	59	96	85	58	96	81	55
1992	97	89	72	96	88	70	93	83	66
1993	98	89	69	96	85	65	94	83	63
1994	97	89	68	97	88	68	97	87	65
1995	96	87	65	95	84	59	96	83	60
1996	98	90	65	96	85	60	93	81	59
1997	98	88	63	98	87	61	96	83	60
1998	97	87	58	96	82	51	96	80	51
1999	98	90	67	97	87	66	96	84	65
2000	98	90	75	97	87	72	95	85	71
2001	97	87	64	96	85	64	95	85	64
2002	96	88	72	95	87	68	95	86	66
2003	97	88	63	95	84	57	95	80	49
2004	98	88	61	97	85	51	95	82	50
2005	97	88	75	96	85	67	94	83	65
2006	97	88	70	96	87	67	94	84	64
2007	97	89	62	96	85	62	96	83	60
2008	97	89	67	97	87	65	96	84	58
Average	97.28	88.13	65.50	96.19	85.16	62.41	94.91	81.97	59.16

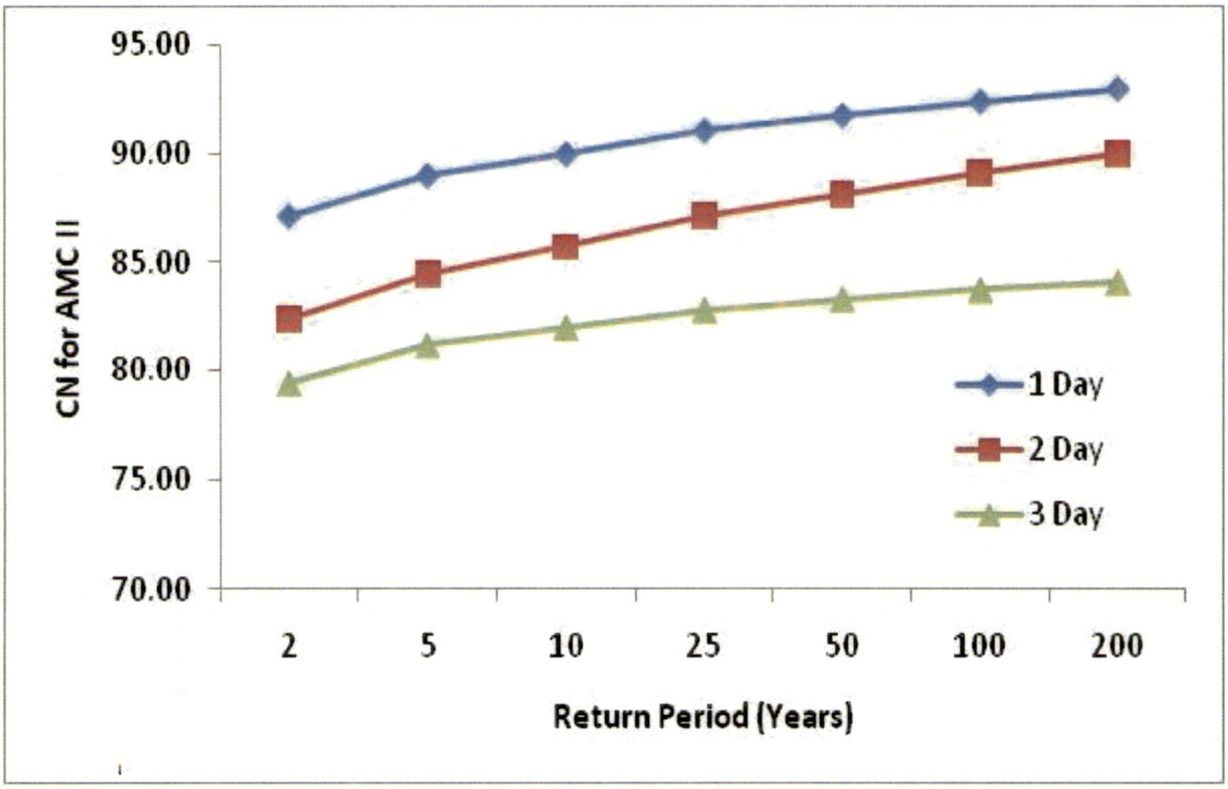
For a given duration and AMC, and considering the above annual CN-series as random, different frequency distributions were employed for deriving CN-values corresponding to different return periods. Three distributions namely Gumbel extreme-value, log-normal, and Log Pearson type III were employed and, based on the standard error and the criterion of CN < 100, the results of Log Pearson type III distribution were adopted and the final results are shown in Tables 5.4a, b & c for Maithon, Ramganga, and Rapti watersheds, respectively. These are depicted in Figs. 5.3a, b & c; Figs. 5.4a, b & c; and Figs. 5.5a, b & c respectively. It is seen from these figures that, for a given return period as duration increases the quantum CN-value decreases, and vice versa. For a given duration, the reverse trend is apparent with return period. Similarly, for a given return period and duration, as AMC increases from I to III, design CN- values also increases.

Table 5.4a: Design CN-values for different AMCs, durations, and return periods derived using Log Pearson type III distribution for Maithon watershed

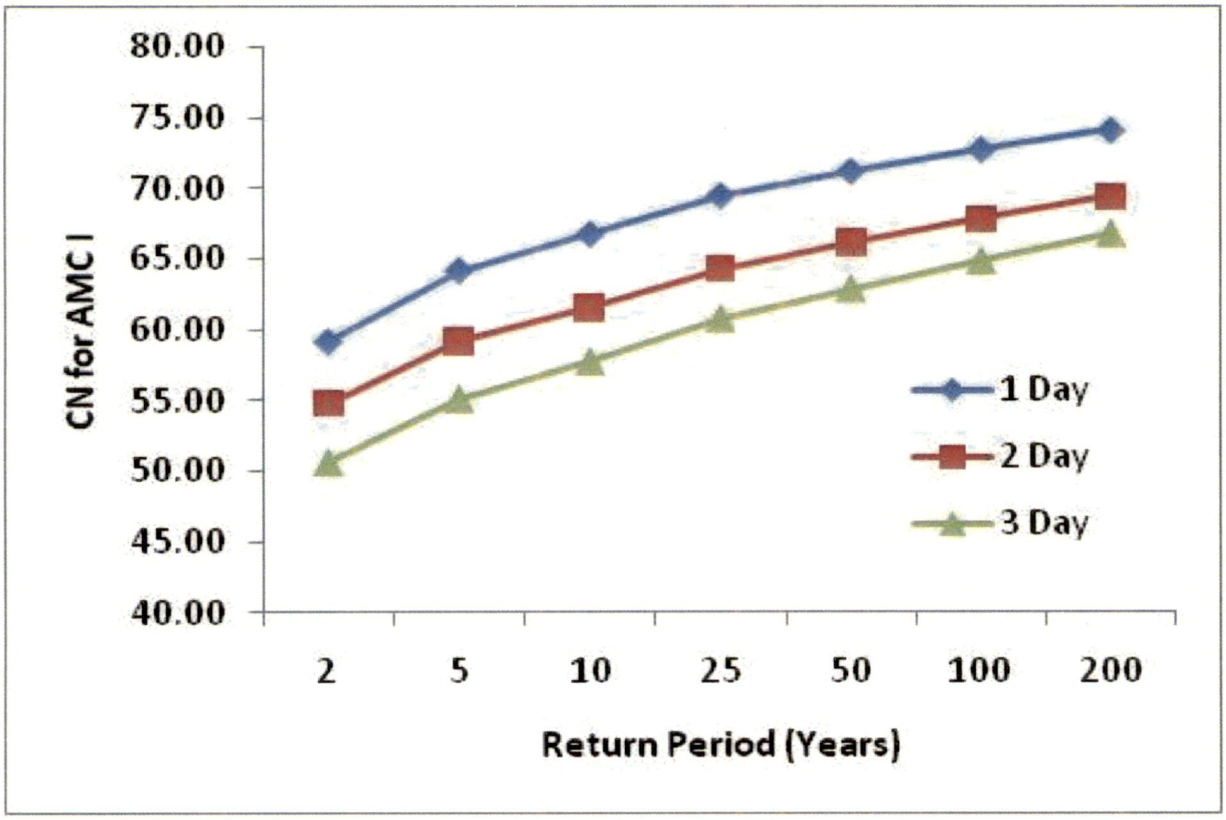
Return Period (T) (year)	**1 - Day**			**2 - Day**			**3 - Day**		
	AMC-III	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**
2	96.89	87.07	59.07	95.55	82.37	54.77	92.86	79.36	50.60
5	97.59	88.93	64.11	96.06	84.45	59.12	93.62	81.13	55.09
10	97.90	89.92	66.70	96.22	85.68	61.54	94.04	81.97	57.71
25	98.21	91.00	69.42	96.32	87.11	64.25	94.51	82.79	60.73
50	98.38	91.71	71.15	96.36	88.10	66.07	94.81	83.29	62.82
100	98.53	92.35	72.68	96.38	89.04	67.75	95.10	83.71	64.80
200	98.66	92.94	74.06	96.39	89.94	69.33	95.36	84.08	66.70



(a)



(b)

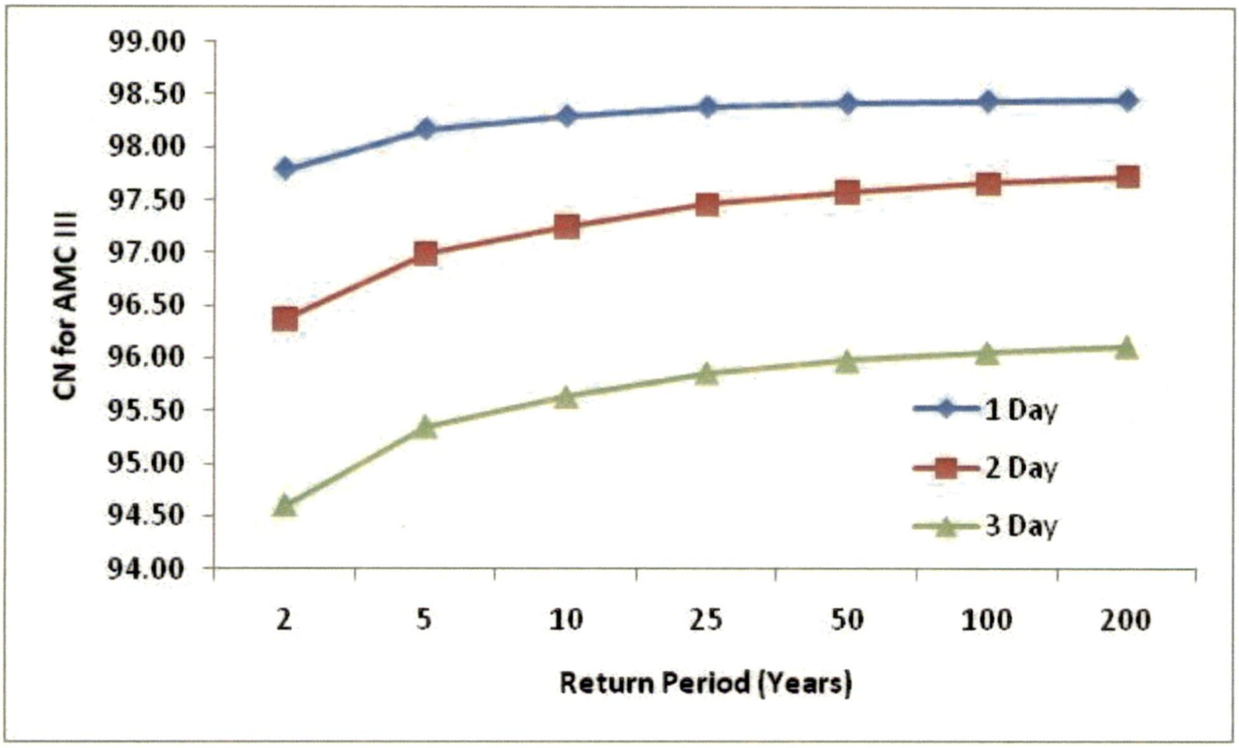


(c)

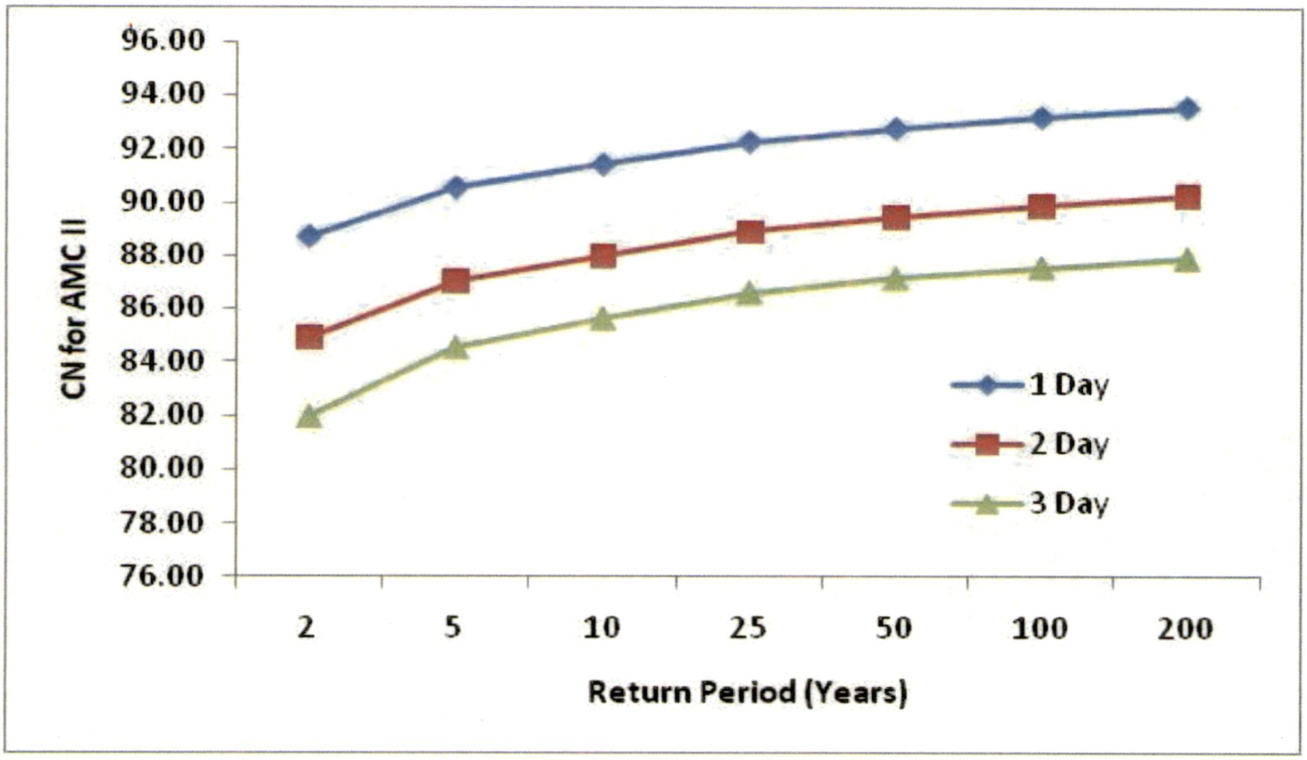
Figure 5.3: Design curve numbers for (a) AMC III, (b) AMC II, and (c) AMC I and different return periods. Third parameter = duration for Maithon watershed

Table 5.4b: Design CN-values for different AMCs, durations, and return periods derived using Log Pearson type III distribution for Ramganga watershed.

Return Period (T) (year)	1 - Day			2 - Day			3 - Day		
	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
2	97.79	88.74	62.27	96.37	84.90	58.13	94.60	81.99	55.35
5	98.16	90.57	68.62	96.99	87.03	63.77	95.35	84.57	61.22
10	98.29	91.43	72.07	97.24	87.99	66.57	95.63	85.65	64.23
25	98.38	92.27	75.86	97.46	88.91	69.43	95.86	86.63	67.35
50	98.42	92.78	78.35	97.57	89.44	71.20	95.97	87.16	69.32
100	98.44	93.21	80.63	97.66	89.88	72.73	96.06	87.58	71.06
200	98.45	93.58	82.74	97.73	90.26	74.08	96.12	87.91	72.61



(a)



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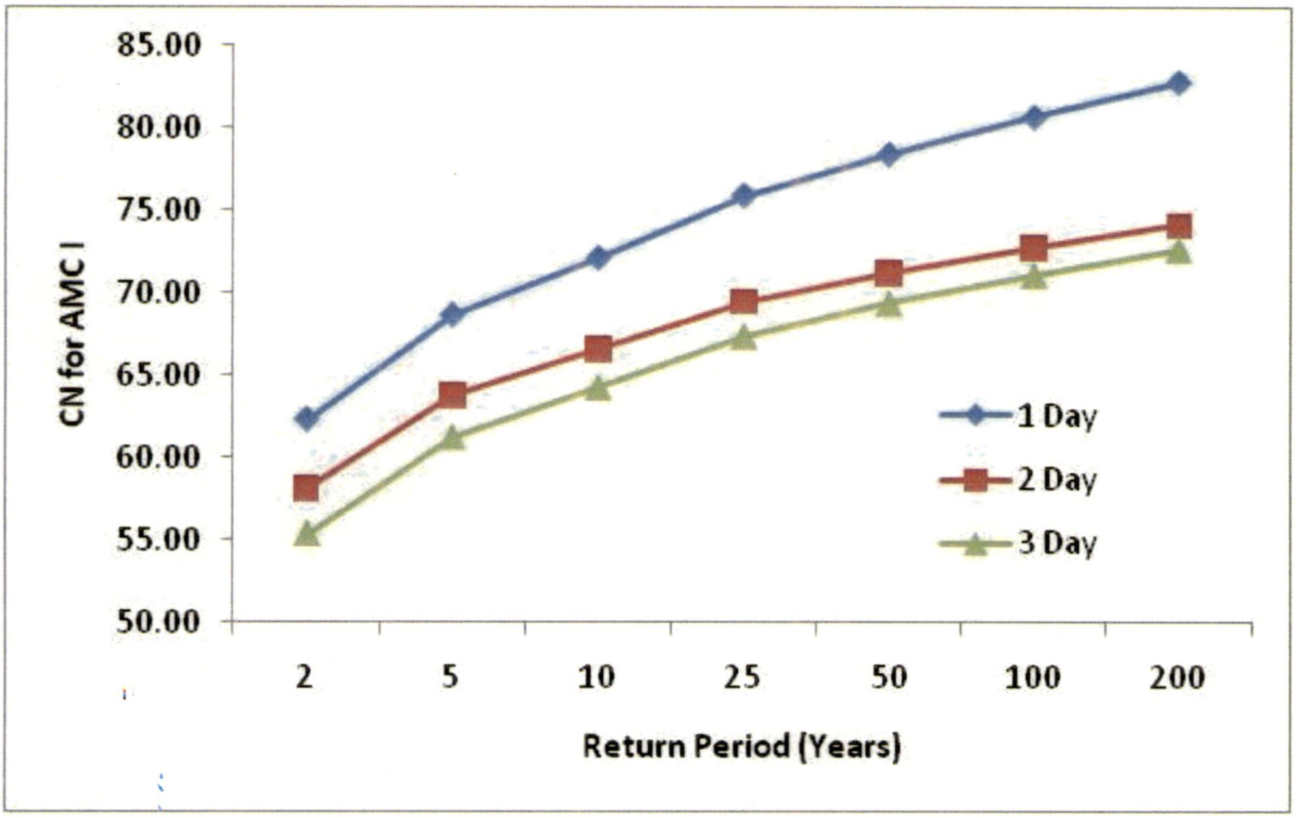
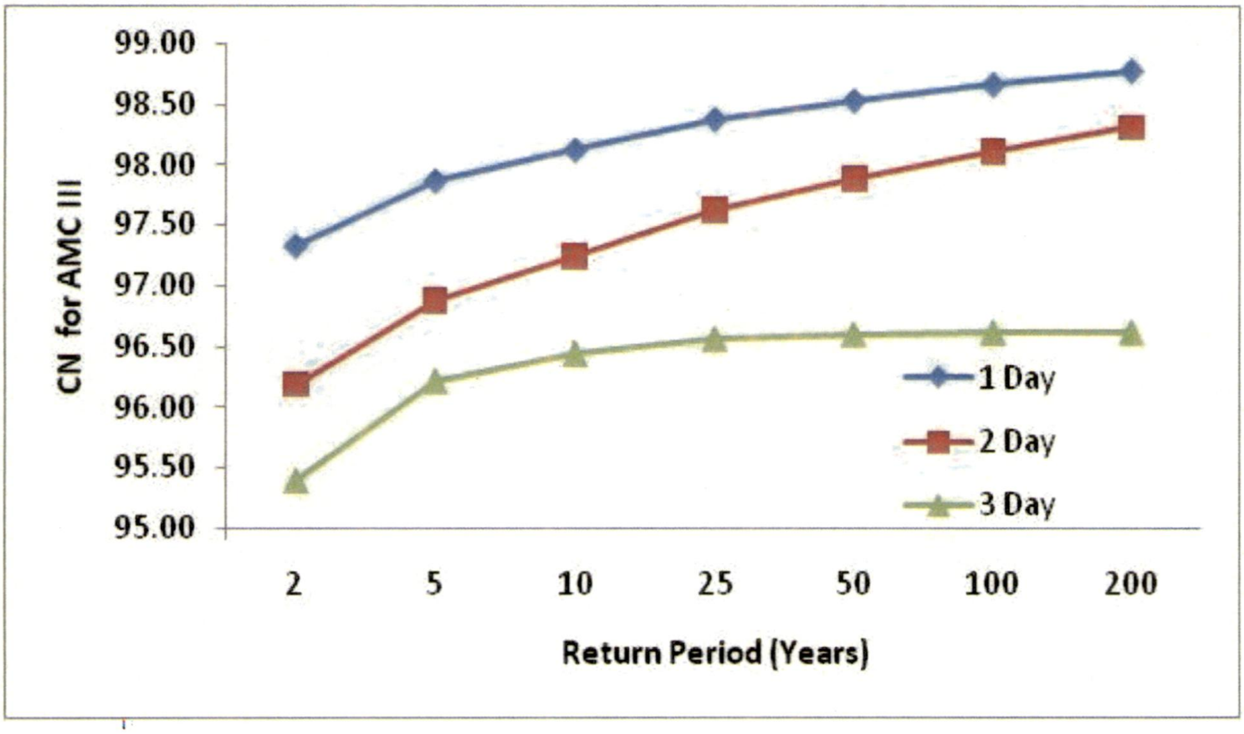


(c)

Figure 5.4: Design curve numbers for (a) AMC III, (b) AMC II, and (c) AMC I and different return periods. Third parameter = duration for Ramganga watershed

Table 5.4c: Design CN-values for different AMCs, durations, and return periods derived using Log Pearson type III distribution for Rapti watershed.

Return Period (T) (year)	1 - Day			2 - Day			3 - Day		
	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
2	97.33	88.38	65.53	96.19	85.38	62.66	95.39	82.55	59.17
5	97.87	89.58	69.83	96.88	86.90	67.28	96.22	84.36	64.18
10	98.12	90.06	72.06	97.24	87.58	69.52	96.44	85.01	66.78
25	98.38	90.50	74.41	97.63	88.22	71.78	96.57	85.52	69.53
50	98.53	90.73	75.92	97.88	88.59	73.16	96.60	85.76	71.29
100	98.66	90.91	77.26	98.10	88.89	74.34	96.62	85.93	72.86
200	98.78	91.05	78.47	98.31	89.14	75.38	96.62	86.04	74.28



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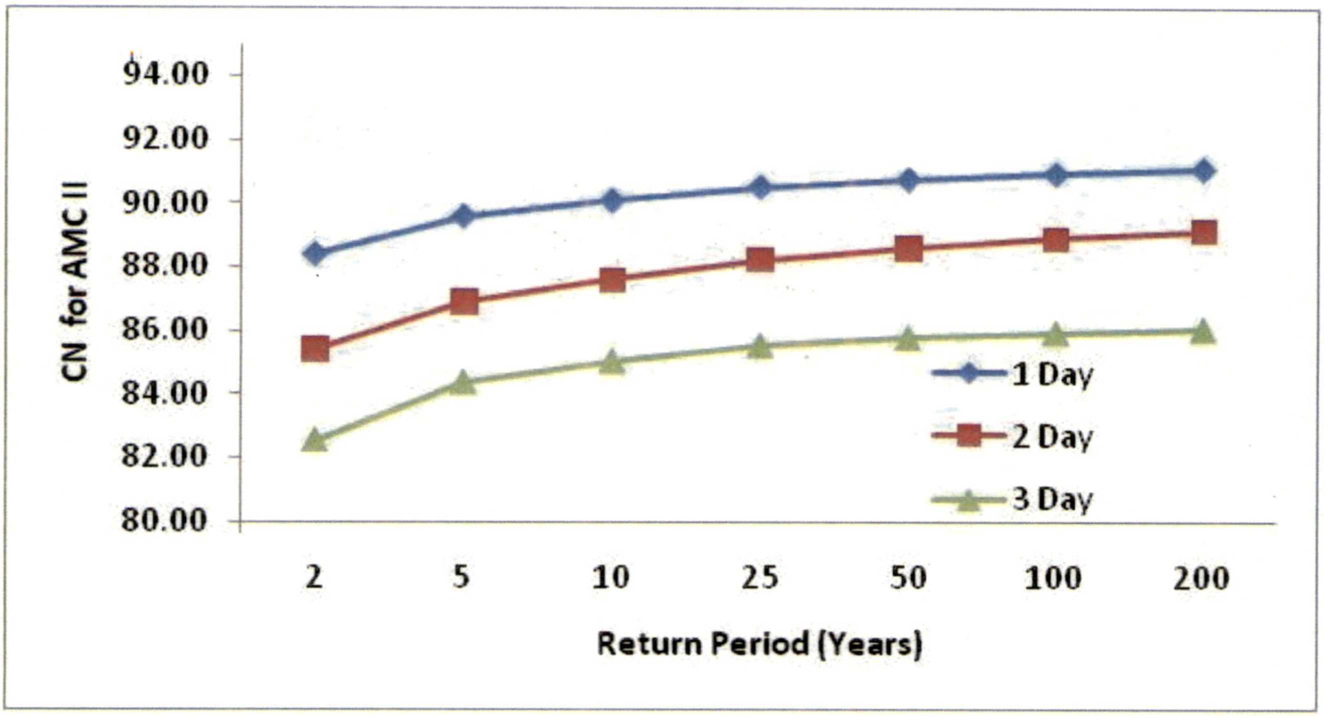

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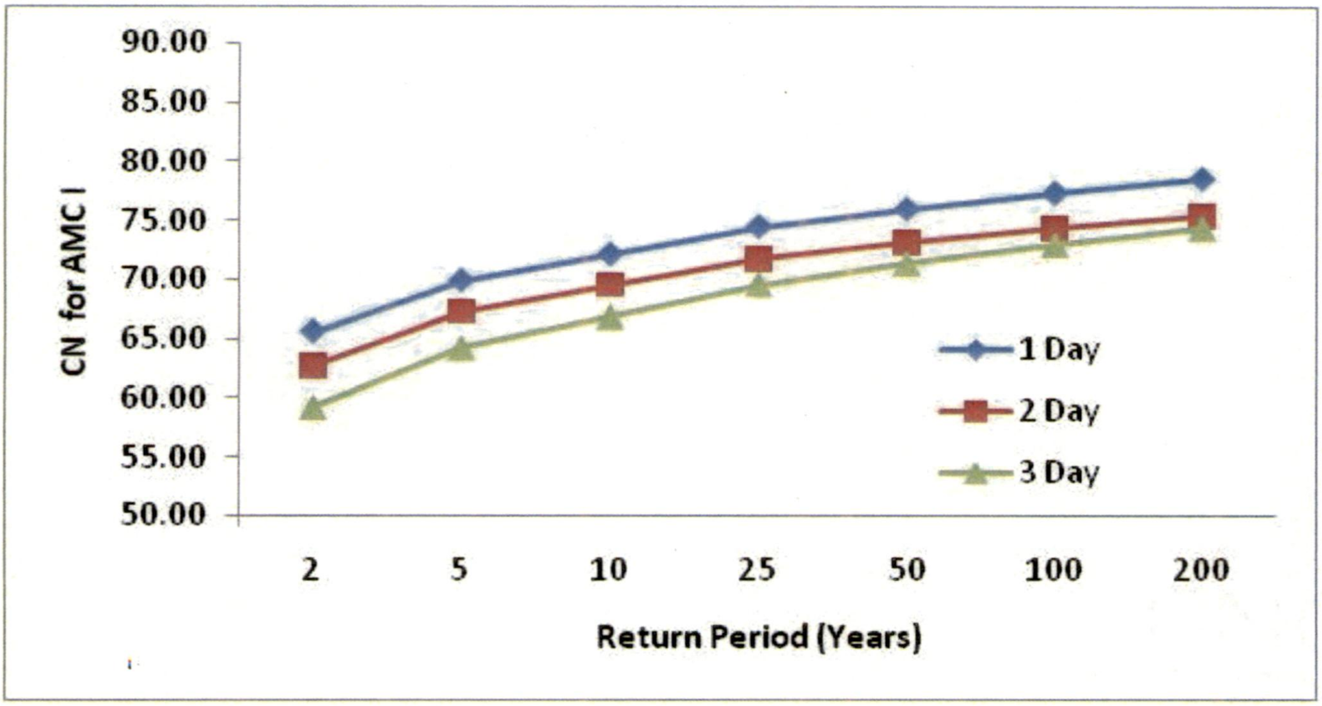


(c)

Figure 5.5: Design curve numbers for (a) AMC III, (b) AMC II, and (c) AMC I and different return periods. Third parameter = duration for Rapti watershed

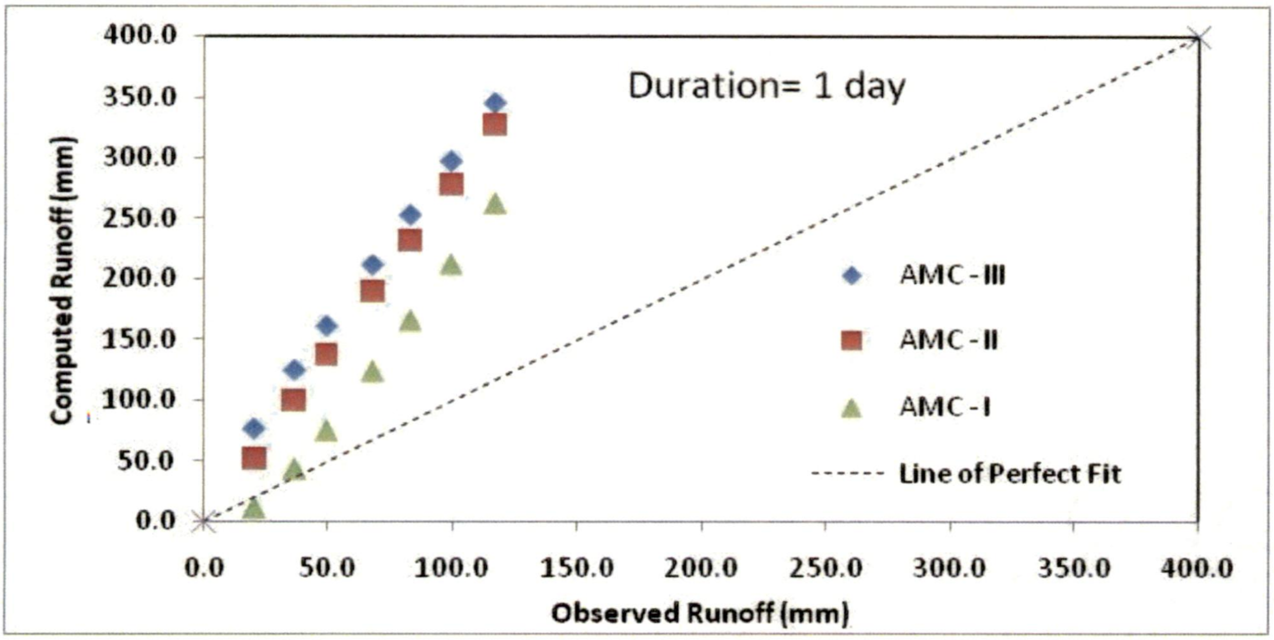
5.5 Validation of the Design Curve Numbers

The above derived design CN-values are validated using the procedure described in Chapter 4. From annual maximum observed rainfall series, rainfall values are computed for different return periods using the Log Pearson type III distribution and the runoff is determined using the CN-values corresponding to the same return period for different AMCs & also observed runoff for different durations and return periods derived using Log Pearson type III distribution and these are shown in Tables 5.5 for Maithon, Ramganga, and Rapti watersheds, respectively. Similarly, runoff for different return periods was directly derived using the same procedure and distribution as for rainfall. The resulting Q-values are termed as observed ones.

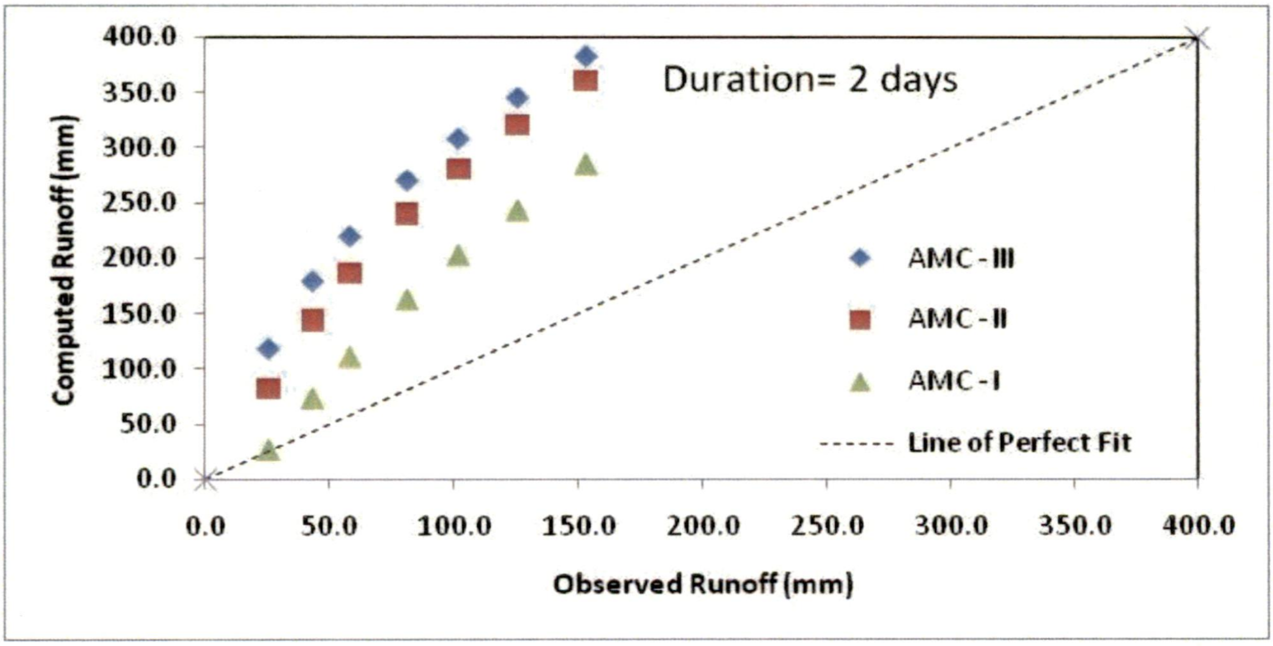
Table 5.5: Runoff computed for different AMCs, durations, and return periods and runoff observed for durations and return periods derived using Log Pearson type III distribution for Maithon, Ramganga, and Rapti watersheds

Return Period (T) (year)	***Computed Runoff(mm)***									***Observed Runoff (mm)***		
	1 - Day			**2 - Day**			**3 - Day**			**1-Day**	**2-Day**	**3-Day**
	AMC-III	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**	**AMC-III**	**AMC -II**	**AMC-I**			
	Maithon Watershed											
2	75.9	52.0	10.9	117.5	82.4	26.4	106.2	72.0	18.4	20.1	25.5	45.4
5	124.3	100.0	43.3	178.5	143.9	72.9	172.7	135.7	63.4	36.3	43.2	102.2
10	160.6	137.1	74.7	218.8	186.2	110.4	224.7	186.8	108.0	49.2	58.1	159.0
25	211.4	189.4	123.5	269.5	240.2	161.9	300.0	261.5	180.1	67.7	81.3	258.0
50	252.9	232.1	165.4	307.0	280.5	202.0	363.5	324.7	244.5	82.8	101.8	355.4
100	297.5	278.1	211.5	344.4	320.6	242.8	433.8	394.8	317.6	99.2	125.6	476.4
200	345.7	327.7	261.9	381.8	360.8	284.3	511.8	472.7	399.8	116.8	153.0	625.5
	Ramganga Watershed											
2	57.6	36.9	5.9	84.7	56.6	14.3	104.8	72.5	22.3	11.9	21.2	26.3
5	87.3	67.2	26.0	124.8	97.1	44.2	149.3	118.4	58.9	23.2	37.7	46.6
10	109.0	89.9	46.3	151.2	124.4	68.7	174.5	144.9	84.5	34.2	51.6	65.2
25	139.1	121.3	78.3	184.5	158.9	102.5	202.3	174.1	115.6	53.2	72.8	96.0
50	163.5	146.7	106.1	209.4	184.5	128.8	220.6	193.3	137.2	72.1	91.4	125.3
100	189.7	173.9	136.6	234.2	210.2	155.7	237.1	210.6	157.3	95.9	112.5	161.0
200	218.0	203.1	169.7	259.3	236.0	183.0	252.2	226.4	176.1	125.7	136.6	204.6
	Rapti Watershed											
2	68.2	46.8	13.3	92.2	64.9	23.8	100.7	68.1	24.6	29.6	42.5	53.3
5	92.4	98.7	61.8	89.6	91.7	56.2	87.7	85.3	49.7	46.2	59.5	73.4
10	110.1	115.5	81.1	107.5	108.7	74.8	105.2	101.8	68.3	58.0	70.3	86.7
25	134.5	135.9	106.2	132.3	129.4	99.0	129.1	121.8	93.0	73.7	83.3	103.5
50	154.2	150.7	125.4	152.3	144.4	117.4	148.5	136.2	112.0	85.8	92.6	116.0
100	175.5	165.2	144.8	173.8	159.2	135.9	169.3	150.4	131.5	98.2	101.5	128.5
200	198.4	179.6	164.5	197.0	173.8	154.8	191.9	164.4	151.3	111.1	110.2	141.0

The computed runoff (Q-computed) and observed runoff (Q-observed) for given durations and return periods in above Tables 5.5 for Maithon, Ramganga, & Rapti watersheds are compared through a line of perfect fit in Figs. 5.6a, 5.6b & 5.6c for Maithon watershed, Figs. 5.7a, 5.7b & 5.7c for Ramganga watershed and Figs. 5.8a, 5.8b & 5.8c for Rapti watershed for different AMC's & return periods. It is seen from these figures that for AMC-I condition of a given day, the computed runoff is relatively close for return periods up to 10 years, 50 years, and 50 years for Maithon, Ramganga, and Rapti watersheds respectively.



(a)



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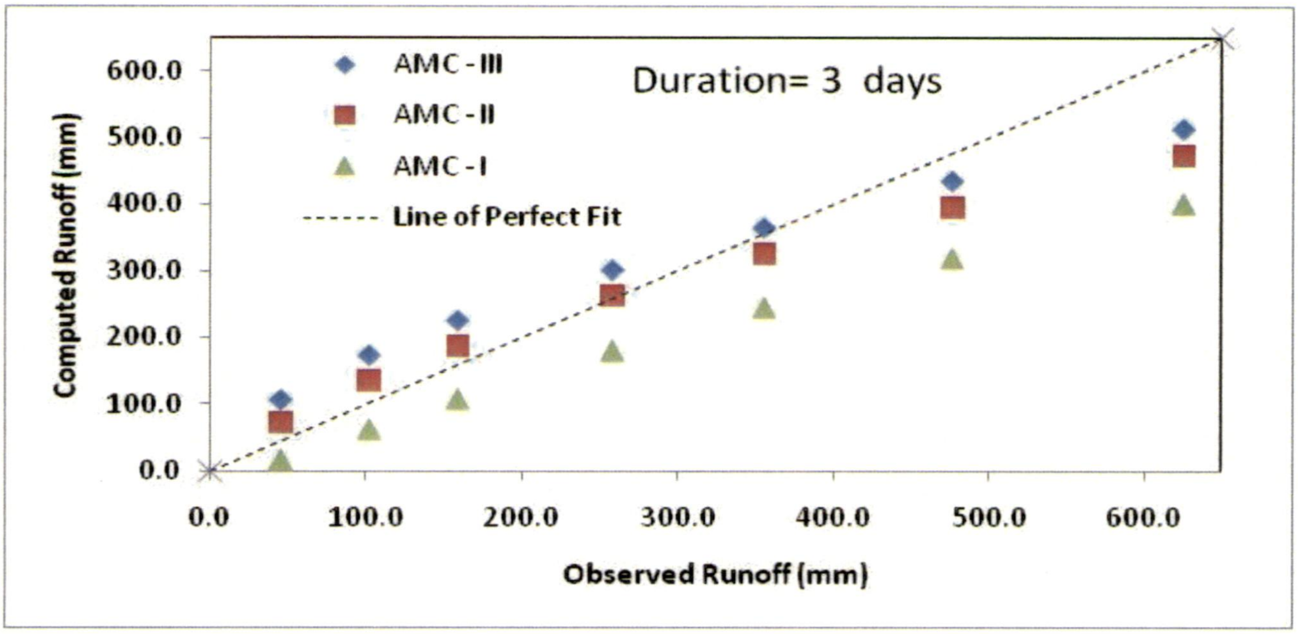
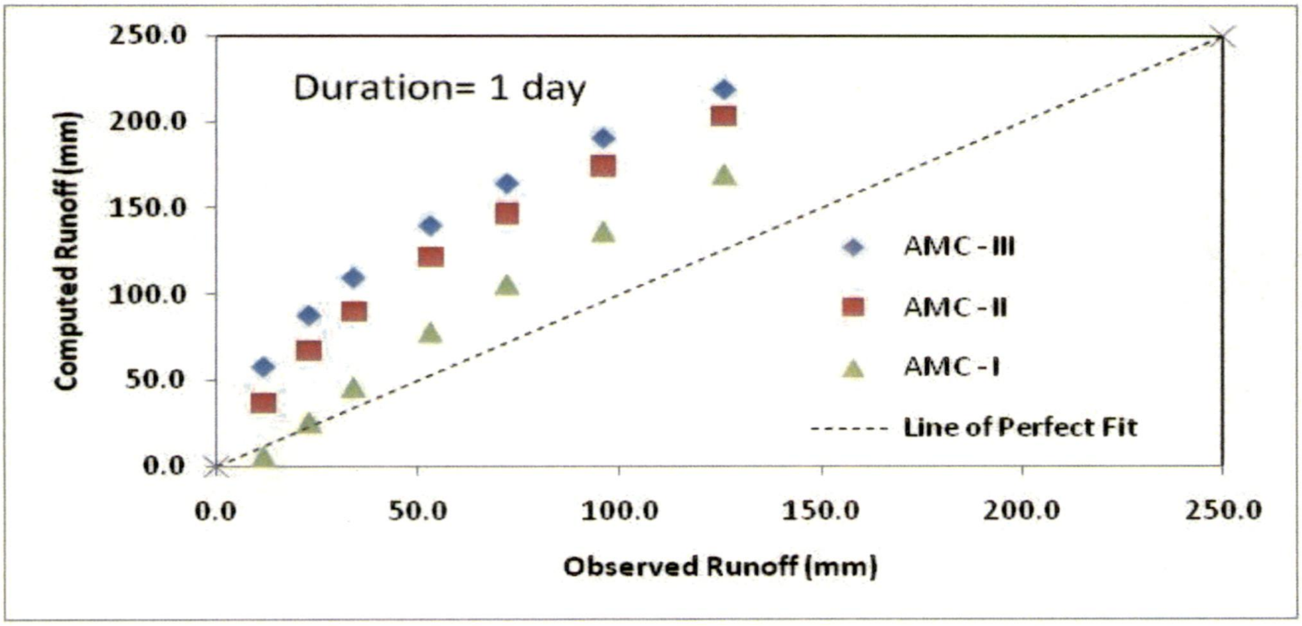


(c)

Figure 5.6: Computed and observed runoff for different AMC's and return periods for Maithon watershed



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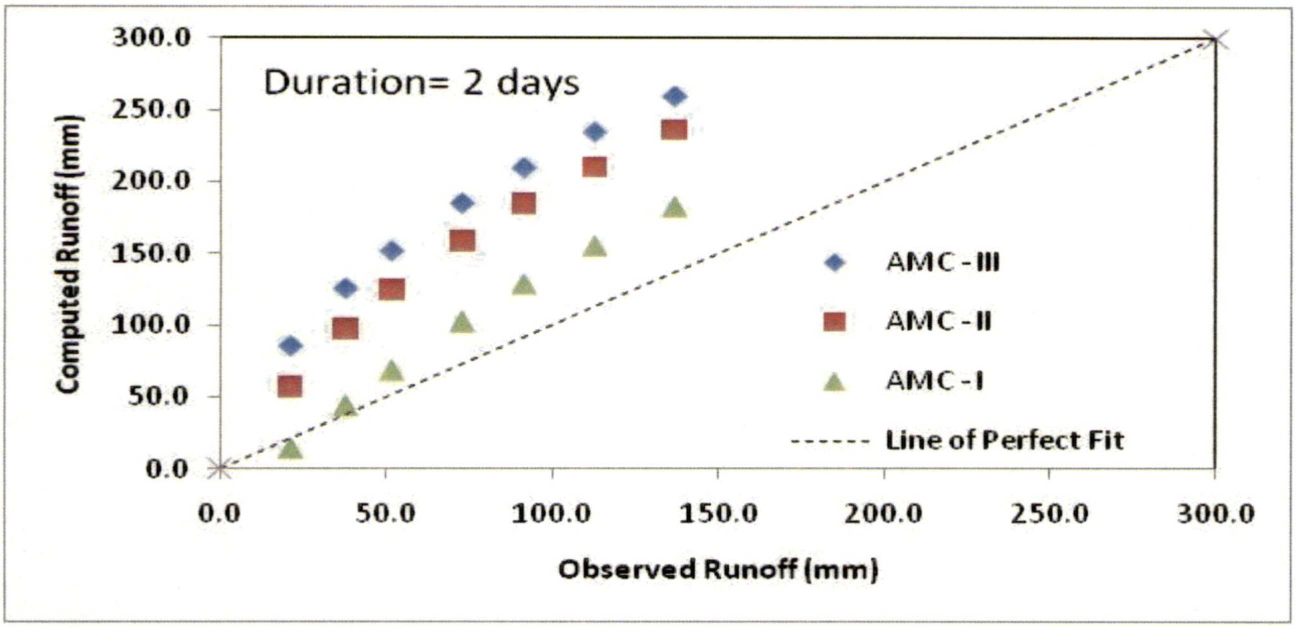

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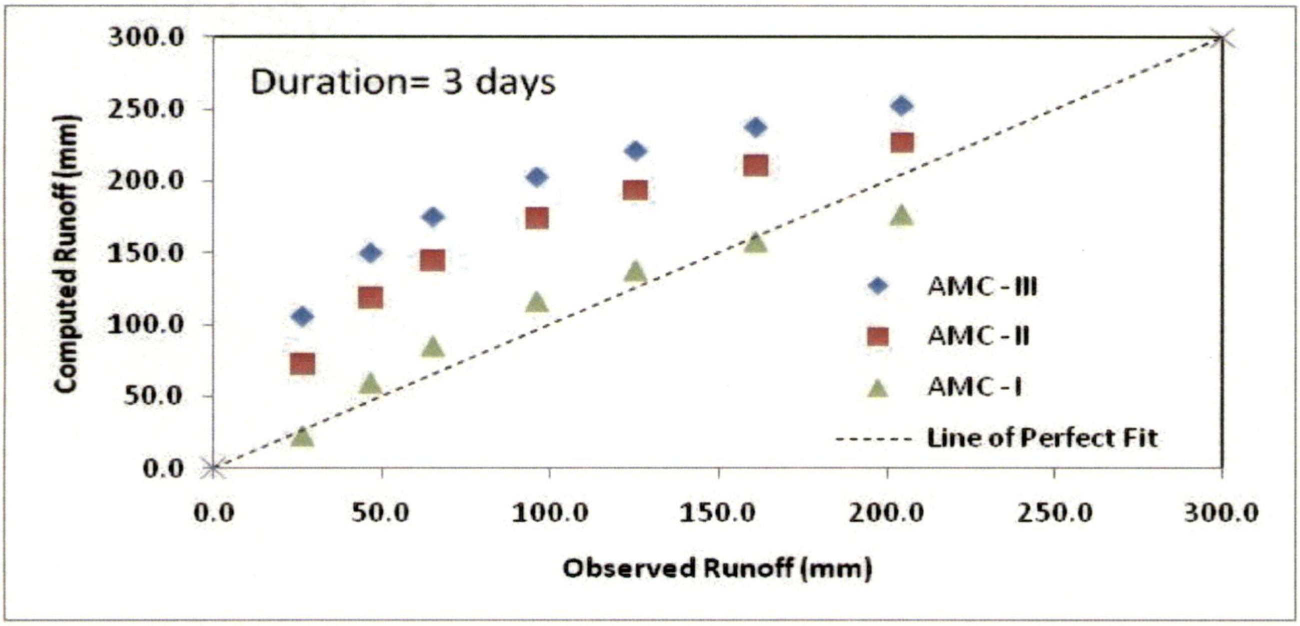
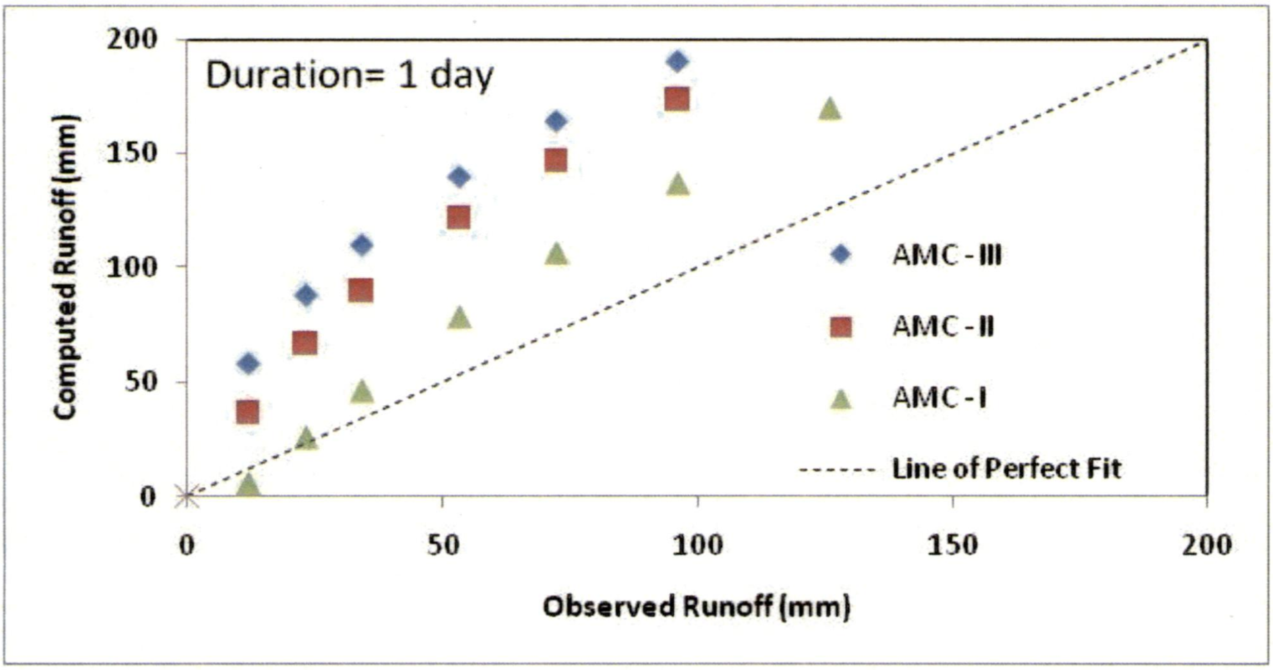
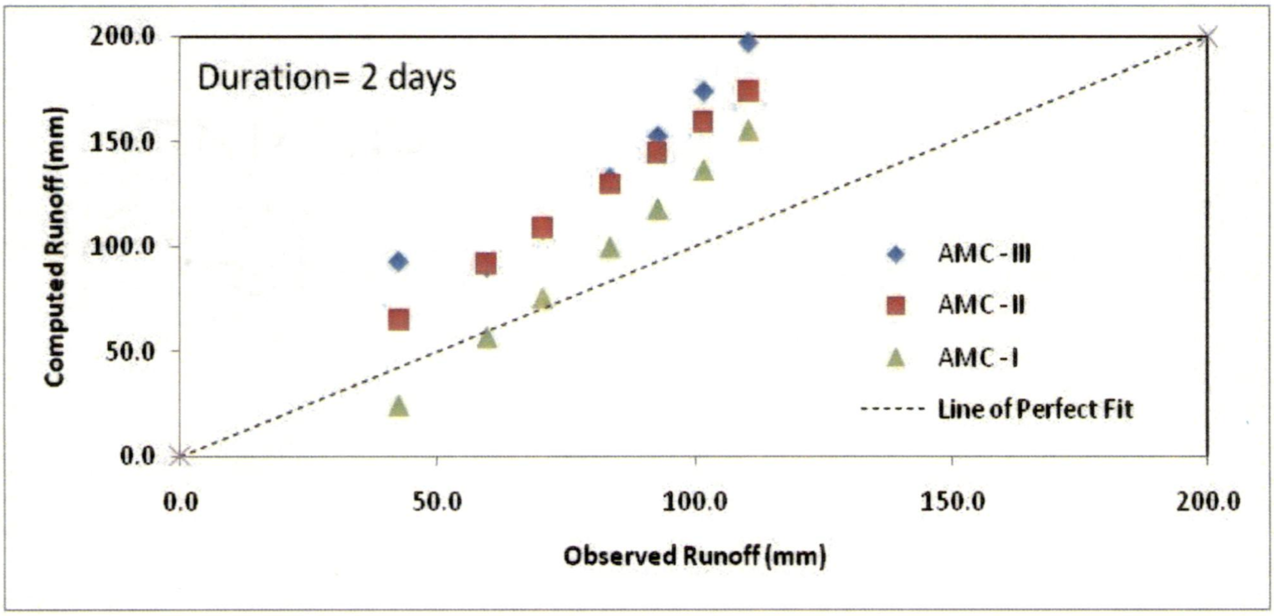


(c)

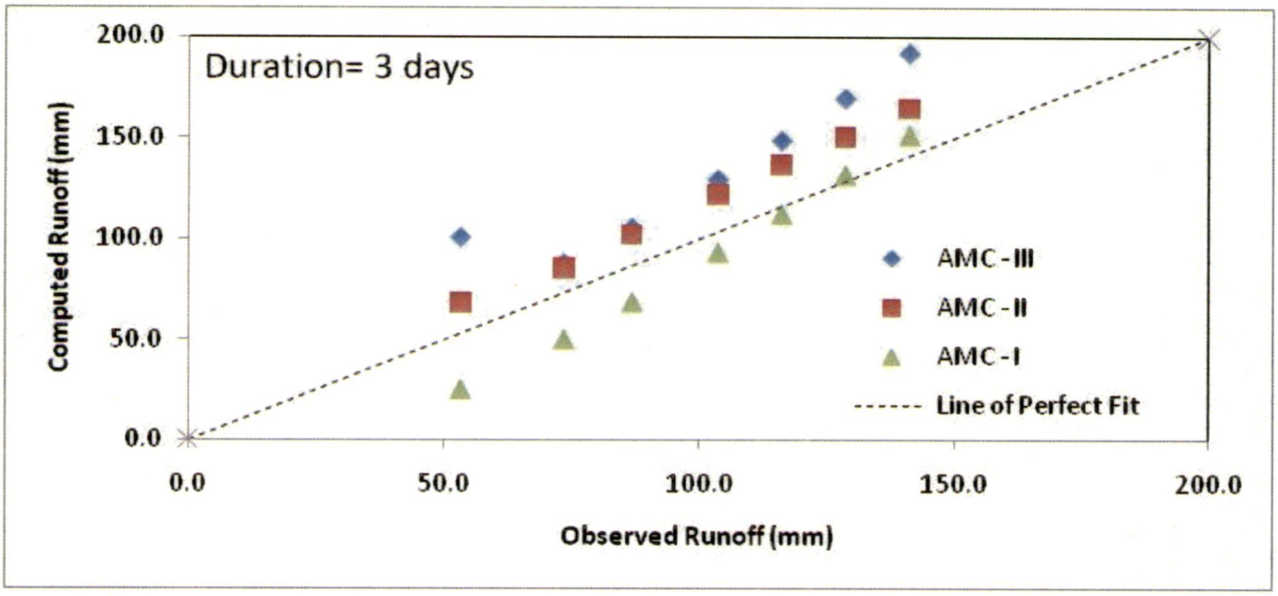
Figure 5.7: Computed and observed runoff for different AMC's and return periods for Ramganga watershed


Duration= 1 day
Computed Runoff (mm)
Observed Runoff (mm)
0
50
100
150
200
0
50
100
150
200
AMC - III
AMC - II
AMC - I
Line of Perfect Fit

(a)


Duration= 2 days
Computed Runoff (mm)
Observed Runoff (mm)
0.0
50.0
100.0
150.0
200.0
0.0
50.0
100.0
150.0
200.0
AMC - III
AMC - II
AMC - I
Line of Perfect Fit

(b)



(c)

Figure 5.8: Computed and observed runoff for different AMC's and return periods for Rapti watershed

Table 5.6: Relationship between observed and computed runoff for different AMCs condition for duration (1-day, 2-day & 3-day) for Maithon, Ramganga & Rapti watersheds

Duration	**Relation**		
	Maithon	**Ramganga**	**Rapti**
	AMC I		
1-day	$y = 0.3794x + 19.132$ $R^2 = 0.9971$	$y = 0.6841x + 3.866$ $R^2 = 0.991$	$y = 0.5547x + 16.569$ $R^2 = 0.9837$
2-day	$y = 0.4897x + 7.0667$ $R^2 = 0.9899$	$y = 0.6778x + 7.306$ $R^2 = 0.9925$	$y = 0.5214x + 30.682$ $R^2 = 0.9989$
3-day	$y = 1.5104x + 1.468$ $R^2 = 0.9954$	$y = 1.1271x - 17.492$ $R^2 = 0.9396$	$y = 0.6864x + 38.523$ $R^2 = 0.9982$
	AMC II		
1-day	$y = 0.3516x + 1.3219$ $R^2 = 0.9999$	$y = 0.6829x - 22.384$ $R^2 = 0.9724$	$y = 0.6286x - 8.3332$ $R^2 = 0.9542$
2-day	$y = 0.4562x - 21.164$ $R^2 = 0.9775$	$y = 0.6431x - 23.282$ $R^2 = 0.9793$	$y = 0.6231x + 2.3575$ $R^2 = 0.9998$
3-day	$y = 1.4526x - 94.67$ $R^2 = 0.9852$	$y = 1.1176x - 78.491$ $R^2 = 0.9018$	$y = 0.8881x - 4.7186$ $R^2 = 0.9977$
	AMC III		
1-day	$y = 0.3601x - 8.0859$ $R^2 = 0.9998$	$y = 0.7089x - 38.191$ $R^2 = 0.9722$	$y = 0.6261x - 11.682$ $R^2 = 0.9987$
2-day	$y = 0.4813x - 40.886$ $R^2 = 0.9742$	$y = 0.6616x - 43.158$ $R^2 = 0.9785$	$y = 0.5551x + 5.0755$ $R^2 = 0.9152$
3-day	$y = 1.4369x - 144.83$ $R^2 = 0.9838$	$y = 1.1678x - 120.14$ $R^2 = 0.9003$	$y = 0.7601x - 0.9028$ $R^2 = 0.8822$

Notation: y = predicted runoff (mm), x = CN-generated runoff (mm).

In an attempt to match the observed and computed runoff values, relations were derived for different AMC conditions as shown in Table 5.6. The high values of R^2 leads to infer that there exists a correlation between the quantum CN-generated runoff values and those directly derived from the observed runoff, and therefore, suggest validity of the approach proposed.

CHAPTER 6

CONCLUSIONS

The following conclusions can be drawn from the study:

1. 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.

2. For a given AMC and return period, CN decreases as rain duration increases, and vice versa. For a given AMC and duration, CN increases as return period increases. For a given duration and return period, CN increases as AMC level increases from AMC I to AMC III.

3. The AMC I CN-generated quantum runoff values are closer than others with the observed ones for a given day and return period up to 10 years, 50 years, and 50 years for Maithon, Ramganga, and Rapti watersheds, respectively.

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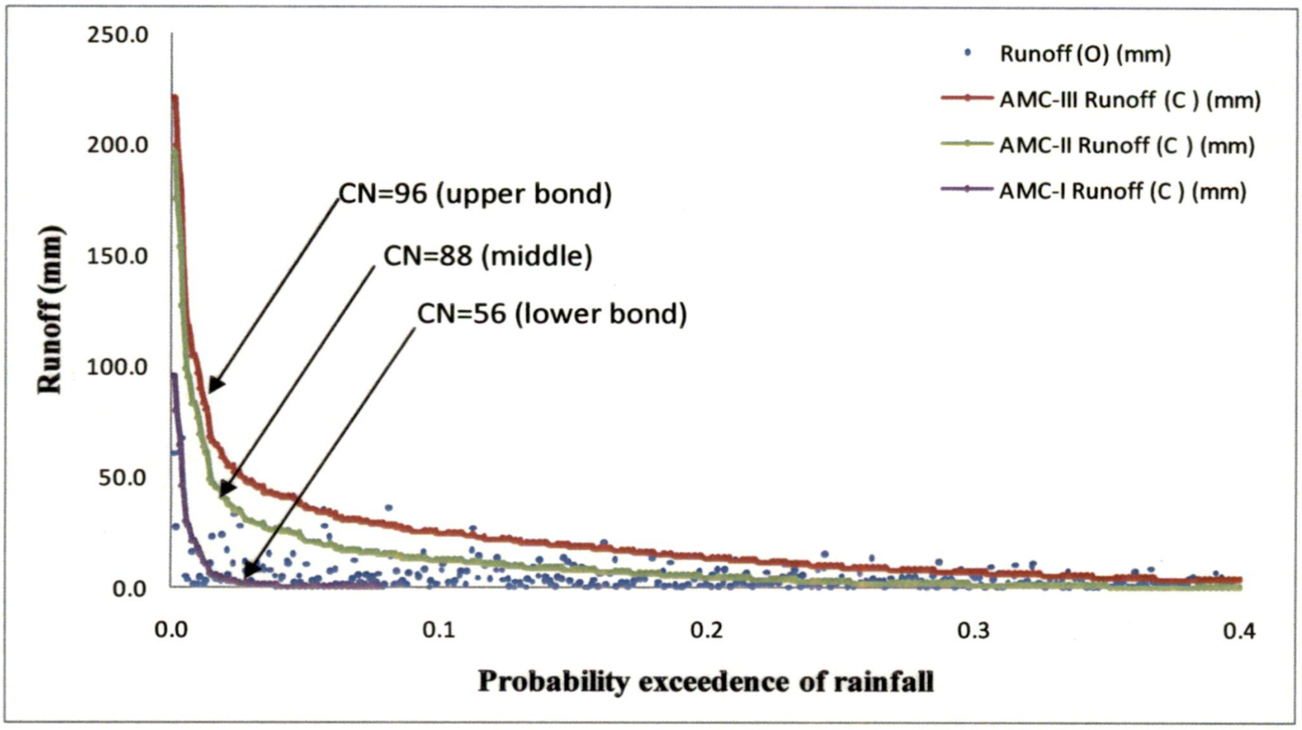
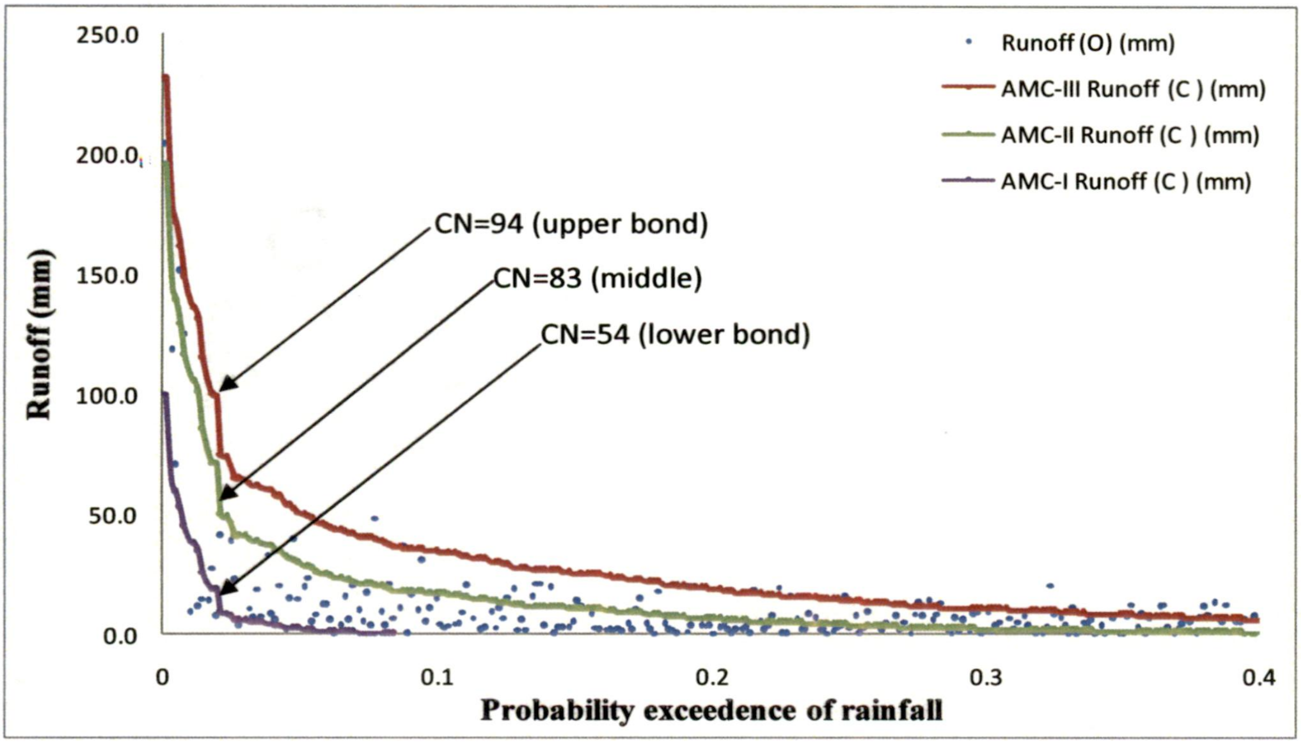
APPENDIX-I

ORDERED DAILY RAINFALL-RUNOFF EVENTS FOR DIFFERENT CATCHMENTS



(a) 2-Daily duration analysis



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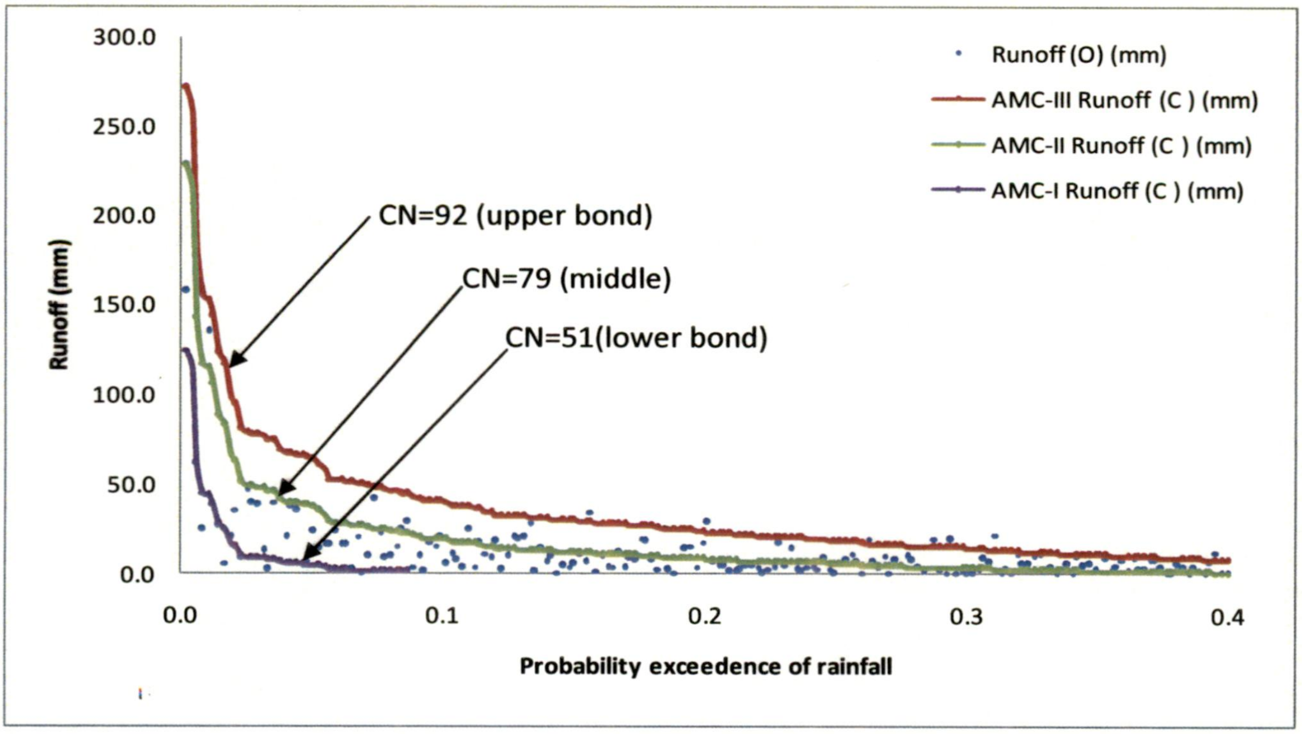

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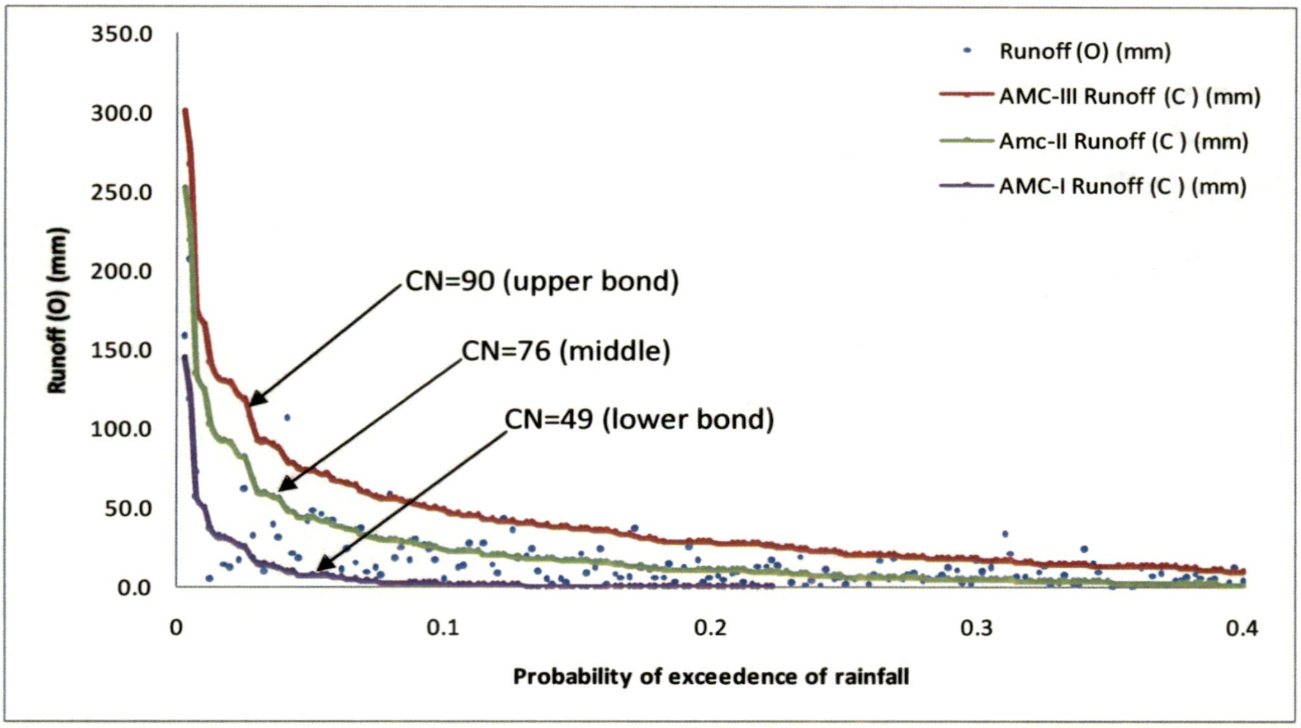
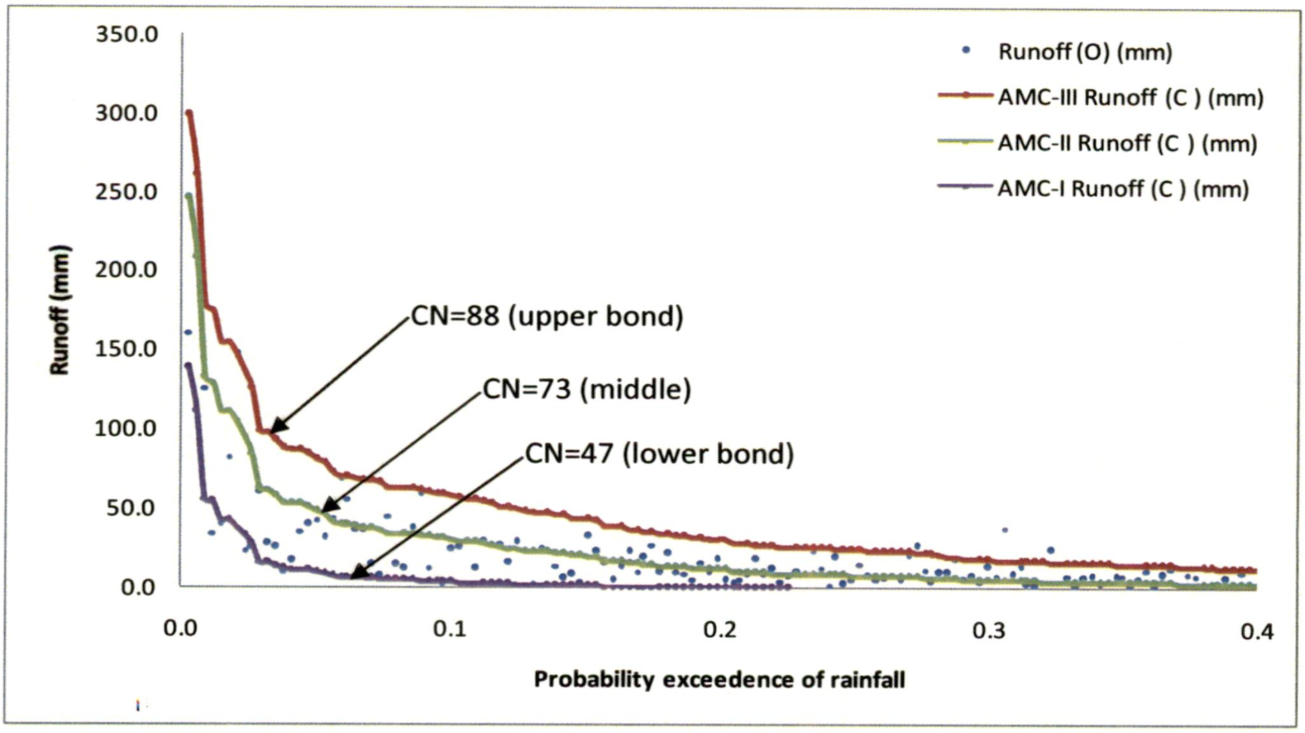
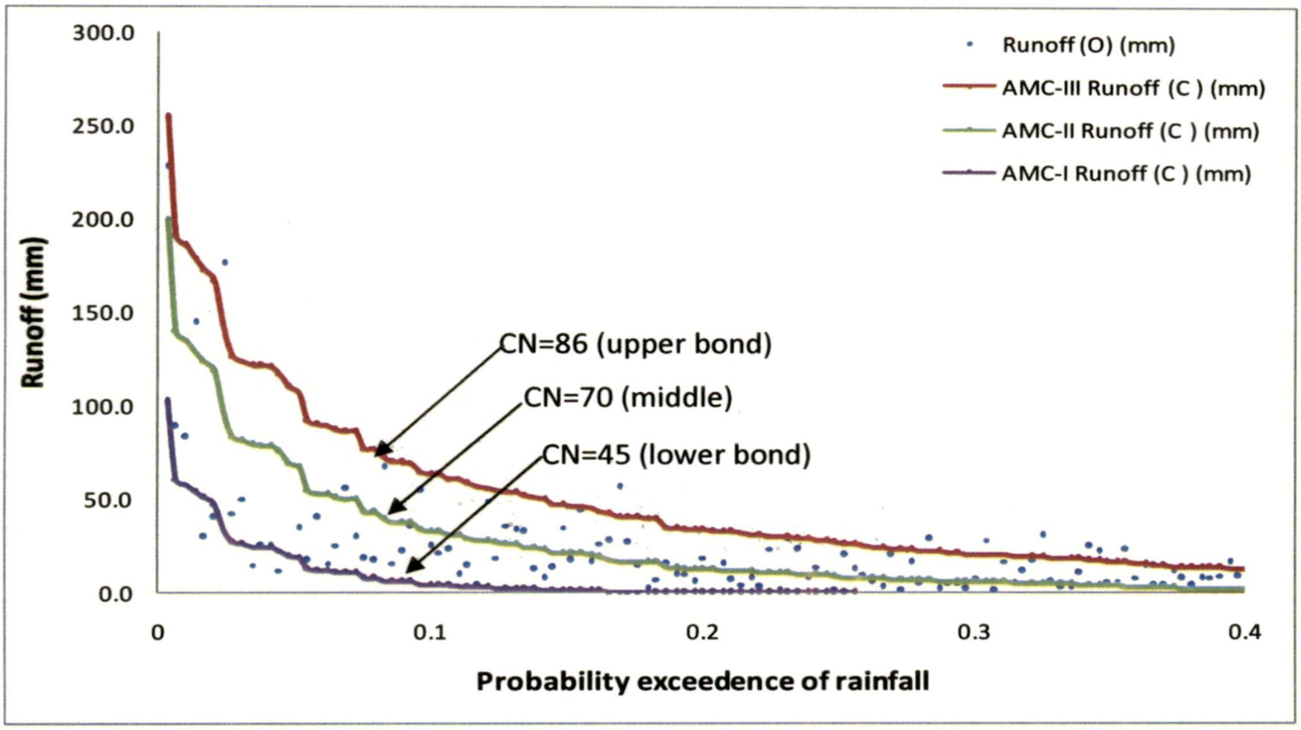


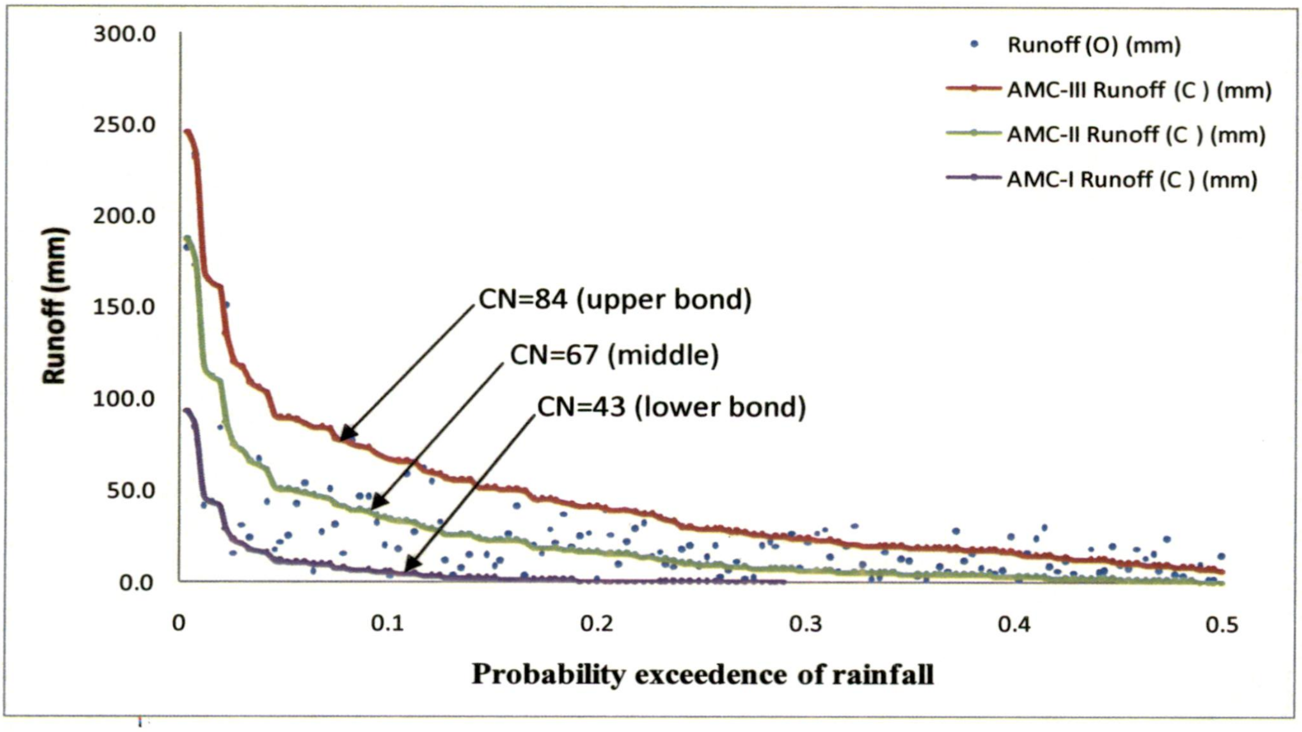
(b) 5-Daily duration analysis



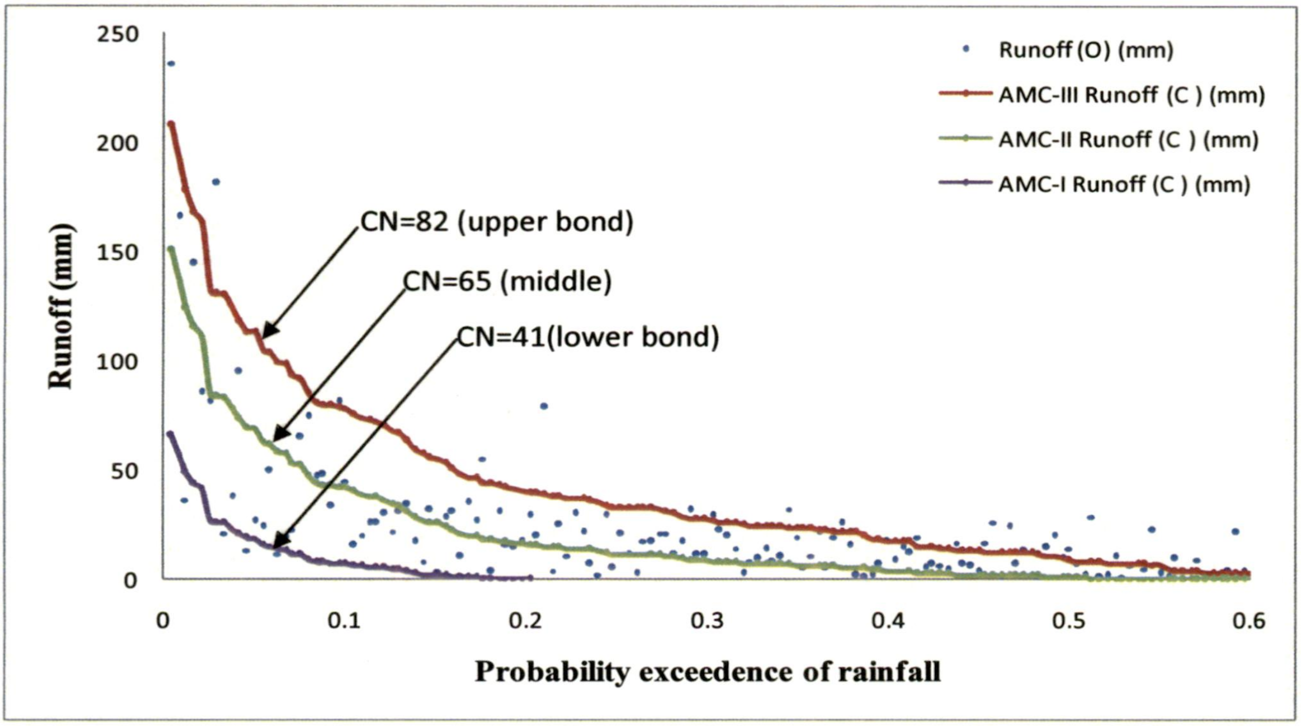
(c) 6-Daily duration analysis



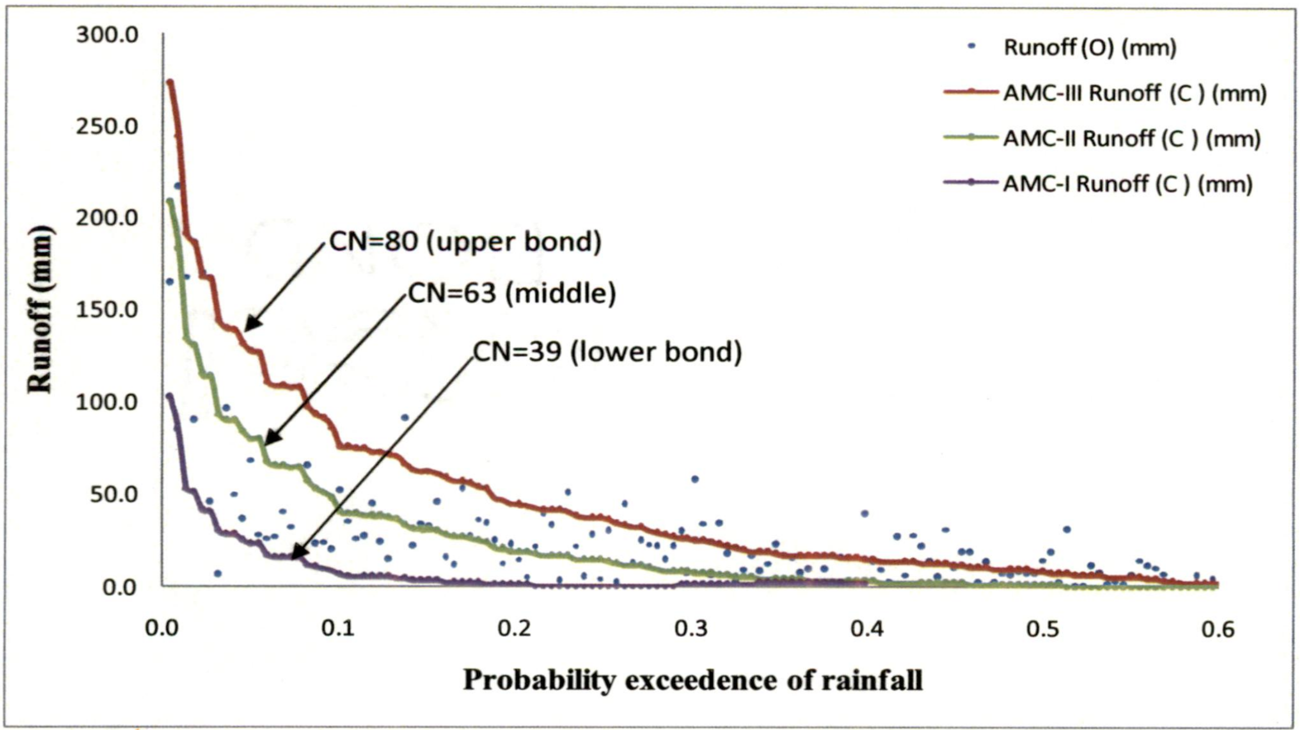
(d) 7-Daily duration analysis



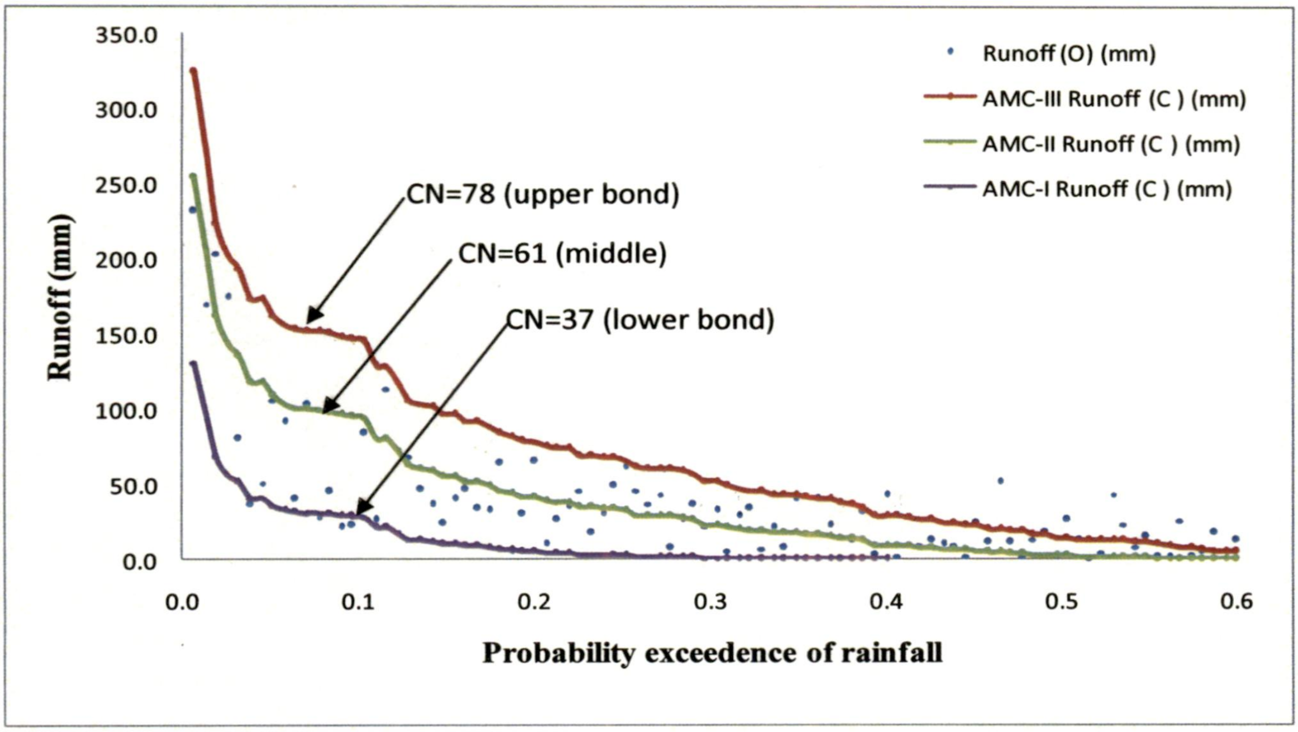
(e) 8-Daily duration analysis



(f) 9-Daily duration analysis



(g) 10-Daily duration analysis



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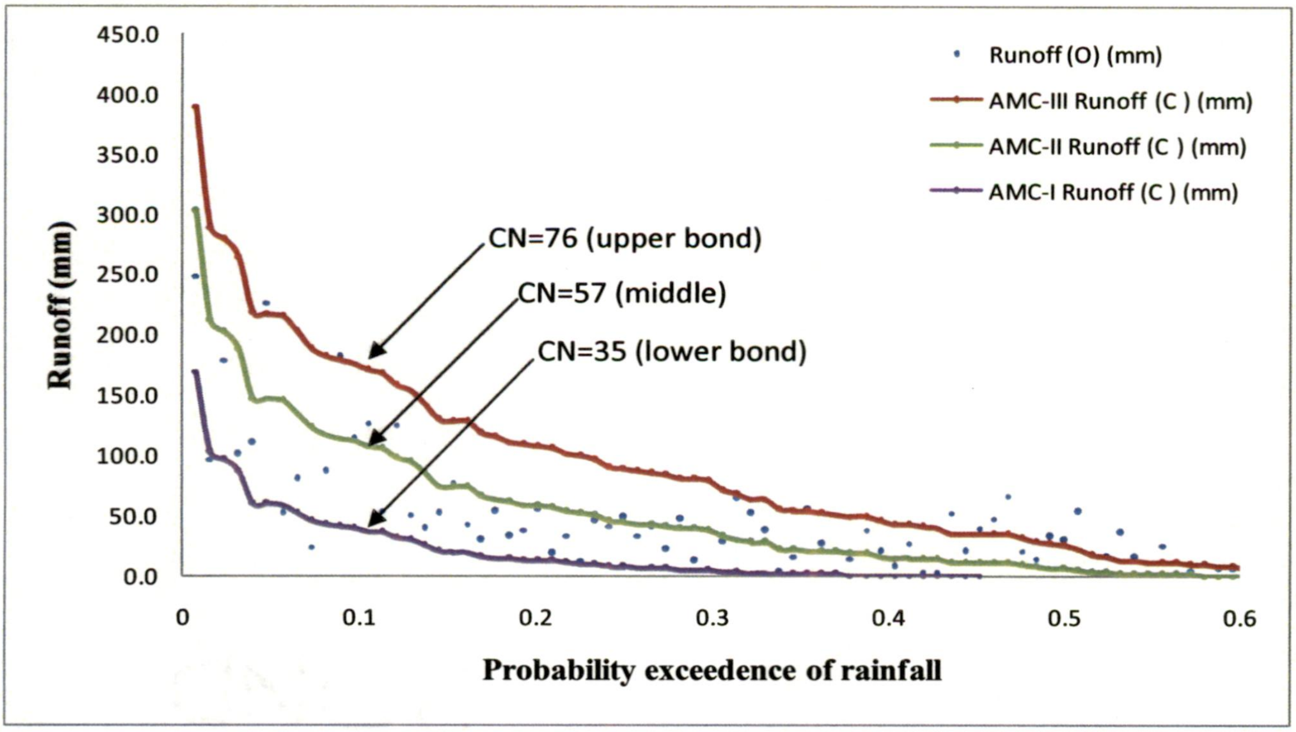
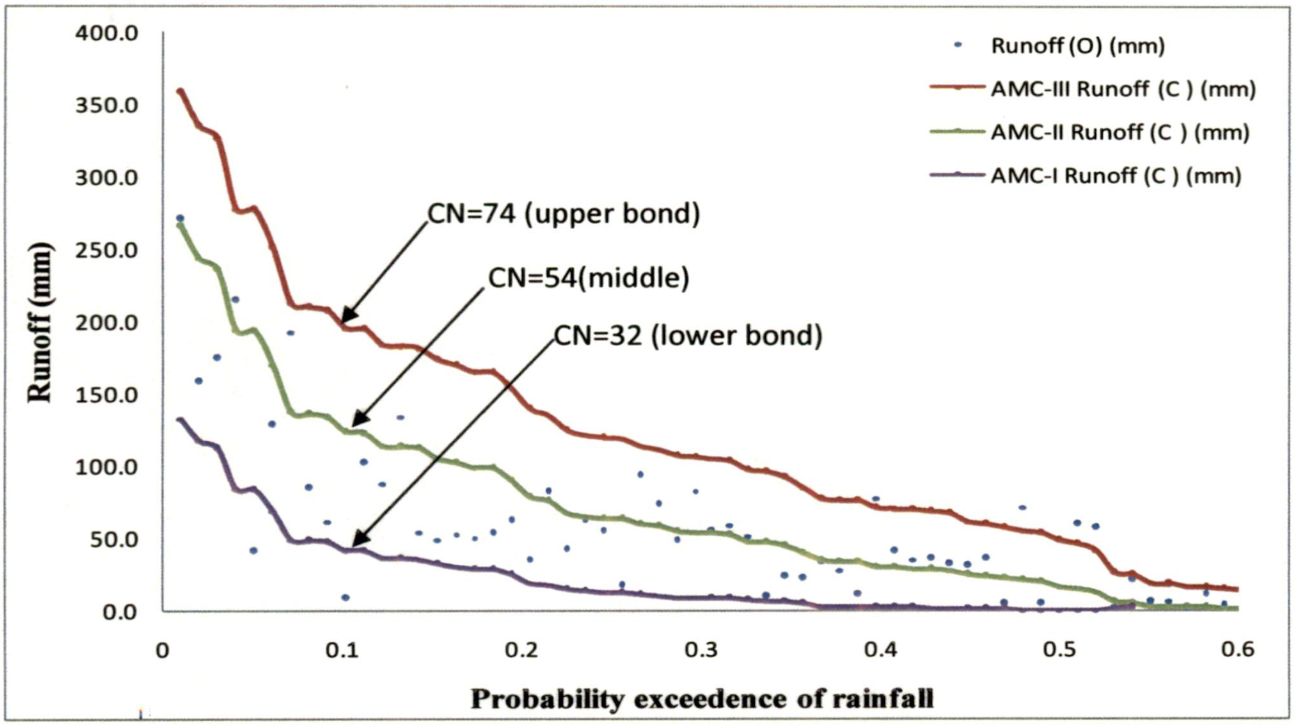
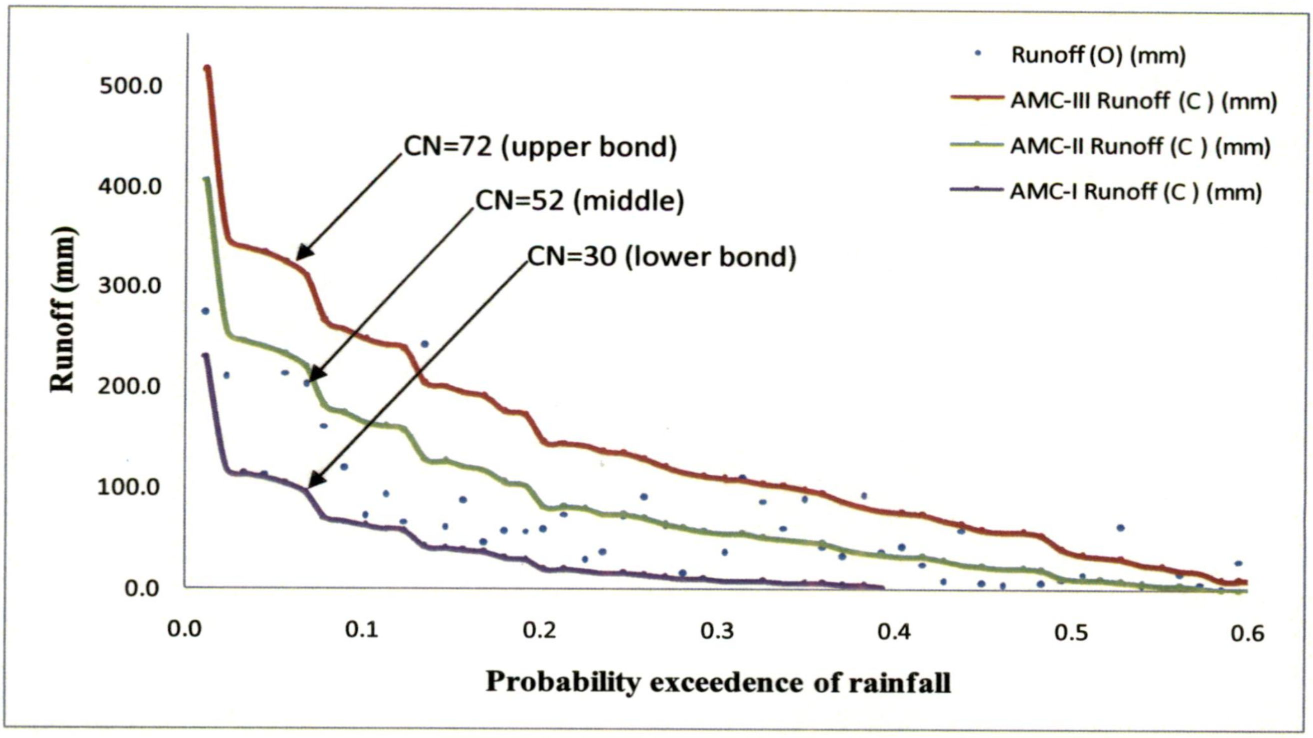


(i) 20-Daily duration analysis

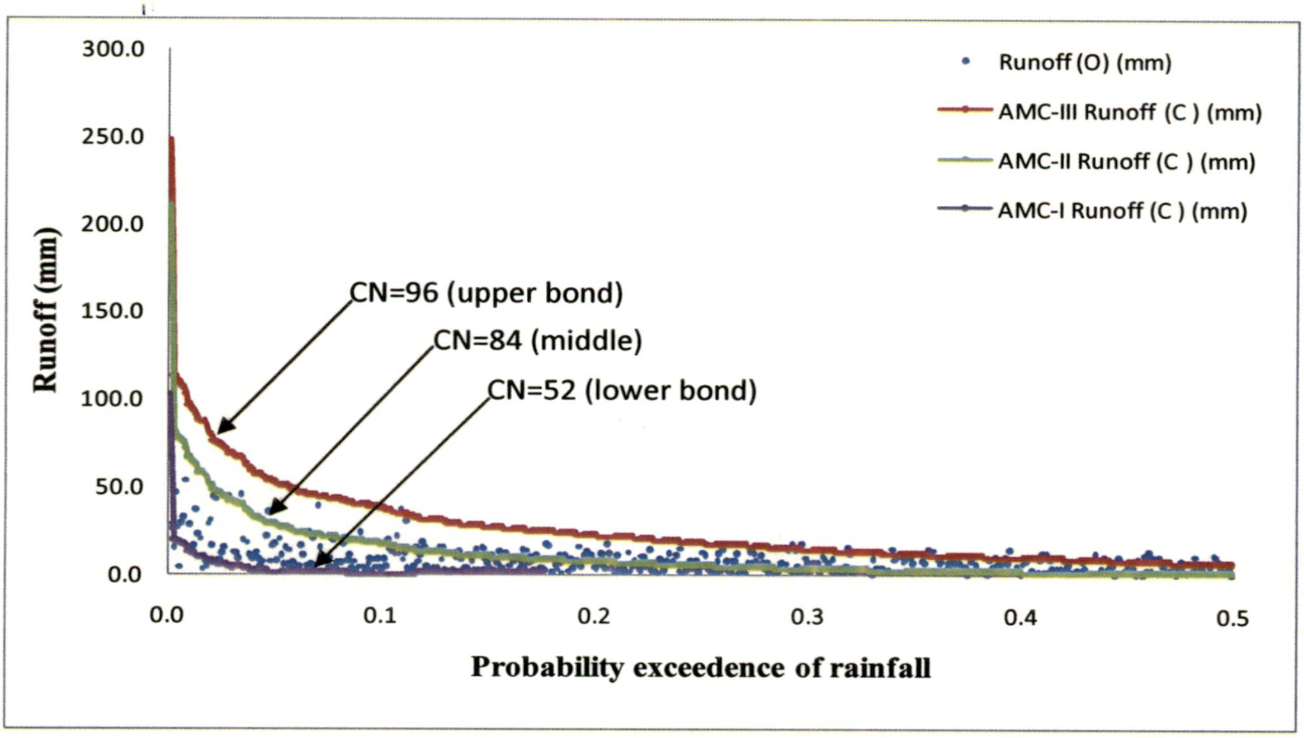


(j) 25-Daily duration analysis

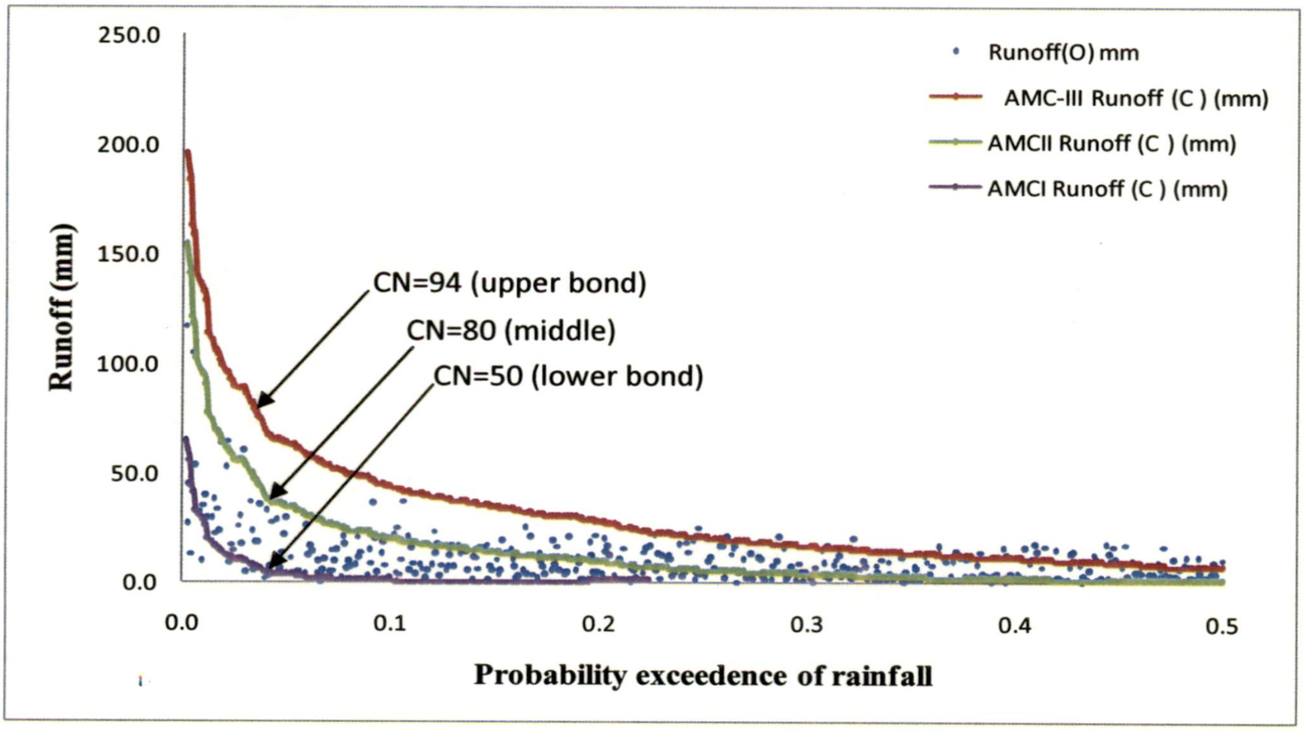


(k) 30-Daily duration analysis

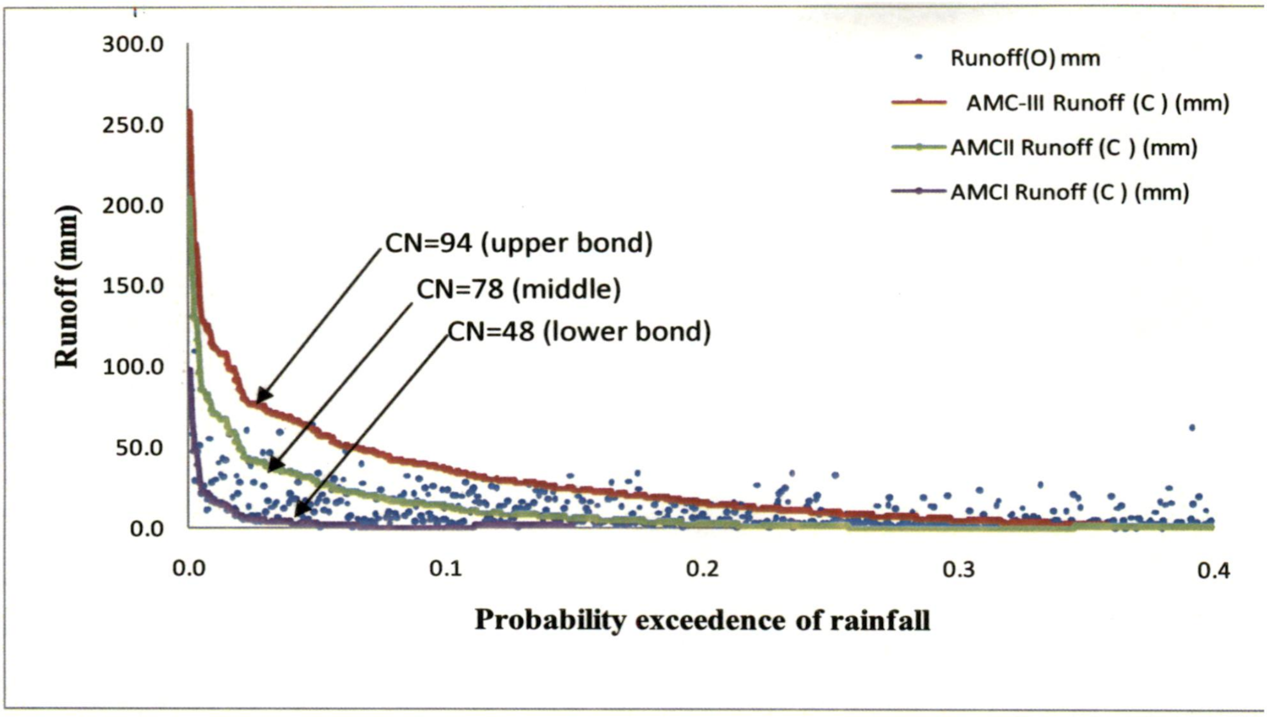
Figure I-1 Ordered different daily runoff data of Maithon catchment for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively and best-fit to AMC-II.



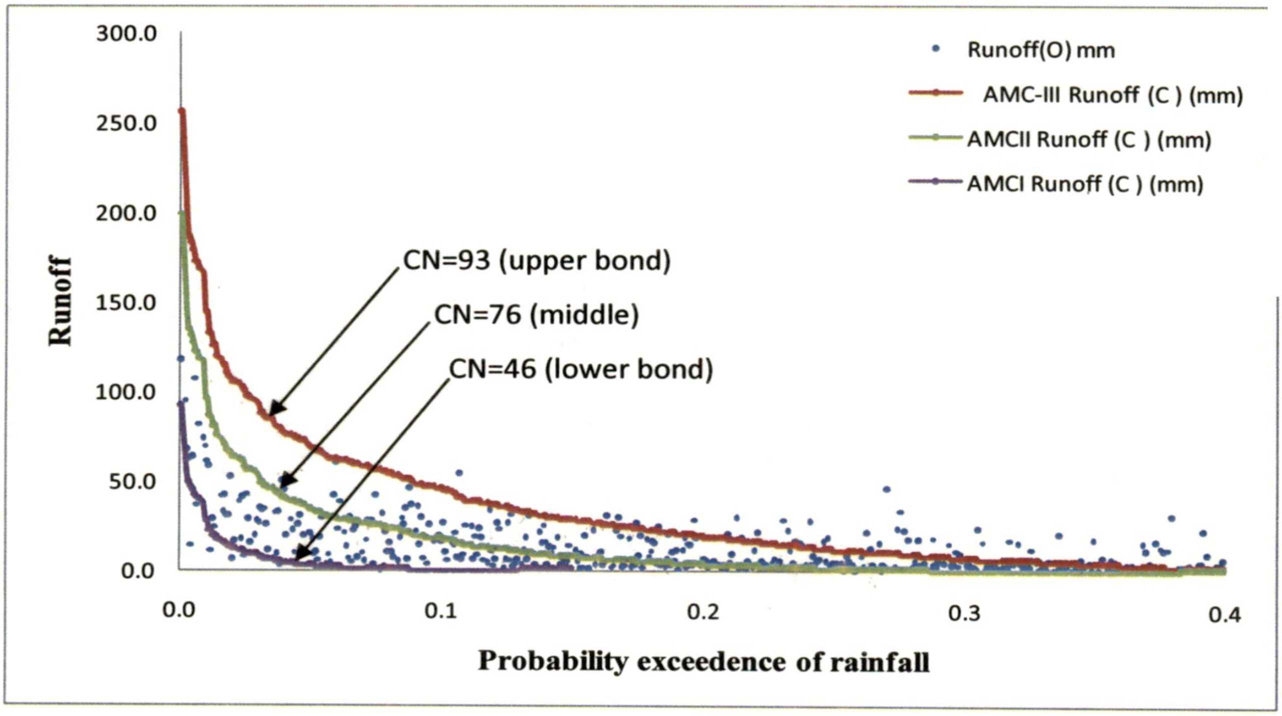
(a) 2-Daily duration analysis



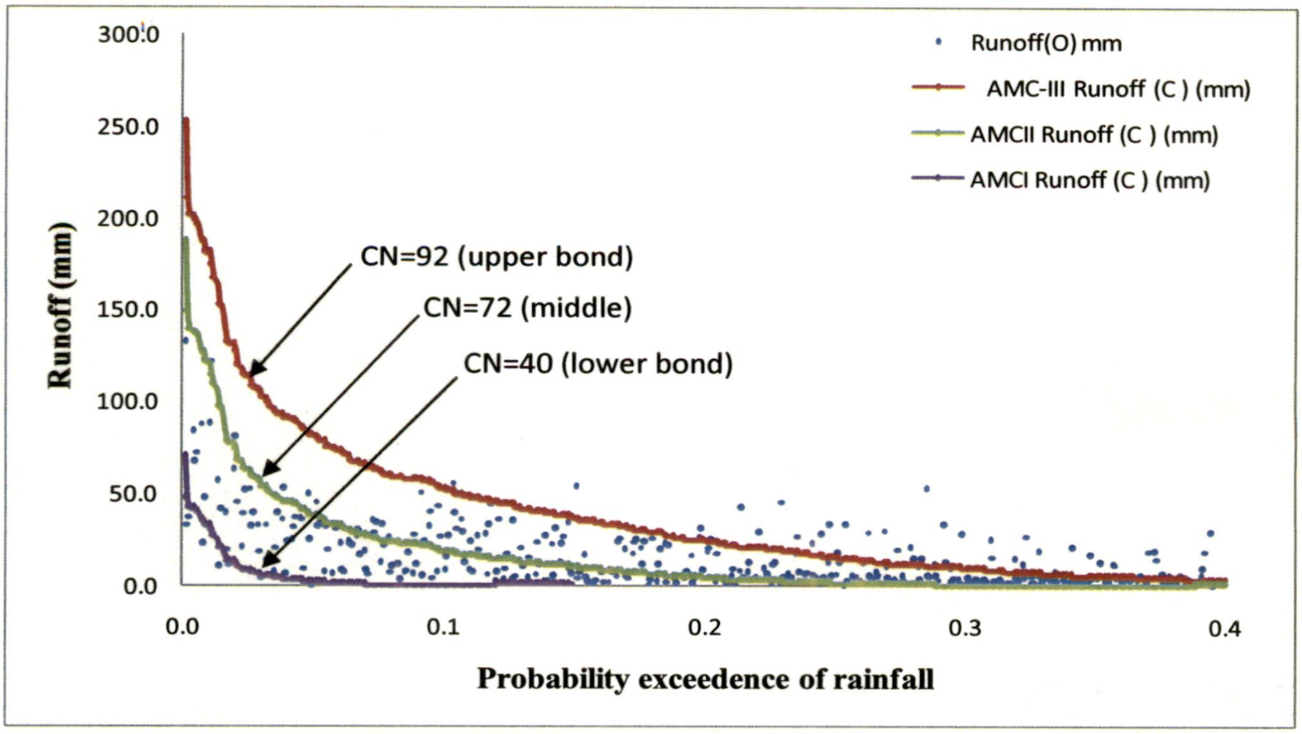
(b) 3-Daily duration analysis



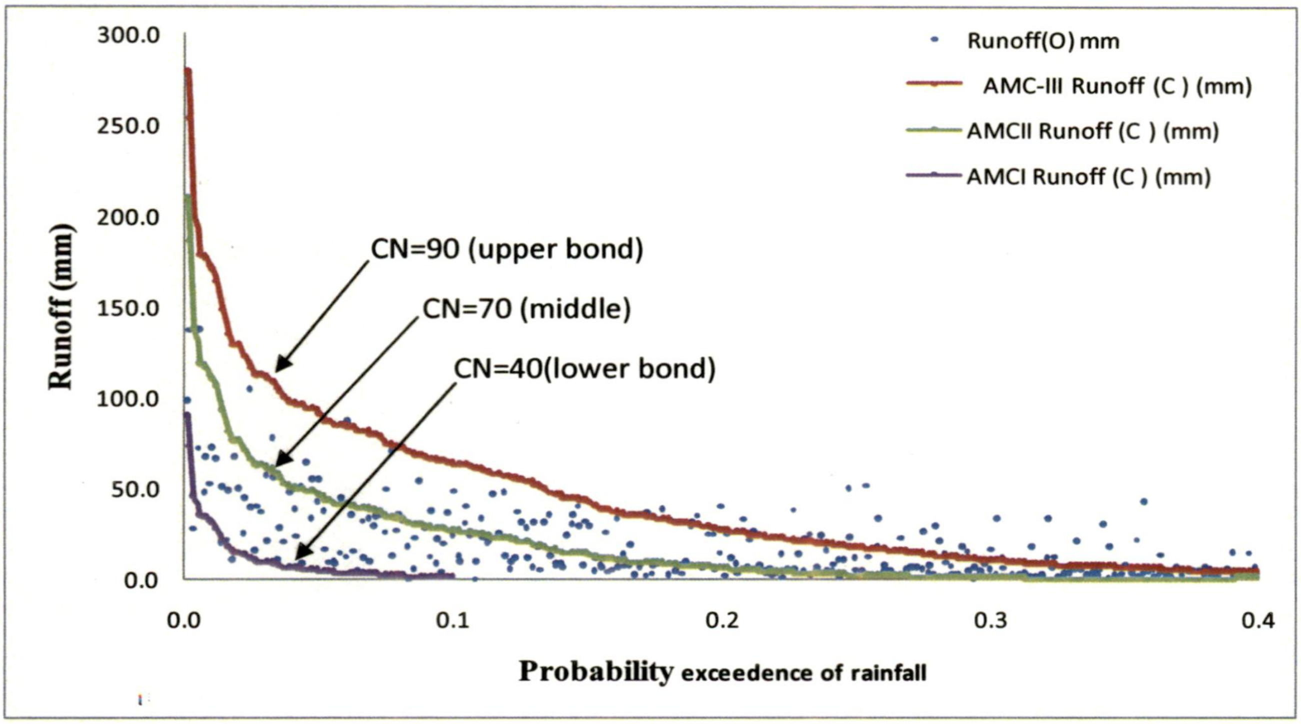
(c) 4-Daily duration analysis



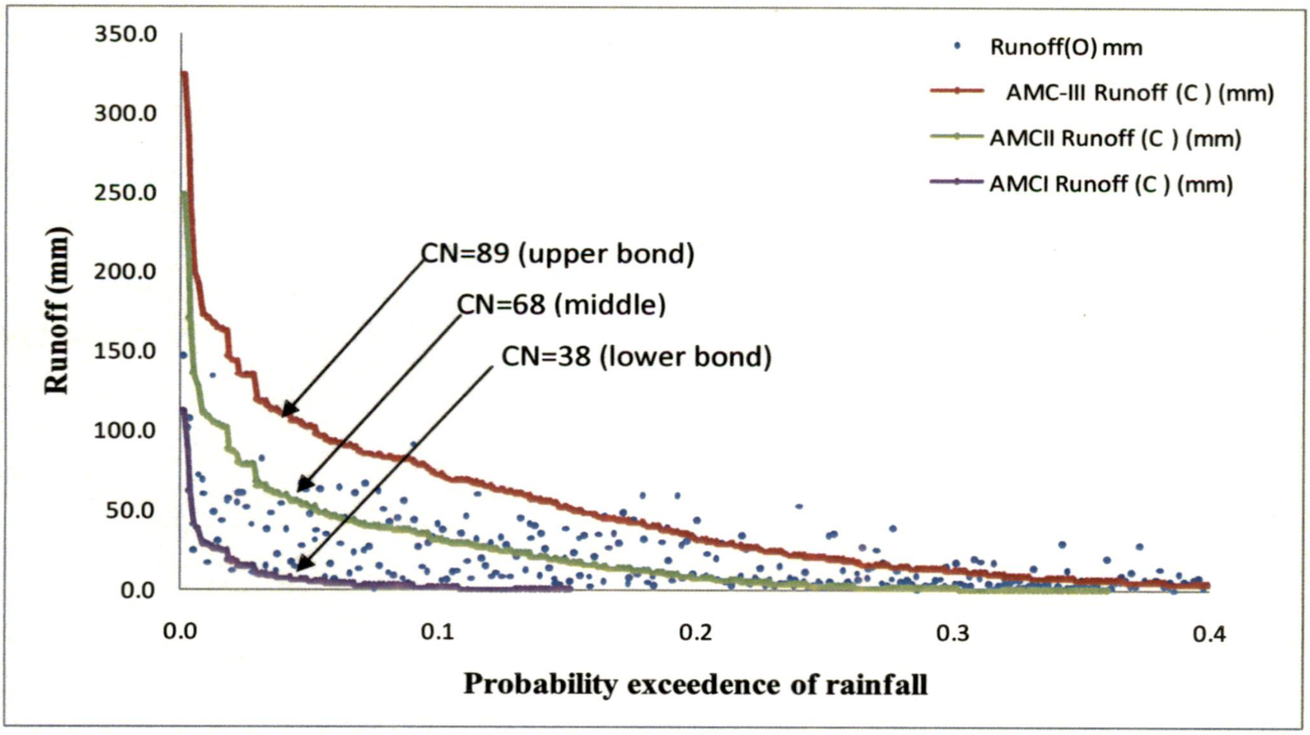
(d) 5-Daily duration analysis



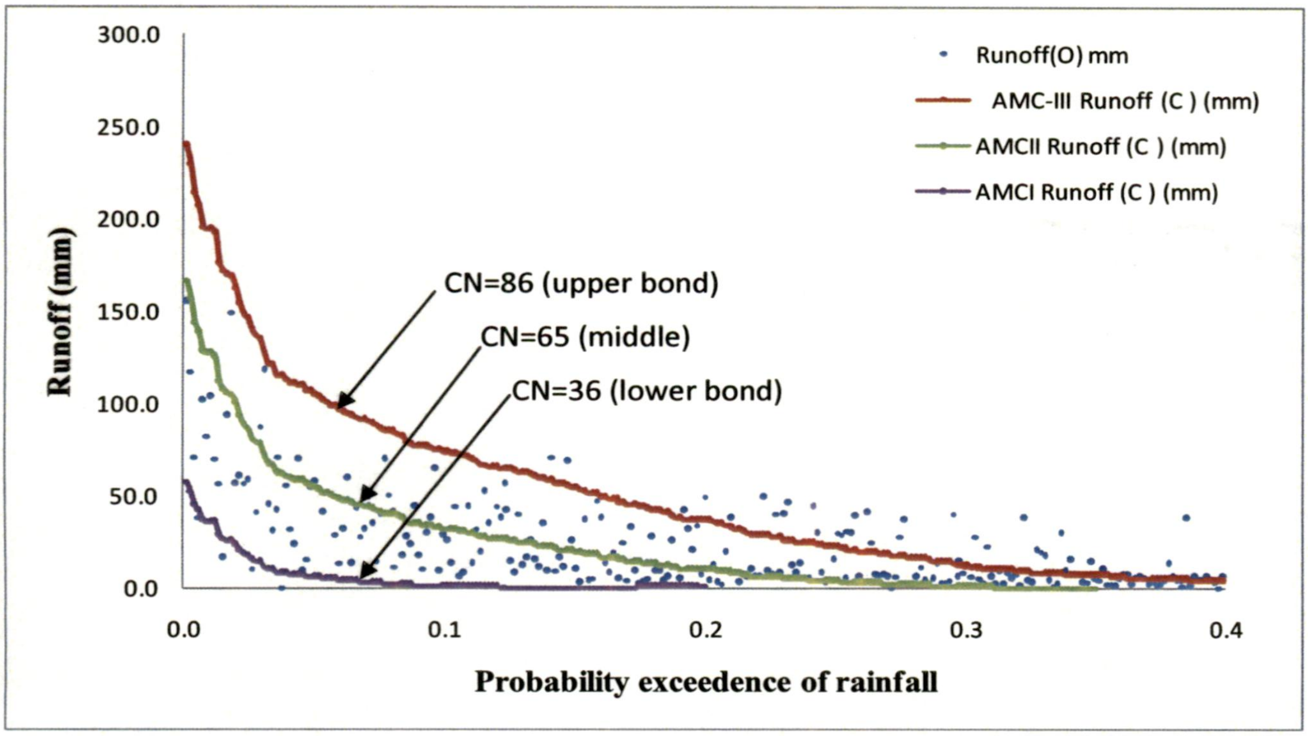
(e) 6-Daily duration analysis



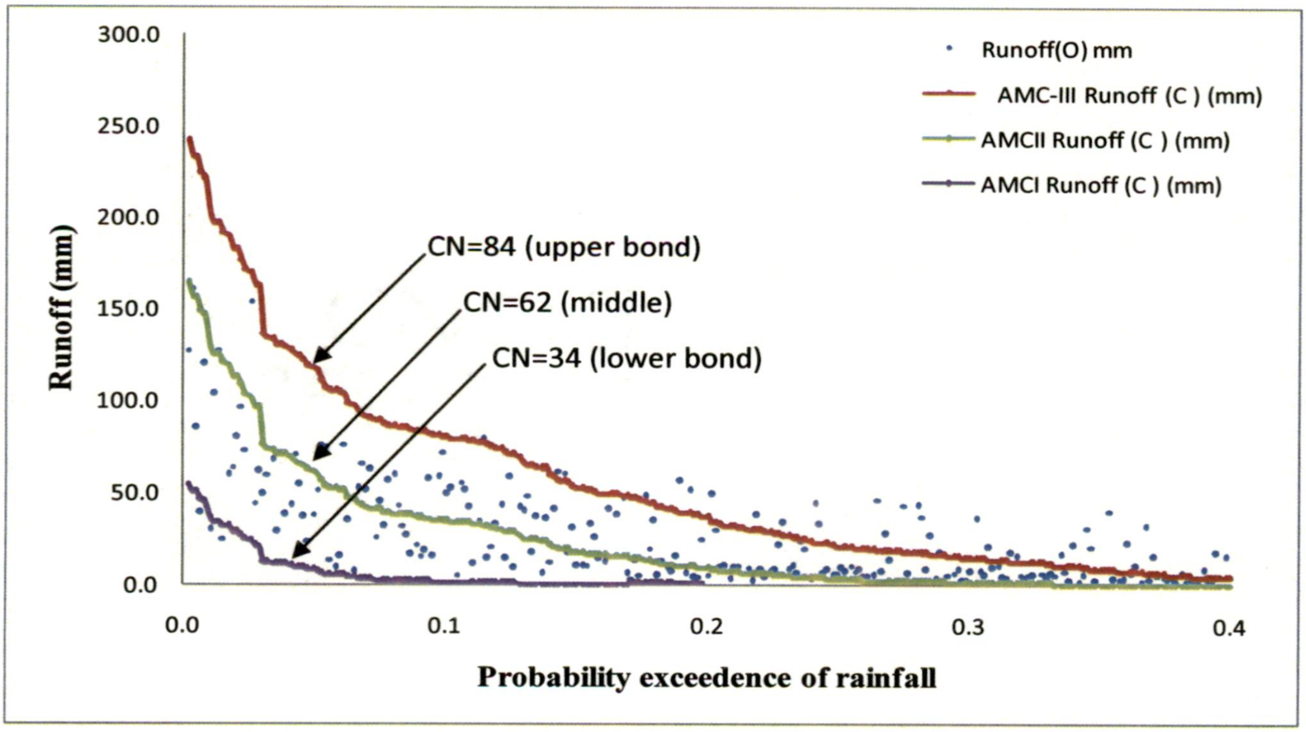
(f) 7-Daily duration analysis



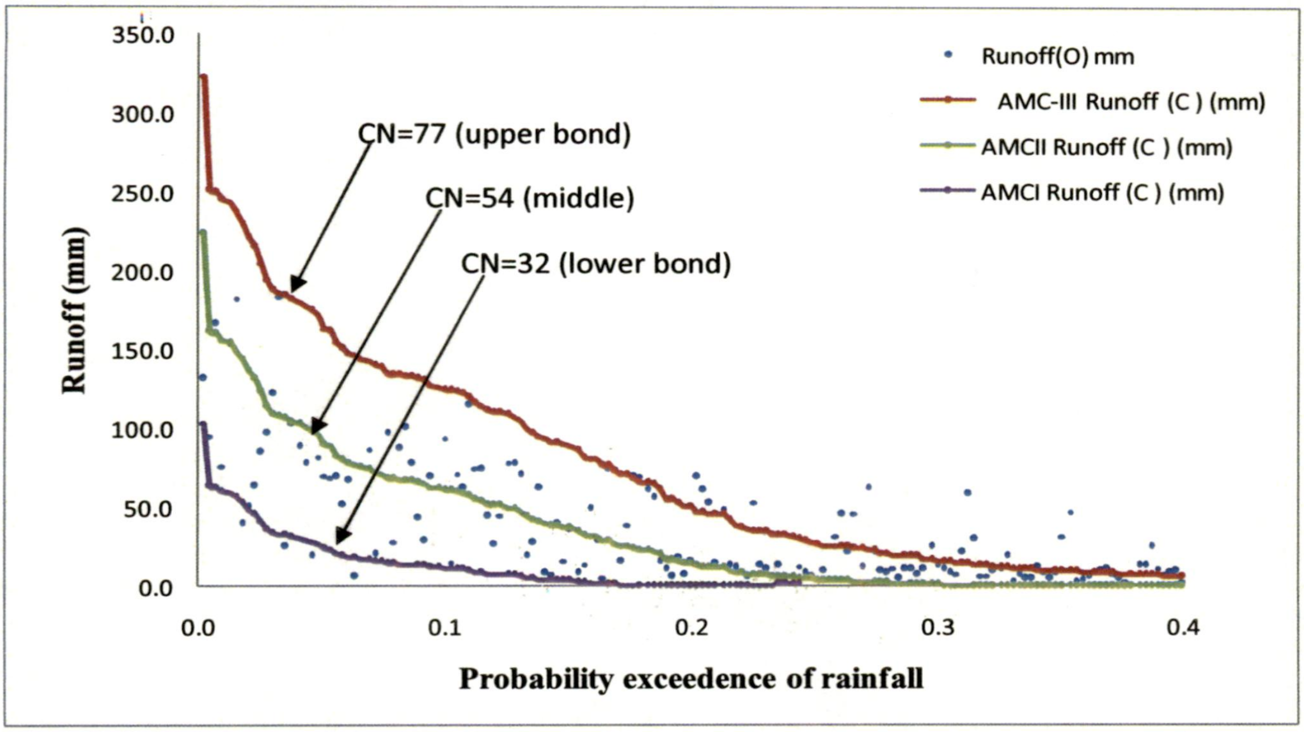
(g) 8-Daily duration analysis



(h) 9-Daily duration analysis



(i) 10-Daily duration analysis



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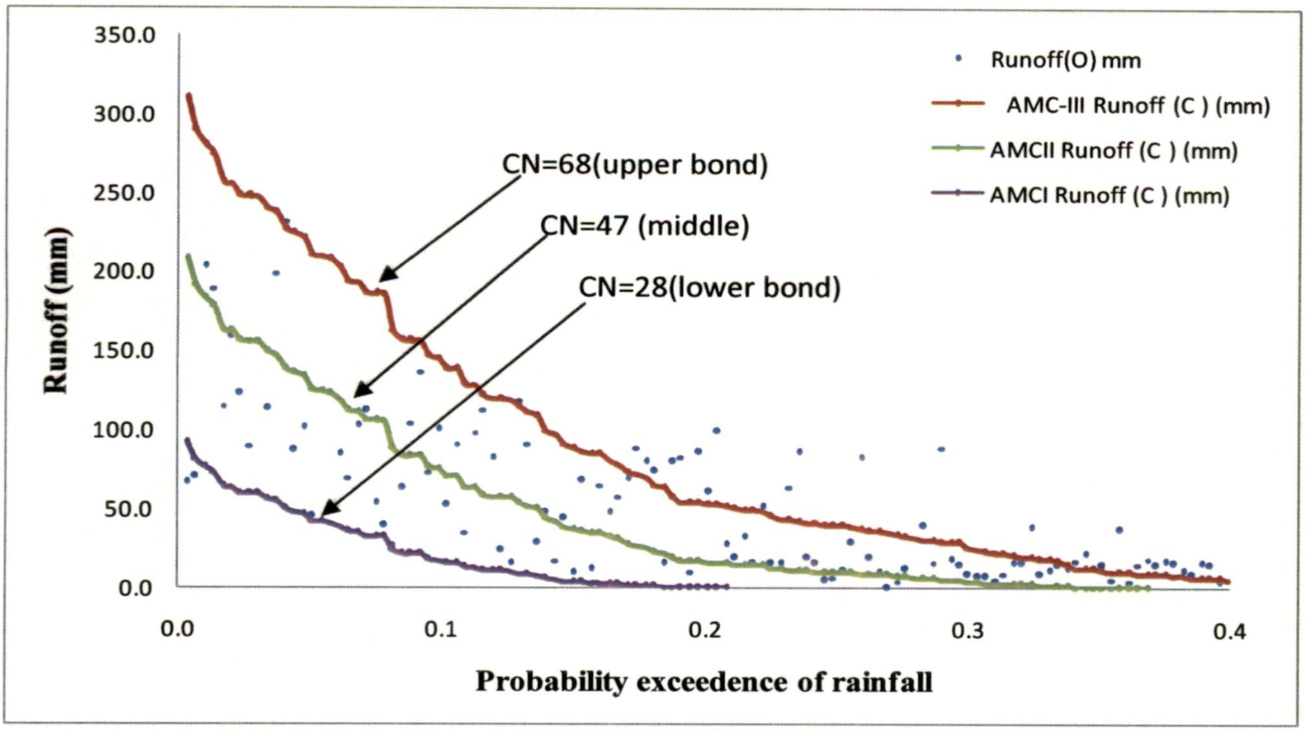

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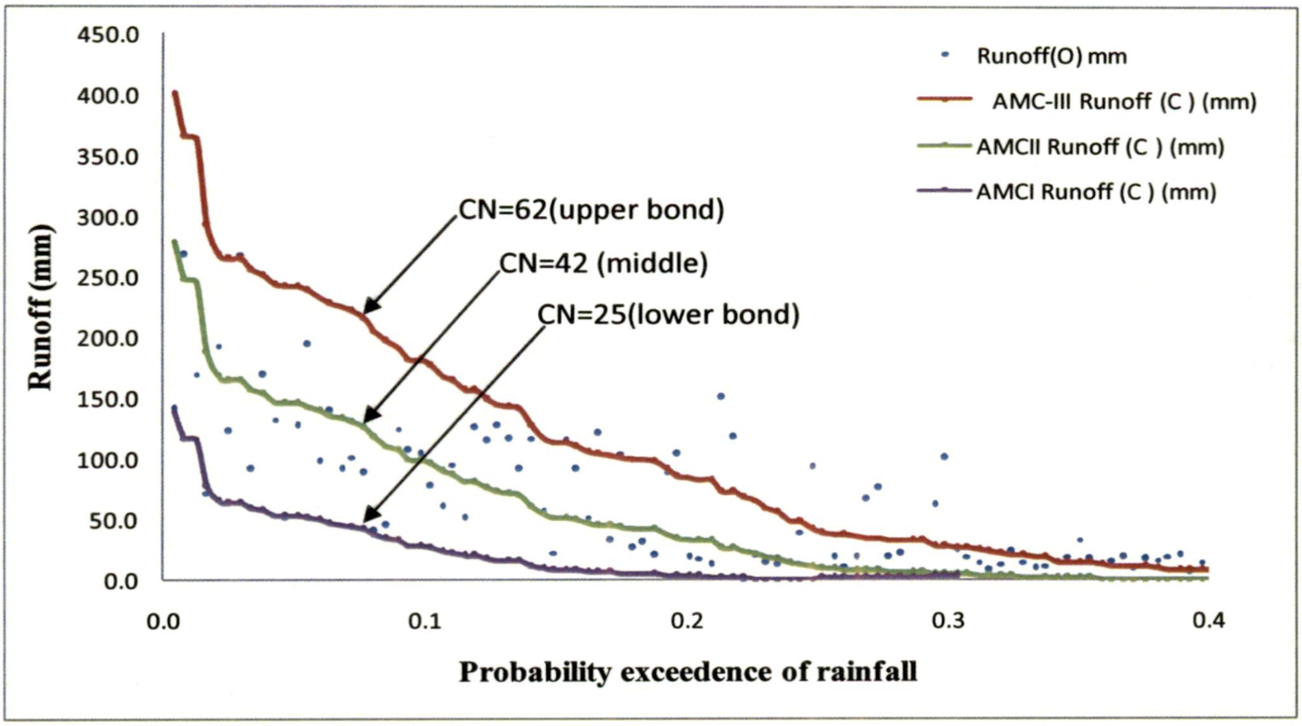

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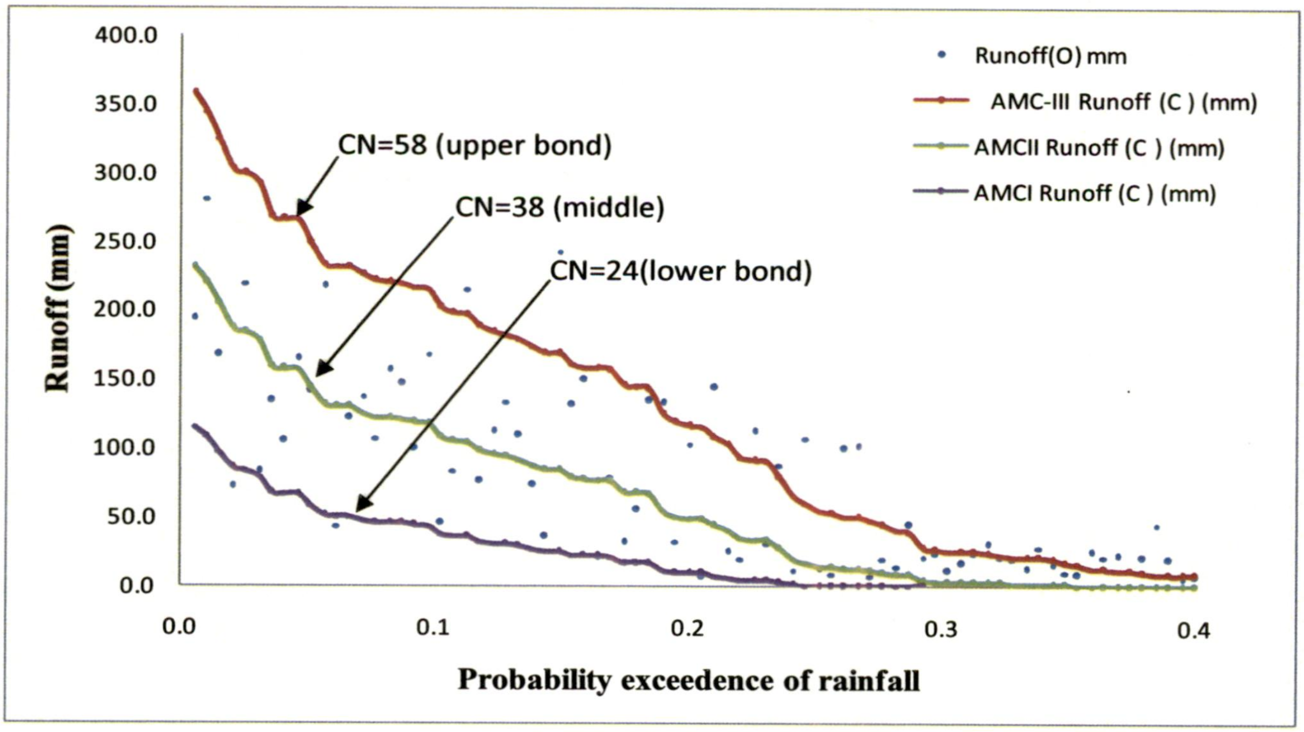
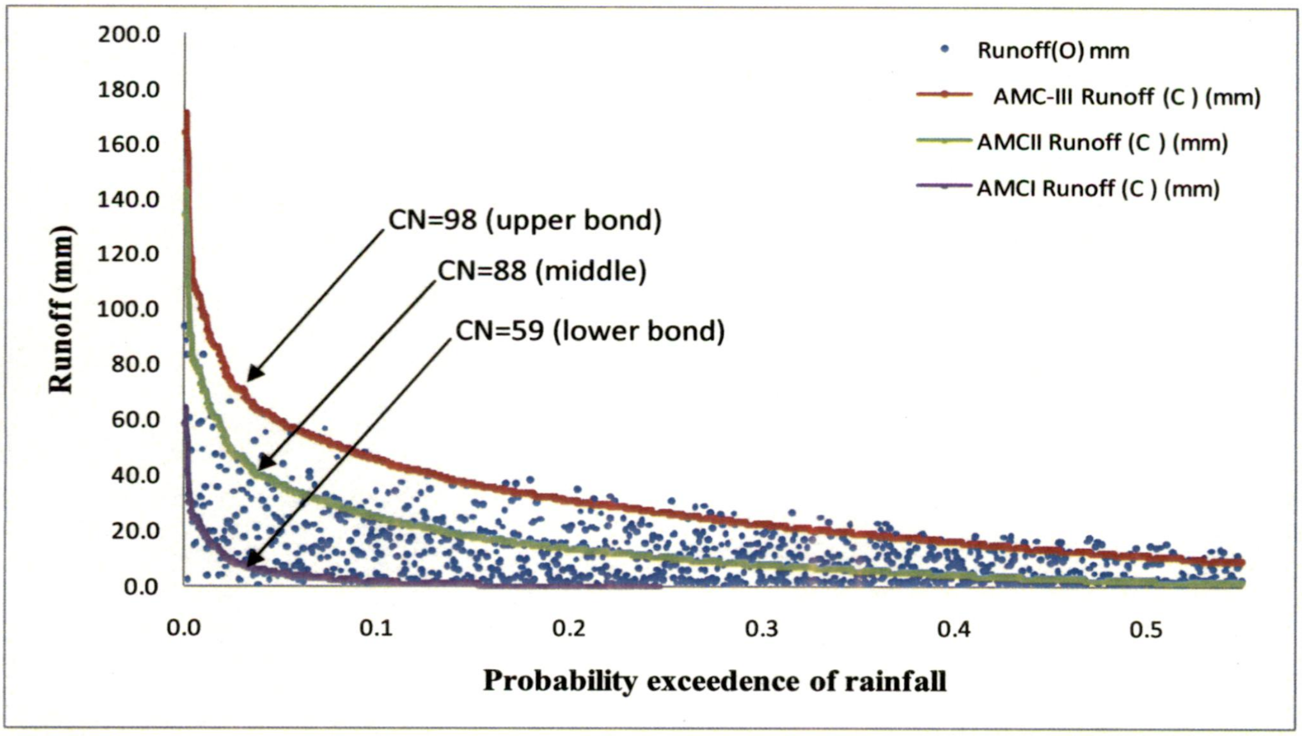
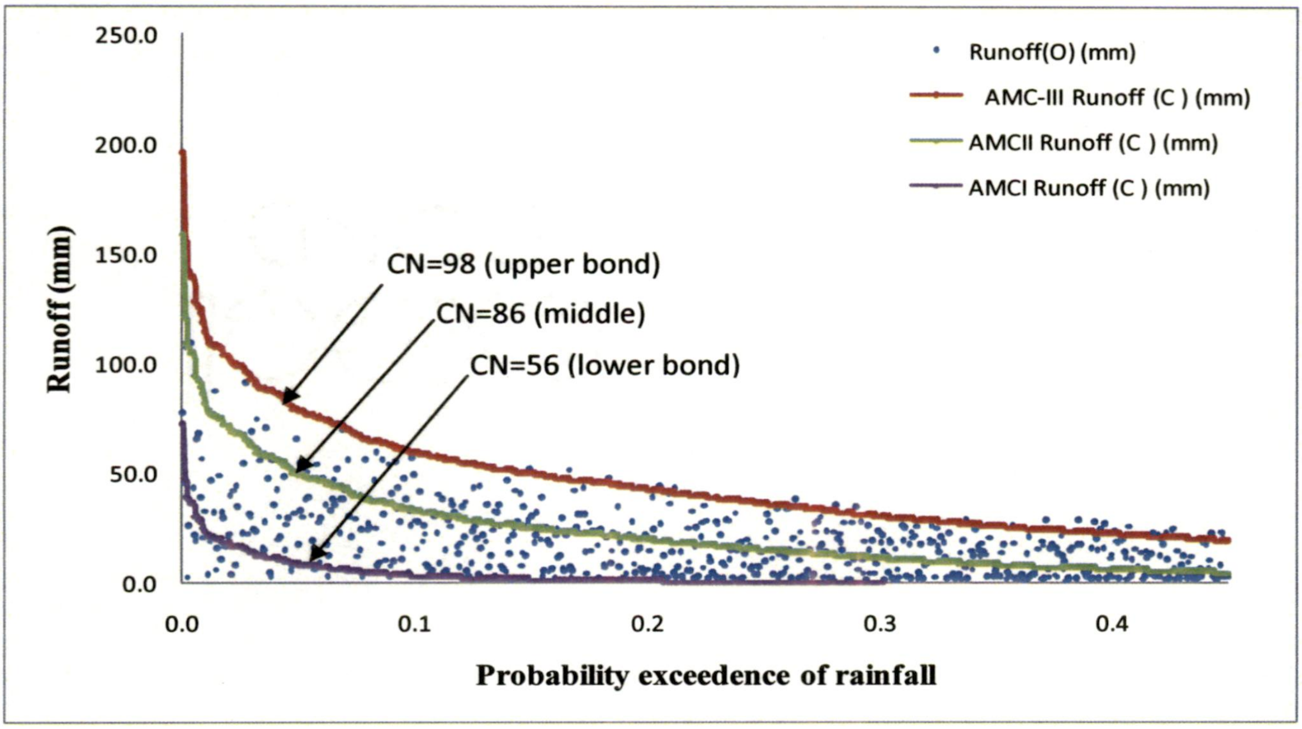


(m) 30-Daily duration analysis

Figure I-2 Ordered different daily runoff data of Ramganga catchment for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively and best-fit to AMC-II.



(a) 2-Daily duration analysis



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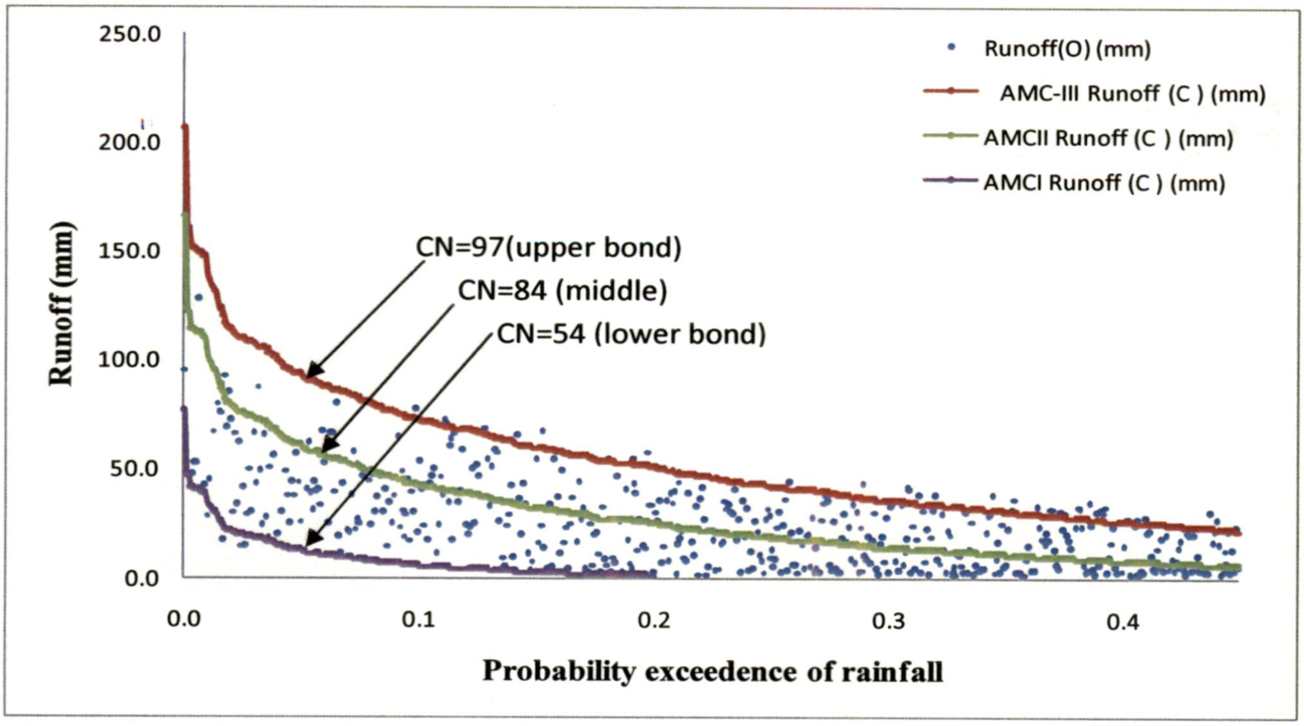
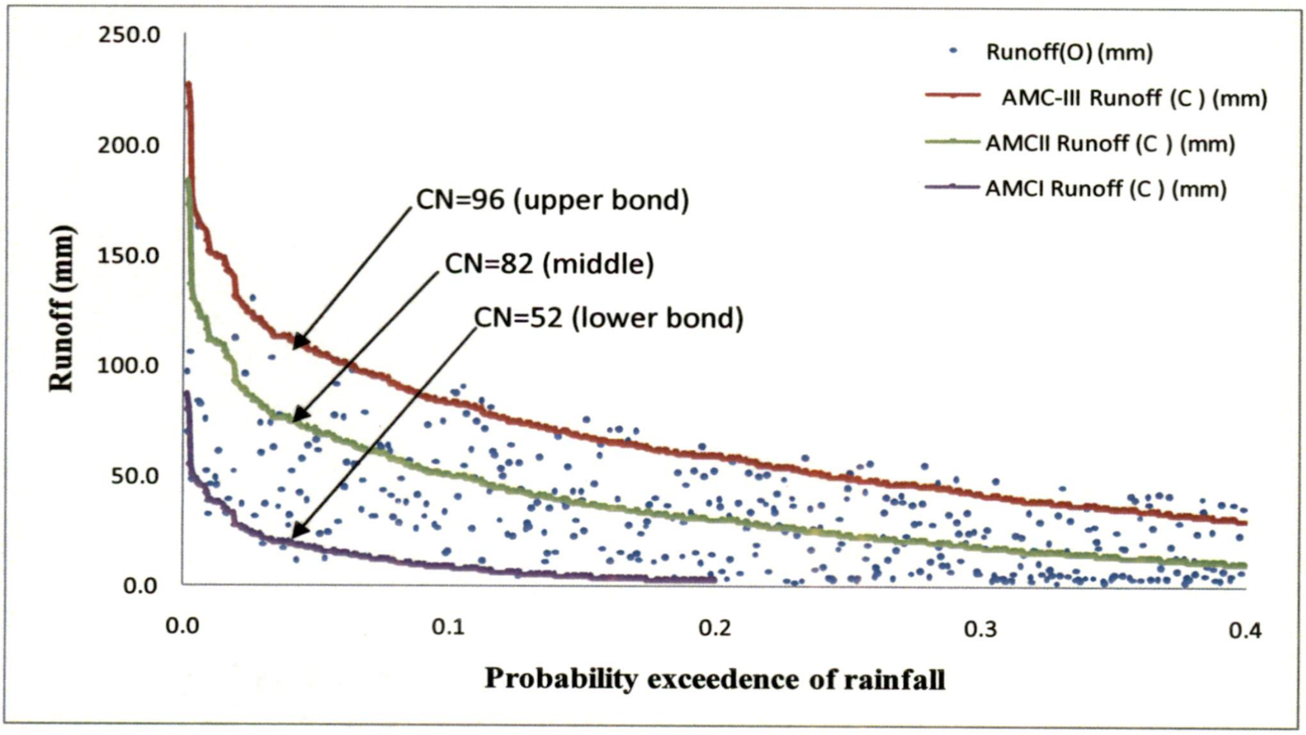


(c) 4-Daily duration analysis



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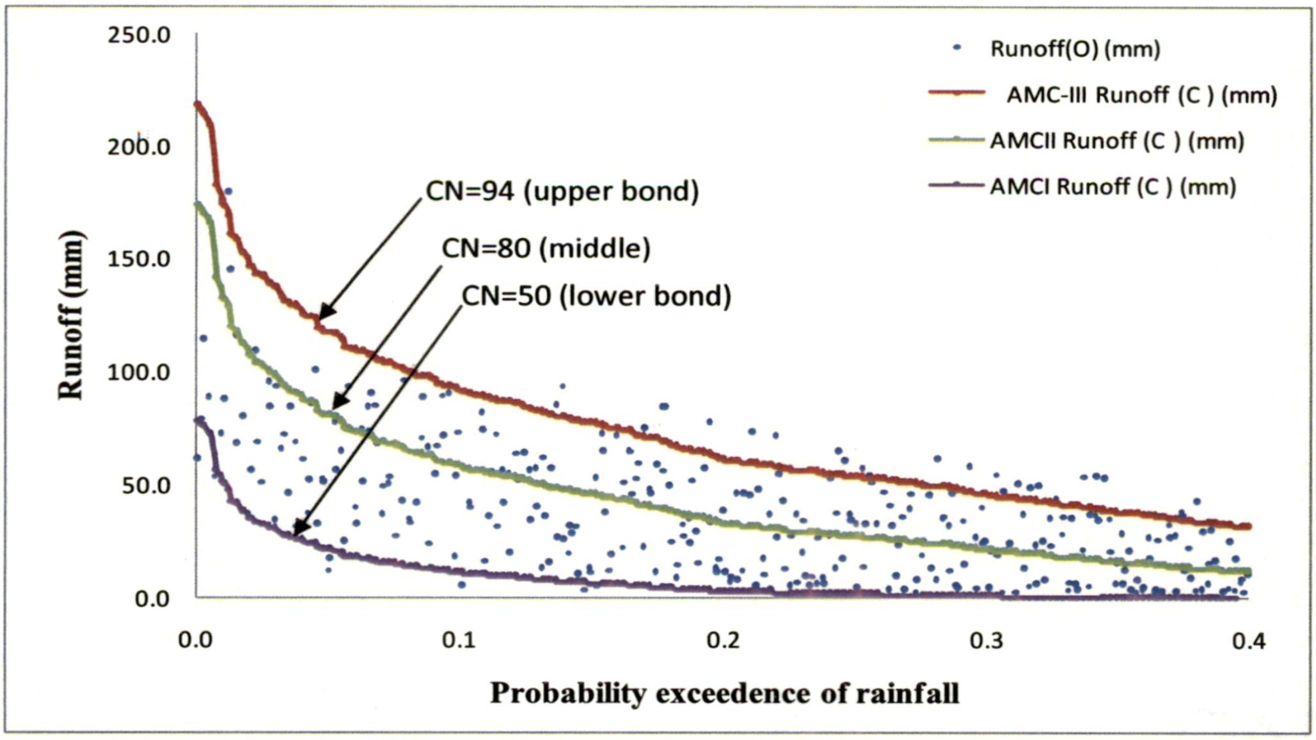

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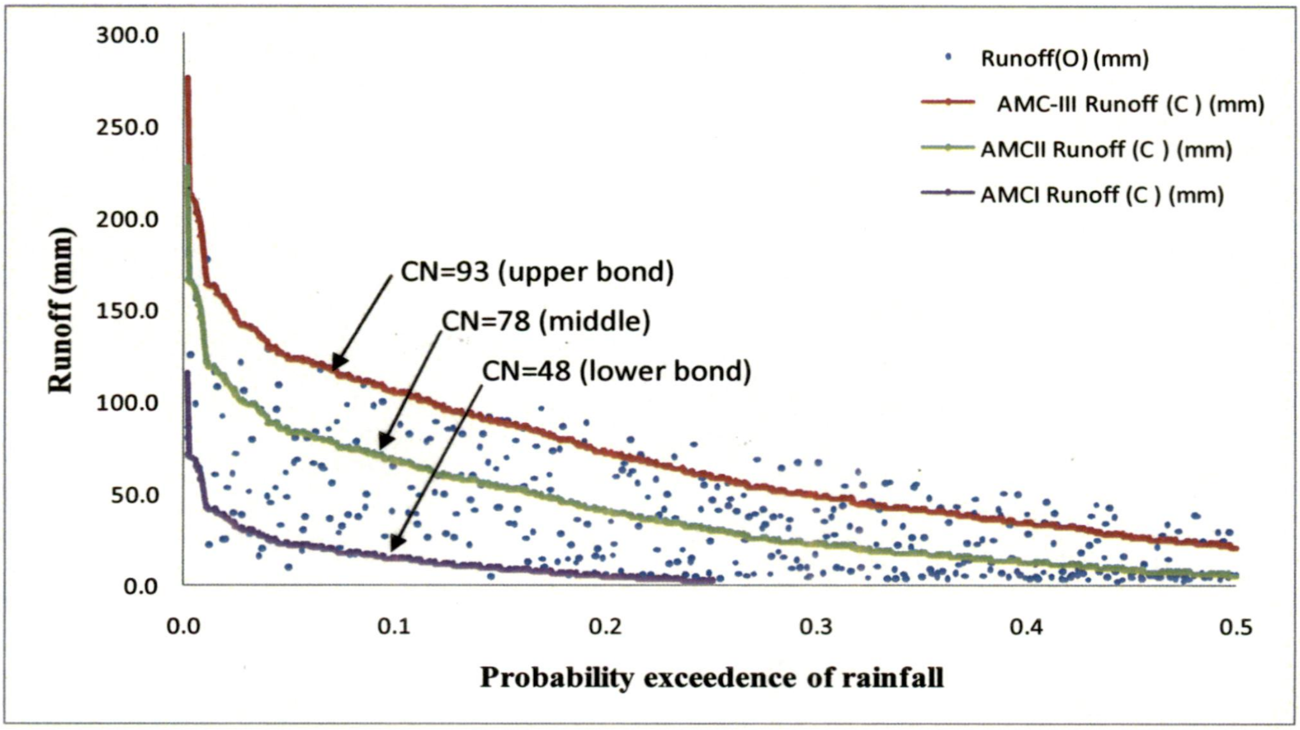
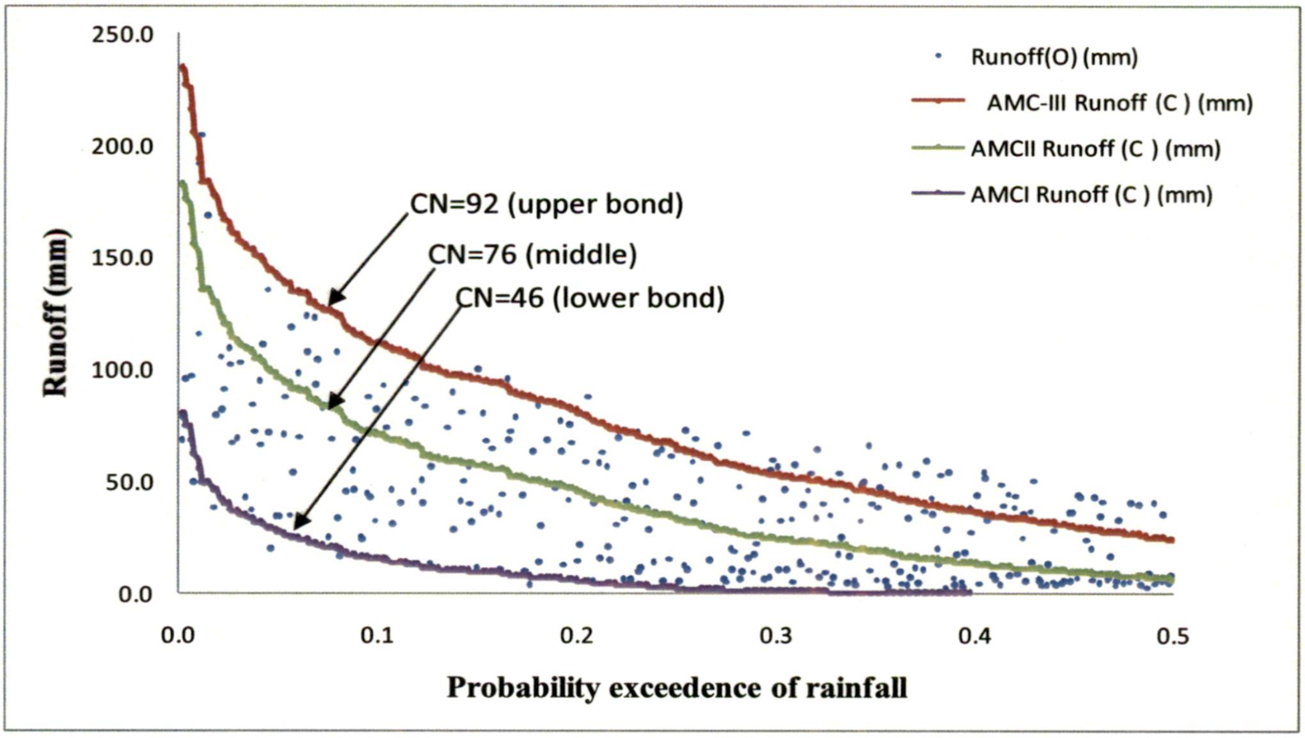
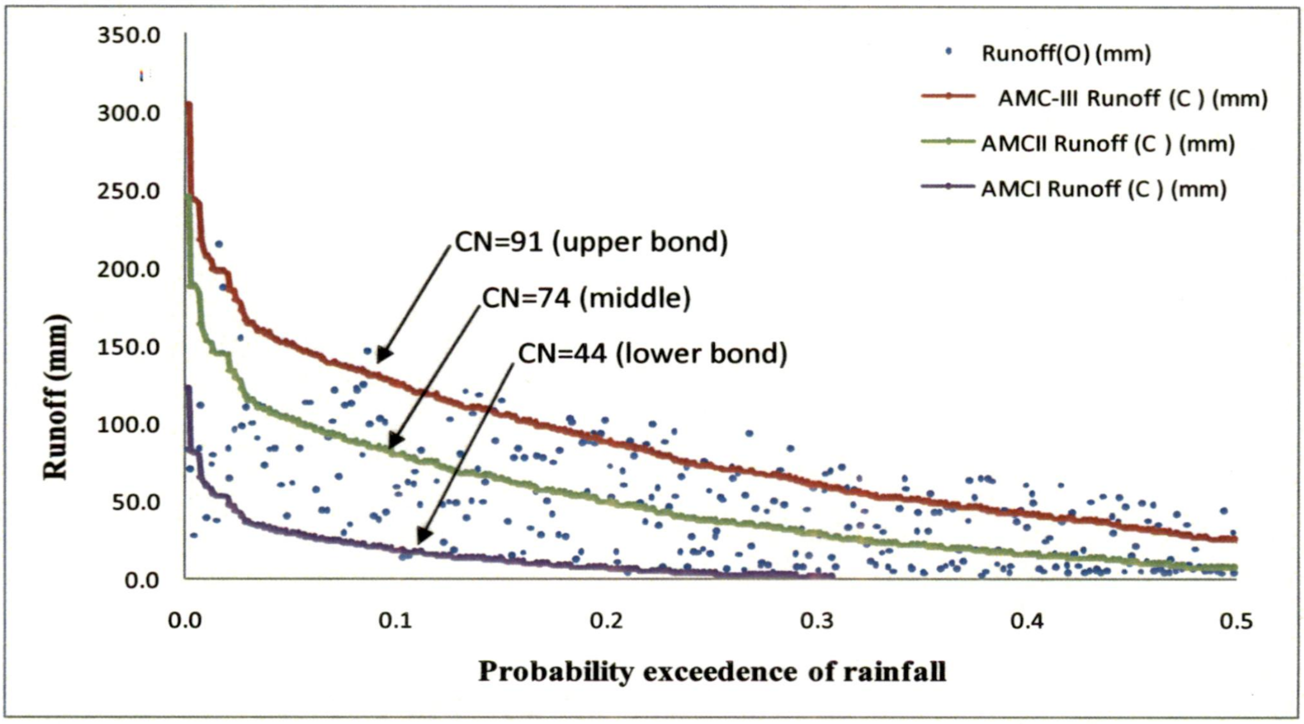


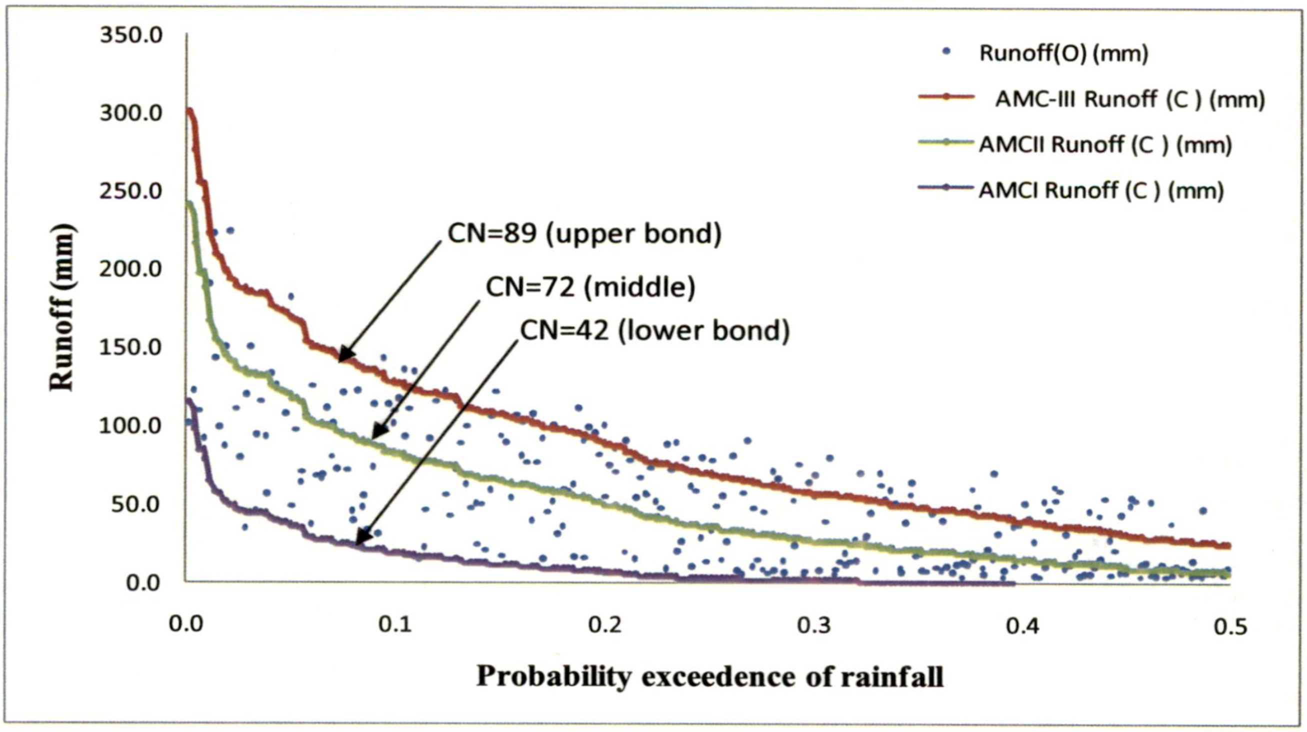
(f) 7-Daily duration analysis



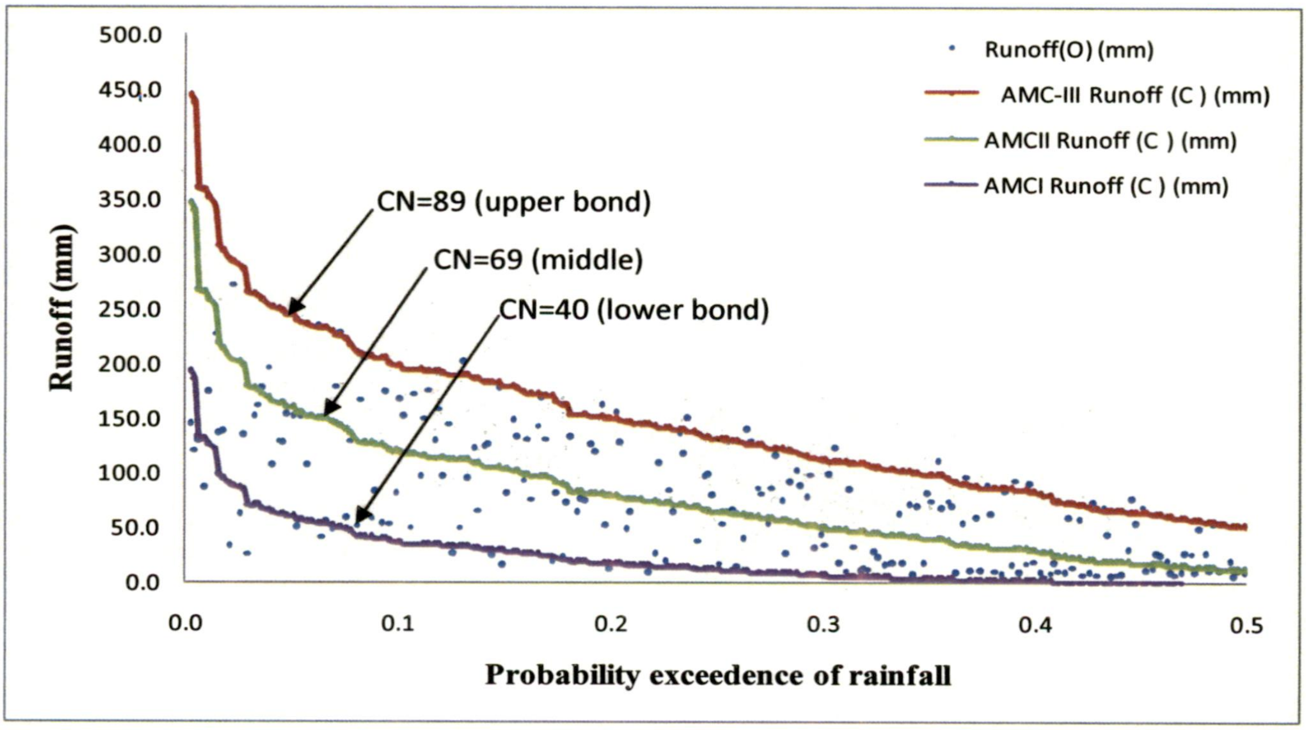
(g) 8-Daily duration analysis



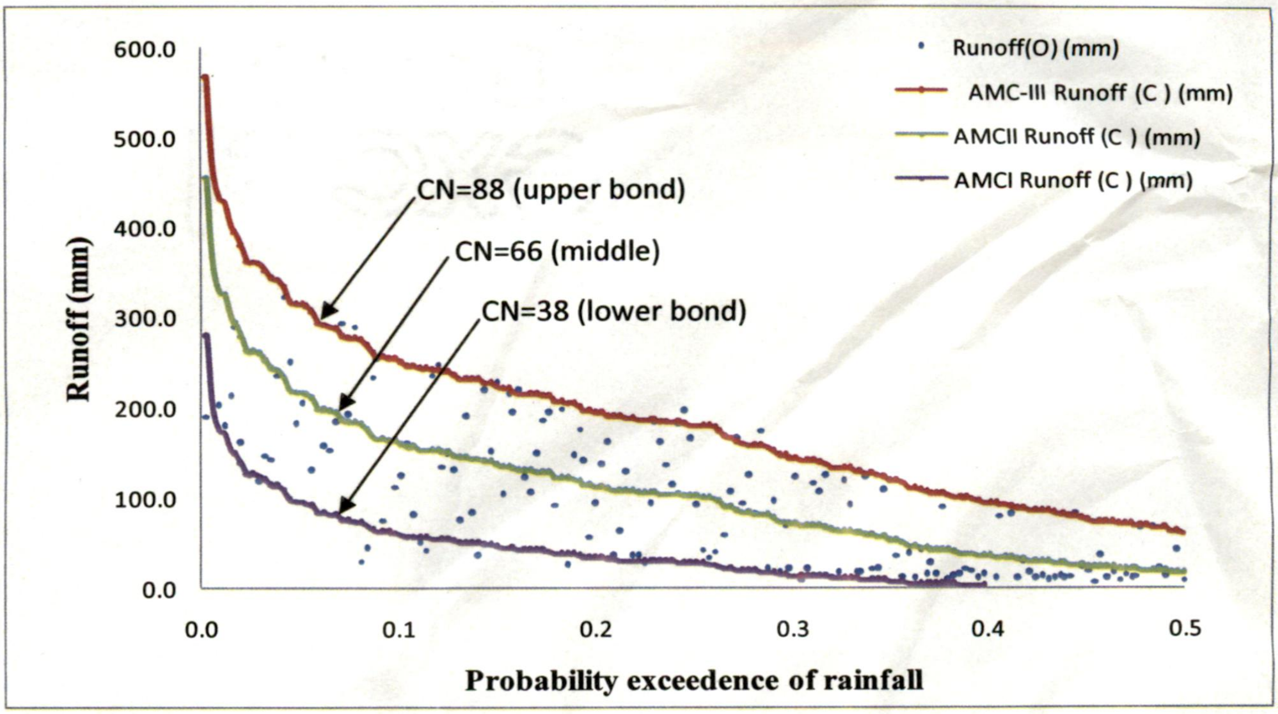
(h) 9-Daily duration analysis



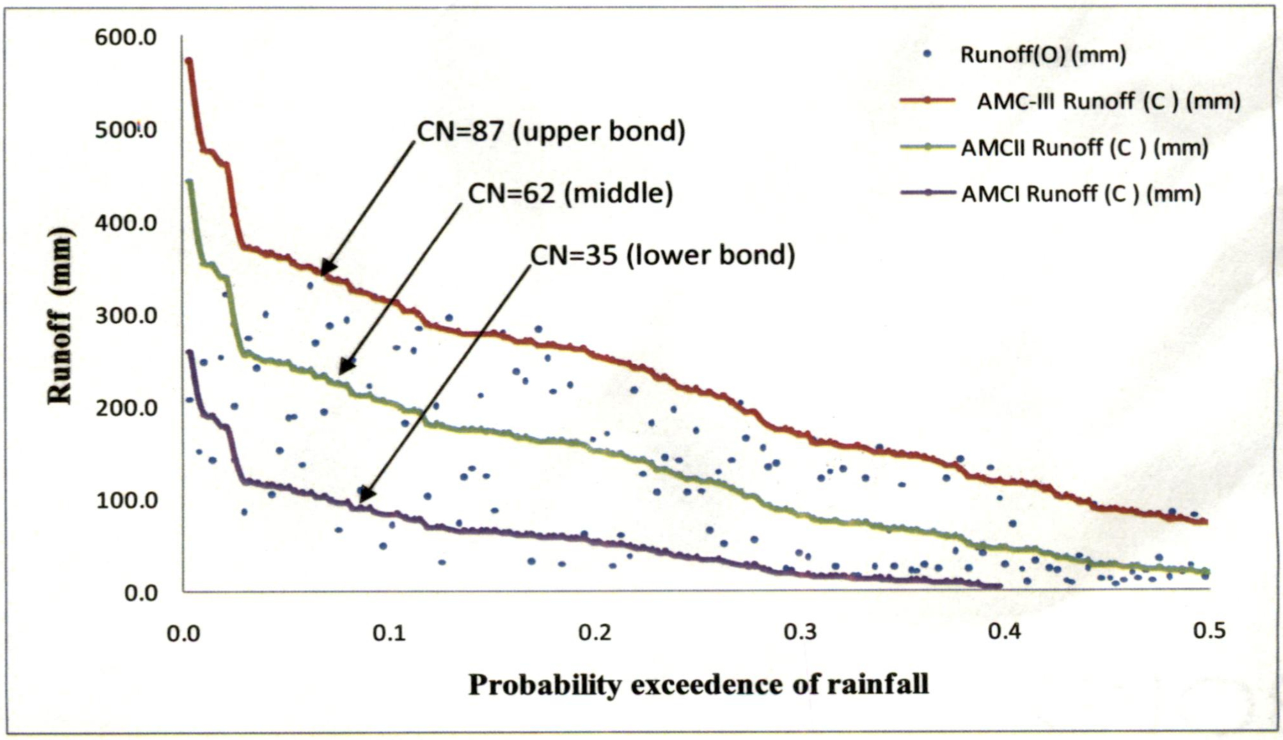
(i) 10-Daily duration analysis



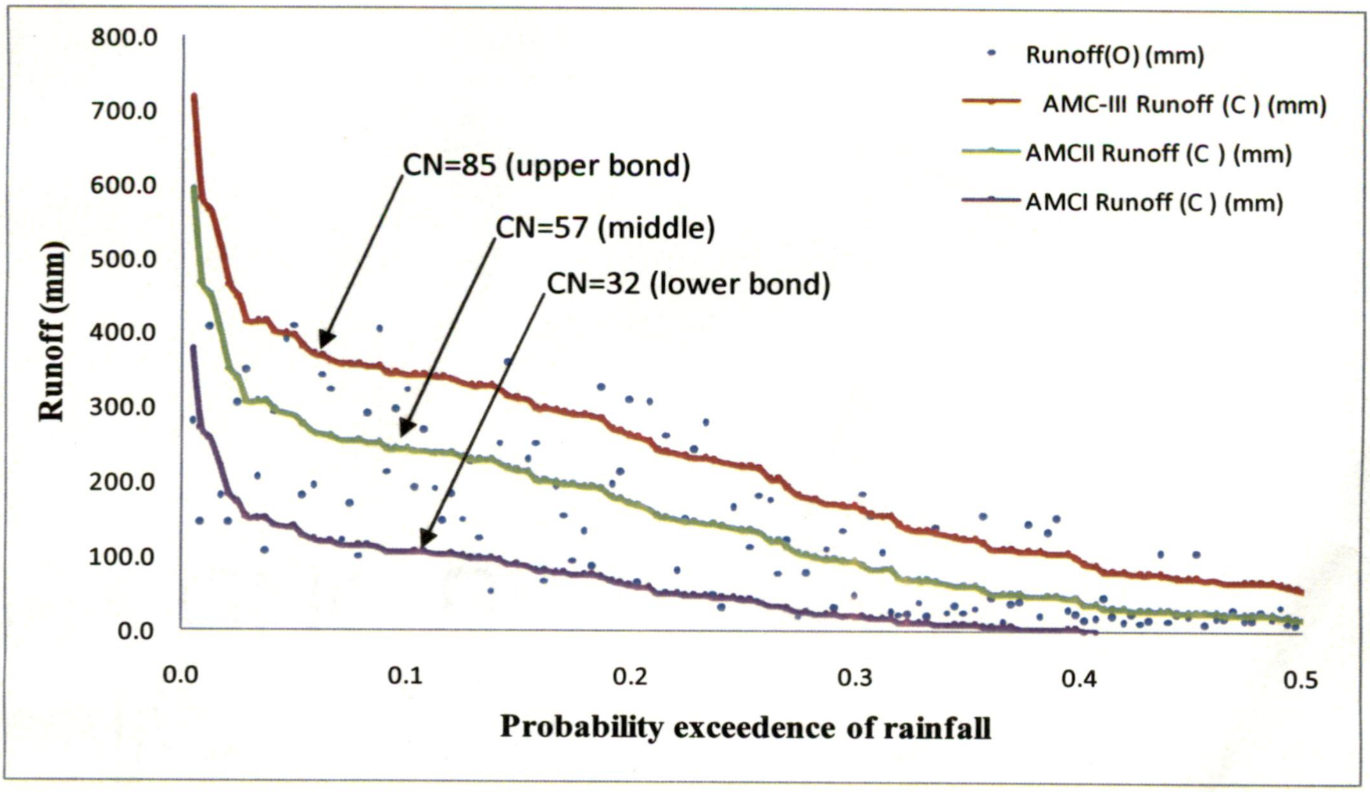
(j) 15-Daily duration analysis



(k) 20-Daily duration analysis



(l) 25-Daily duration analysis



(m) 30-Daily duration analysis

Figure I-3 Ordered different daily runoff data of Rapti catchment for determination of CN for three AMCs. Upper and lower bound curve numbers refer to AMC-III and AMC-I respectively and best-fit to AMC-II.