DEVELOPMENT OF CN-RAINFALL DURATION RELATIONSHIP FOR AN INDONESIAN WATERSHED

A DISSERTATION

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

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By

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CANDIDATES DECLARATION

I hereby declare that the dissertation titled "DEVELOPMENT OF CN RAINFALL DURATION RELATIONSHIP FOR AN INDONESIAN WATERSHED ", which is being submitted in partial fulfillment of the requirement for the award of Degree of Master of Technology in Water Resources Development (Civil) at Department of Water Resources Development and Management (WRD & M), Indian Institute of Technology (IIT)-Roorkee, is an authentic record of my own work carried out during the period July 2009 to June 2010 under the supervision and guidance of Dr. S.K. Mishra, Associate Professor Department of Water Resources Development and Management, IIT-Roorkee, INDIA.

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

Roorkee

June, 2010

(Samuelson Hansen Sianipar)

This is to certify that above 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 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). 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 antecedent moisture conditions (AMC). Of late, an approach based on the ordering of rainfall has been suggested in literature.

In this study, employing the data of an Indonesian watershed, 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. 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 suitable method for design CN development.

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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,
Po	=	observed rainfall
Pc	=	adjusted rainfall
P5	=	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
S1	=	potential maximum retention for AMC I
Sr	=	degree of saturation
$\bar{t}_p$	=	mean storm duration
tp	=	storm duration
USDA	=	United States Department of Agriculture
V_w	=	volume of water

CHAPTER 1
INTRODUCTION

Rain is liquid precipitation, as opposed to other kinds of precipitation such as snow, hail and sleet. The rain requires the presence of a thick layer of the atmosphere to have temperatures above the melting point of water near and above the Earth's surface. On Earth, it is the condensation of atmospheric water vapor into drops of water heavy enough to fall, often making it to the surface. Two processes, possibly acting together, can lead to air becoming saturated leading to rainfall: cooling the air or adding water vapour to the air. Virga is precipitation that begins falling to the earth but evaporates before reaching the surface; it is one of the ways air can become saturated. Precipitation forms via collision with other rain drops or ice crystals within a cloud. Rain drops range in size from oblate, pancake-like shapes for larger drops, to small spheres for smaller drops. (http://en.wikipedia.org/wiki/Rain)

When the rain falls on the ground it may cause infiltration and surface where surface runoff is the water flow that occurs when soil is infiltrated to full capacity and excess water from rain, snowmelt, or other sources flows over the land. This is a major component of the hydrologic cycle. Runoff that occurs on surfaces before reaching a channel is also called a non-point source. If a non-point source contains man-made contaminants, the runoff is called non-point source pollution. A land area which produces runoff that drains to a common point is called a watershed. When runoff flows along the ground, it can pick up soil contaminants such as petroleum, pesticides (in particular herbicides and insecticides), or fertilizers that become discharge or non-point source pollution (http://en.wikipedia.org/wiki/Surface_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 (Yu et. al., 1993) 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. 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. 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 Objective of Study

The objectives of this study are to

(1) propose a simple approach for CN derivation for three levels of AMC from long-term daily rainfall-runoff data using long-duration rainfall-runoff data from an Indonesian watershed,

(2) investigate the impact of rain duration on curve numbers and develop a CN-rainfall duration relationship, and

(3) determine the curve numbers for hydrologic design.

1.2 Organization of Dissertation Work

This study is organized as follows:

Chapter 1 introduces the problem and defines the objectives of the study. Chapter 2 provides a literature review on the topic. Chapters 3 and 4 describe the methodology and study area, respectively. Chapter 5 applies the methodology to the data of selected study area and discusses the results. 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 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 utmost difficult task to estimate the likely runoff from a particular storm. Precipitation (rain) falling on the land surface has several pathways as shown in Figure 2.1.

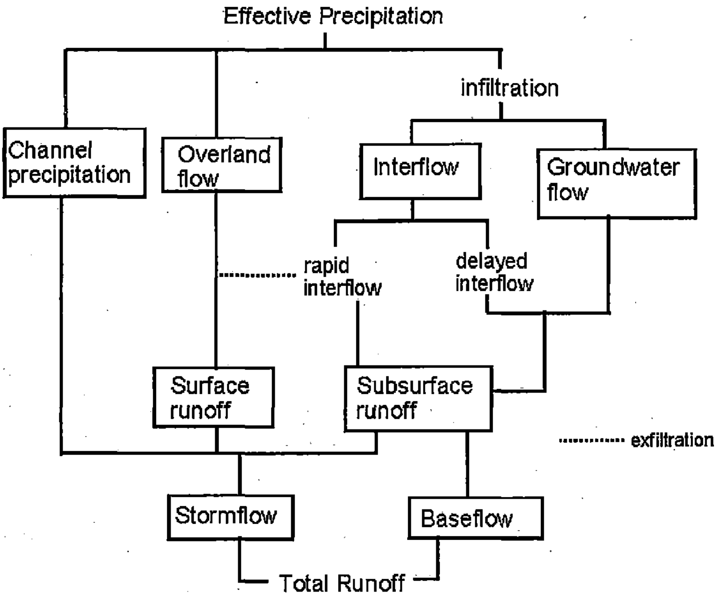

Figure 2.1 Generation of runoff from effective rainfall in a catchment

(source :- www.cartage.org.lb/.....sourcesofrunoff.htm)

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. 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 that are illustrated in Figures 2.2 and 2.3. 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.

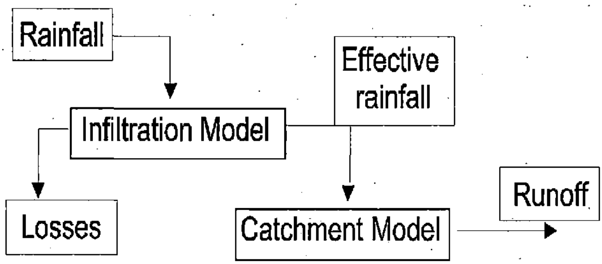

Figure 2.2 A rainfall-runoff model using effective rainfall
(source :- www.alanasmith.com/theory- calculating../ runoff models.htm)

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.

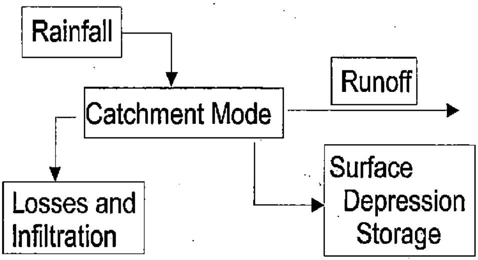

Figure 2.3 A rainfall-runoff model using a surface water budget (source :- www.alanasmith.com/theory- calculating../ runoff models. htm)

The origin of rainfall- runoff modeling, widely used for flow simulation, can be found in the second half of the 19^{th} century when engineers faced the problems of urban drainage and river training networks. During the last part of 19^{th} century and early part of 20^{th} 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 subwatershed as a single system and use the basin-wide averaged data as input parameters. This method assumes that the hydrologic characteristics of subwatersheds are homogeneous. A spatially distributed model accounts for variations in water budget characteristics. Various methods are available, such as division 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:

$$Q_p = CA\overline{R} \qquad 2.1$$

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 $\overline{R}$ = 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, $\overline{R}$, 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 (Babu, 2006), which is simple, lumped, conceptual, and empirical.

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

The USDA Soil Conservation Service Curve Number (SCS-CN) method has its origins in the unit hydrograph approach to rainfall-runoff modeling. The unit hydrograph approach always requires a method of predicting how much of the rainfall contributes to the 'storm runoff'. 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) related storm runoff to rainfalls and showed that the ratio of cumulative discharge to cumulative storm rainfall shows a characteristic form as shown in Figure.2.4

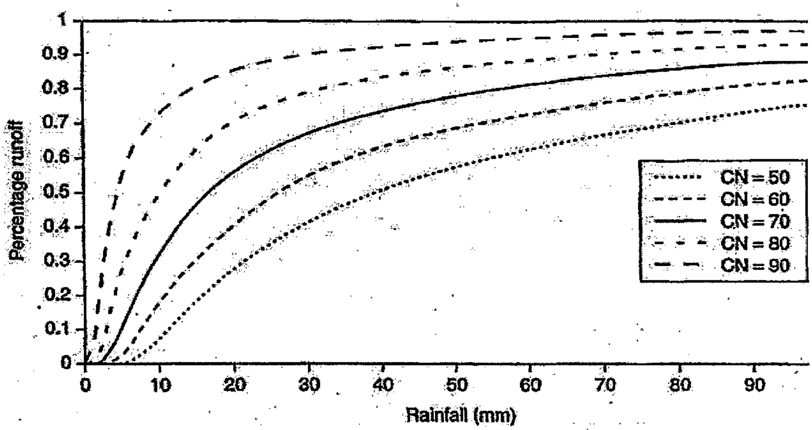

Figure 2.4 Typical Graph showing relationship between storm rainfall and percentage runoff predicted by the USDA SCS method

Mockus (1949) proposed that such data could be represented by an equation of the following form:

$$\frac{Q}{P - I_a} = \left[1 - (10)^{-b(P-I_a)}\right] \qquad 2.2$$

or

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

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 $(P-I_a)<1$. Approximating the right hand side of equation 2.3 as a series expansion results into an equation equivalent to standard SCS-CN formulation

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

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:

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

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

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

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 λ 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:

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

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

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

which is the existing SCS-CN method.

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 (Mishra et al., 2006).

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) ∞ 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 absorptivity 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 (Mishra et al., 2006),

2.4.1 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.

2.4.2 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 labeled 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 excedance 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. (Mishra et al 2006).

2.4.3 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.

2.4.4 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 nonagricultural 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.

2.4.5 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.

2.4.6 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:

a) 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.
b) It is easy to apply and useful for ungauged watersheds.
c) The method relies on only one parameter-CN.
d) 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) The three AMC levels used with the SCS-CN method permit unreasonable sudden jumps in the computed runoff.
(ii) There is a lack of clear guidance on how to vary antecedent moisture condition.

(iii) There is no explicit dependency of initial abstraction on the antecedent moisture.

(iv) The initial abstraction coefficient (λ), which largely depends on climatic and geologic conditions (Ponce and Hawkins, 1996), has been taken as constant (=0.2).

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

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

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

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

(ix) 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 and Roesner, 2000; Jacobs et al., 2003). Though the SCS-CN method was originally developed for computation of direct surface runoff from the storm rainfall, it has ince been applied to other areas, such as long-term hydrologic simulation rediction of infiltration and rainfall-excess rates, hydrograph simulation, sedimen ield modeling, partitioning of heavy metals and determination of sub-surface flow he method has also been successfully applied to distributed watershed modelinc White, 1988; Moglen, 2000; and Mishra and Singh, 2003a).

.7 SCS-CN Inspired Methods

.7.1 Mishra et al. model:

The Mishra et al. (1998) model assumes CN variation with time t dependent or MC (Ponce and Hawkins, 1996) only. The computed rainfall-excess Q (equation 2.5) ; transformed to direct runoff amount DO_t using a linear regression approach nalogous to the unit hydrograph scheme. Taking base flow (Ob) as a fraction of F ong with the time lag, the total daily flow, Q_t, is computed as the sum of DO_t anc O_b. The model parameters are optimized utilizing the objective function of minimizinc he errors between the computed and observed data.

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

1. It does not distinguish between dynamic and static infiltration, similar tc the Williams–Laseur and Hawkins models.
2. It allows sudden jumps in CN values when changing from one AMC tc 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 ir long-term hydrological simulation.
4. The base flow is taken as a fraction of F, which is not rational. The watei 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 0), 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 0, where C is the runoff coefficient (=Q/ (P- I_a)). Using this C=Sr concept, Mishra and Singh (2002a) modified Equation 0 for antecedent moisture M as:

$$\frac{Q}{P_a} = \frac{F + M}{S + M} \qquad 2.9$$

which is termed as 'Mishra-Singh proportionality concept'. A further substitution into Equation 0 leads to

$$Q = \frac{(P - I_a)(P - I_a + M)}{P - I_a + M + S} \qquad 2.10$$

When P>I_a,

$$M = \frac{S_1 (P_5 - \lambda S_1)}{P_5 + (1 - \lambda) S_1} \quad \text{Q=0 otherwise} \qquad 2.11$$

Here, P_5=antecedent 5-day precipitation amount and S1 is the potential maximum retention corresponding to AMC I. Equation 2.10 can be further simplified as (Babu, 2006; Sahu, 2007):

$$M = \gamma P_5 \qquad 2.12$$

where γ = proportionality coefficient which can be determined using regression analysis.

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:

$$Q = \frac{(P_c - I_{ad})(P_c - I_{ad} + M)}{P_c - I_{ad} + M + S} \qquad 2.13$$

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

$$I_{ad} = \lambda S\left(\frac{P_c}{P_c + S}\right)^{\alpha} \qquad 2.14$$

M, the 5-day antecedent moisture, is computed using the Equation 2.12, as in Mishra and Singh model; and P_c and S are calculated as follows:

$$P_c = P_o\left(\frac{t_P}{\bar{t}_P}\right)^{\beta} \qquad 2.15$$

$$S = \frac{25400}{CN} - 254 \qquad 2.16$$

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. Eqs. 0 to 2.16 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.

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 using long-duration rainfall-runoff data from an Indonesian watershed. 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 develops a CN-rainfall duration relationship developed. The availability of approaches based on ordering of rainfall, CN values are derived. There is however no rational approach suggested for derivation of curve numbers for design purpose associated with return periods. This study also investigates this aspect and proposes a suitable method for design CN development.

CHAPTER 3

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 following the SCS-CN method.

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. 3.1 graphically 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 sub-surface water F for given watershed characteristics.

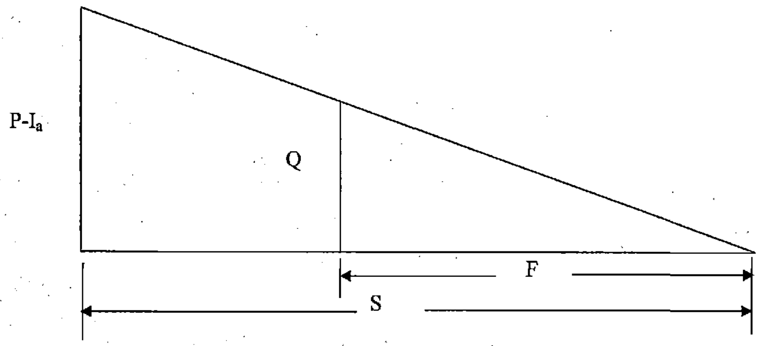

Figure 3. 1Proportionality concept of the existing SCS-CN method

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. Coupling Eqs. 3.1 and 3.2, the expression for Q can be given as:

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

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 Eqs. 3.3 and 3.4 results

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

Eq. 3.50 is the popular form of existing SCS-CN method. Thus, the existing SCS-CN method with $\lambda = 0.2$ is a one-parameter model for computing surface runoff from a storm rainfall event.

3.2 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. 2.15.
    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 by summing the rainfall and corresponding runoff values. Note both P & Q are in depth units.

   b. Repeat steps 1(b) through 1(h) for deriving CN values for different AMCs and a particular duration P-Q series.

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 determination of design CN, annual daily, 2-daily, 3-daily, and so on P-Q data series are developed.

b. For each (annual) P-Q series, CN values are derived from the three AMCs. Thus for a given AMC and duration, there is one CN-value available for a year. Thus, corresponding to each P-Q series, a series of CN values for a given AMC and duration can be derived. This series can be safely assumed to be a random series as there exists no correlation between the two consecutive annual CN-values.

c. Fit a suitable frequency distribution in the annual CN-series available for a given AMC and duration and derive CN-values of 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.

CHAPTER 4

STUDY AREA AND DATA DESCRIPTION

4.1 Location of Study Area

The Brantas River is the second largest river on the Java Island, Indonesia. Its length is 320 km and catchment area is about 11,800 km^2 lying on East Java Province, Indonesia, which covers around 9% of the total area of the Java Island. The river basin geographically extends between 110°30′ and 112°55′ of east longitude and between 7°01′ and 8°15′ of south latitude. The basin covers nine regencies or districts: Sidoarjo, Mojokerto, Malang, Blitar, Kediri, Nganjuk, Jombang, Tulungagung, Trenggalek, and five urban centers or municipalities: Surabaya (capital of East Java), Mojokerto, Malang, Kediri, Blitar.

Based on Jasa Tirta Public corporation, Brantas River basin is divided into three parts, upper, middle and lower basins. The study area is located in the Upper part of the above Brantas River, named as Upper Brantas River, which is laid on Malang regent, as shown in Figure 4.1. The area of study extends between 112°24′ and 112°57′ of east longitude and between 7°43′ and 8°15′ of south latitude. The river system originates from the southeastern side of Mt. Anjasmoro located in the center of its basin, flows eastward, turns its course southward around the Semeru volcanic zone, and then runs to the west parallel to the southern hills until it reaches the reservoir of the Sutami Dam. The area of study is about 1,912 km^2. It consists of five (5) sub basin areas that are described as below:

- Sub Basin Bango = 223.93 km^2
- Sub Basin Metro = 249.141 km^2
- Sub Basin Amprong = 323.459 km^2
- Sub Basin Lesti = 611.96 km^2
- Sub Basin Brantas = 503.551 km^2

4.2 Topography

General topography in the Upper Brantas basin is hilly area. On West Northern and Eastern, most parts of the catchment have the highest elevation ranges and the lowest range are located respectively. The Upper Brantas basin can be divided into landform in terms of geomorphology :

a. Steep Volcano and highland, generally above elevation of 1,000 meters. Slopes are steep with more than 40%, and covered almost with dense vegetation.

b. Midland and hilly land, between the highland and the alluvial plains. This area ranges in altitude from 200 to 1,000 meters with a slope gradient of 15% to 40%, and comprises the main agricultural production area. In addition, hills are often below 500 meters and covered with much vegetation.

c. Lowland and Alluvial plain, mostly below elevation 200 meters. This area consists of the lower basin of the rivers as well as the agricultural production resettlement areas, with the slope 8%-15%

d. Lowland and plain, below 100 meters in altitude, comprise the main agricultural production area, with slope < 8%

4.3 Geology and Soil

Geology of the Brantas River basin consists mainly of Neogene volcanic rocks such as basalt, andesite, tuff breccia and tuff, and locally contains coral limestone. These rocks are overlaid mostly by Quaternary volcanic deposits with various degrees of weathering.

According to the soil distribution map prepared by the Central Soil Research Institute of Bogor in 1967, the natural land of the basin is classified into 9 class, Alluvial, Andosol, Latosol, Lithosol, Mediterranian Soil, Brown Forest Soil, Gleysol, Grumusol, Regosol. The characteristics of the main soil groups in the Upper Brantas catchment are described below:

a. Alluvial soil is characterized by a clayey/silty loam texture and distributed on lowland and plains, especially along the Brantas River. The soil is highly productive agriculturally, mainly under rice cultivation.

b. Latosol and andosol, of volcanic original, are distributed in the upland area. These soils, especially derived from volcanic ash, are subject to erosion.

c. Lithosol developed on the bedrock area of limestone and volcanic rocks, thus including a large amount of gravel. Because of its low productivity, the soil is not intensively farmed.

4.4 Climate and Hydrology

The Brantas River basin belongs to the tropical monsoon zone. In the normal years, the wet season is about 6 months long from November to April, and the dry season covers from May to October. The annual mean temperature in the basin ranges from 24.7°C in Malang to 26.6°C in Porong. The annual mean rainfall over the basin is around 2,000 mm, of which more than 80% occurs in the rainy season. Variation of annual rainfall is large 2,960 mm in a water rich year and 1,370 mm in a drought year. The annual mean rainfall in the high elevation areas is generally high, it reaches 3,000 mm through 4,000 mm especially in southern and western slopes of Mt. Kelud. The annual mean relative humidity in the basin ranges from 74% to 83% depending on the location.

4.5 Data Availability

The data network which is used in this study:

1) Daily rainfall. Data is obtained from Jasa Tirta Public Corporation and Brantas River Basin Agency for the period 1984-2006. The number of stations measuring rainfall are variously positioned in and around the basin. It contains nine rainfall stations. The altitude and of the rainfall stations varied from 425 - 635 m. The location of the rainfall station in the are shown in Figure 4.2 and Table 4.1 below

2) Daily Discharge. Daily discharge data from one water level station Tawang Renjeni (1984-2006) was taken. Data is obtained from Jasa Tirta Public

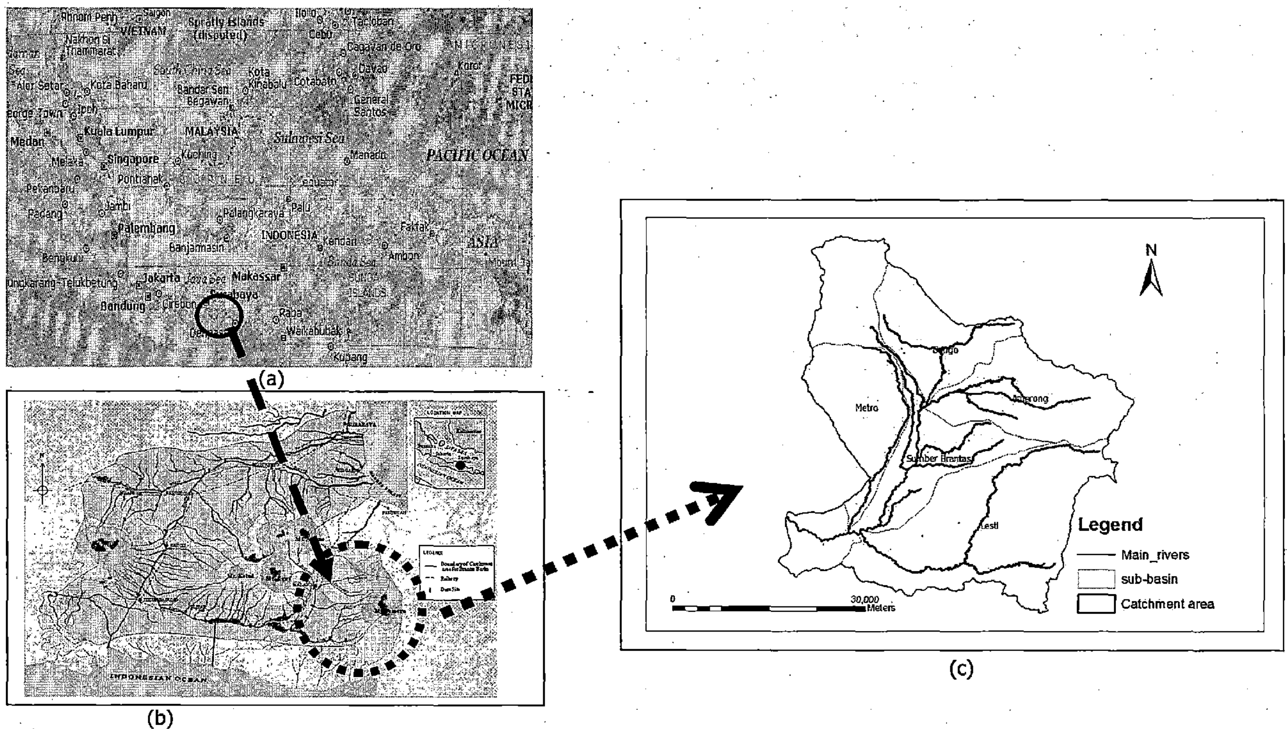

Figure 4.1 (a) Location of East Java Province (b) Brantas River Basin (c) Upper Brantas River basin

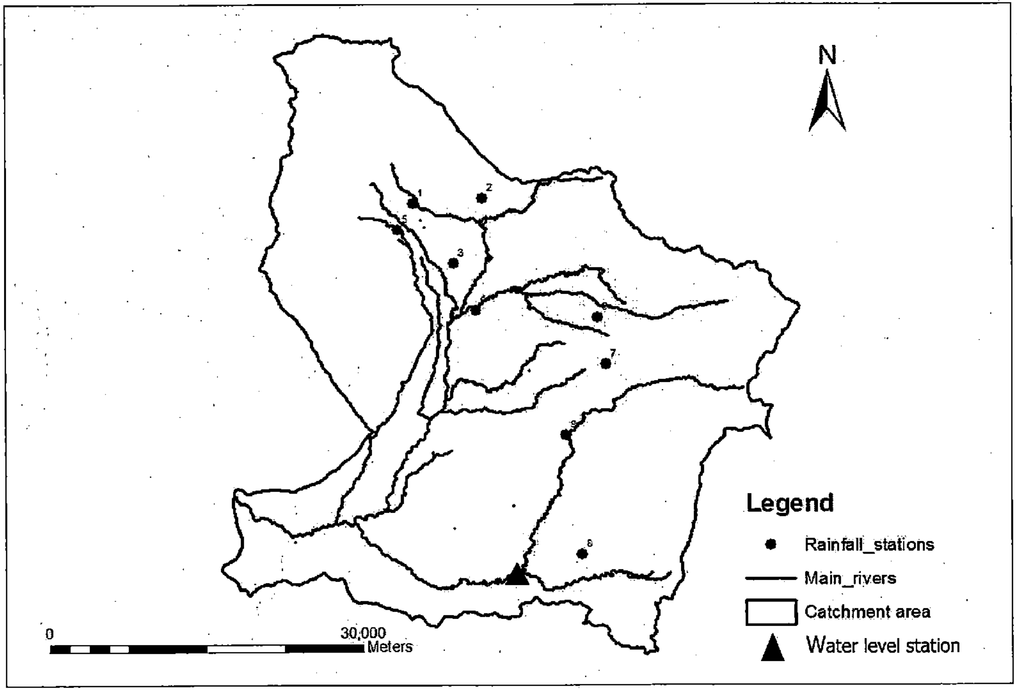

Figure 4.2 Location of rainfall water level stations station at the Upper Brantas

Table 4.1 Latitude, longitude, and elevation of the rainfall station.

No	Station	Lat (S)	Long (E)	Elev.
1	Karangploso	112.60	-7.89	575
2	Singosari	112.66	-7.89	635
3	Lowok	112.64	-7.95	455
4	Kedungkandang	112.66	-7.99	437
5	Jabung	112.75	-7.95	530
6	Tumpang	112.76	-8.00	550
7	Poncokusumo	112.77	-8.04	608
1B	Dampit	112.75	-8.21	593
2B	Wajak	112.73	-8.10	425
B	AWLR Station Tawang Rejeni			

CHAPTER 5

APPLICATION AND DISCUSSION OF RESULTS

The proposed methodology (Chapter 3) was employed to the data of an Indonesian watershed (area 1912 km^2) (Chapter 4) and the results are discussed in sequence of steps suggested in Chapter 3 as follows:

The daily rainfall (P)-runoff (Q) data series for 23 years was first arranged in chronological order. This 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. The processed data series was sorted in the descending order of P, and probability assigned to P using Weibull's plotting position formula. The sorted series is plotted in Figure. 5.1. Then assuming a suitable value of CN (or S), Q-values were computed for all P-values using Eq. 2.15 and these were plotted in Figure. 5.1. 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 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. 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. In this manner, CN values were derived for different AMCs and durations as shown in Table 5.1. Figure. 5.1 shows for AMC-I through AMC III for 1-day duration for Tawang Renjeni watershed of upper Brantas basin (others figure of derivation for 2 daily, 3 daily, 4 daily, etc, can be seen in the appendix 1) and Figure. 5.2 depicts the variation of CN with rainfall duration. As shown in Figure 5.2 and Table 5.1, 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 23 years data, which forms to be quite a large data set, is used in this study, these curve number values are representative to the characteristic of the watershed.

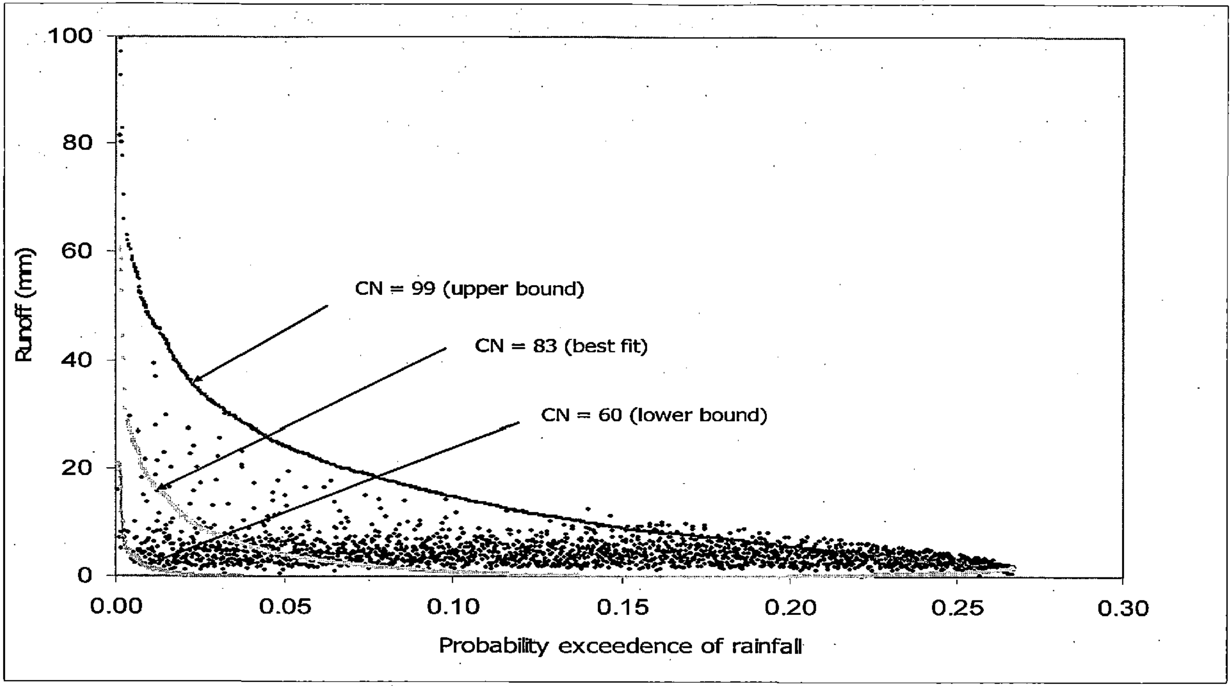

Figure 5. 1 Derivation of CN-Value of Tawang Renjeni watershed of upper Brantas basin, for 1 day duration for three level AMC, AMC I through AMC III

Table 5. 1 CN values for different AMCs and duration for Tawang Renjeni watershed of upper Brantas basin

Duration	**CN**			**Potential maximum retention S**		
Day(s)	**AMC-III**	**AMC-II**	**AMC-I**	**AMC-III**	**AMC-II**	**AMC-I**
1	99	87	60	2.57	37.95	169.3
2	97	82	51	7.86	55.76	244.0
3	97	78	50	7.86	71.64	254.0
4	96	76	50	10.58	80.24	254.0
5	95	74	50	13.37	89.2	254.0
6	94	72	48	28.22	136.77	471.71
8	92	70	45	22.09	108.9	310.4
10	92	68	42	22.09	119.5	350.76
12	90	64	35	28.22	136.77	471.71
14	90	64	35	28.22	142.88	471.7
16	90	63	35	28.22	149.17	471.71
18	89	62	32	31.39	155.68	539.75
20	88	60	30	34.64	169.33	592.67
25	87	55	25	34.64	169.33	592.67
30	85	50	25	44.82	254.0	762.0

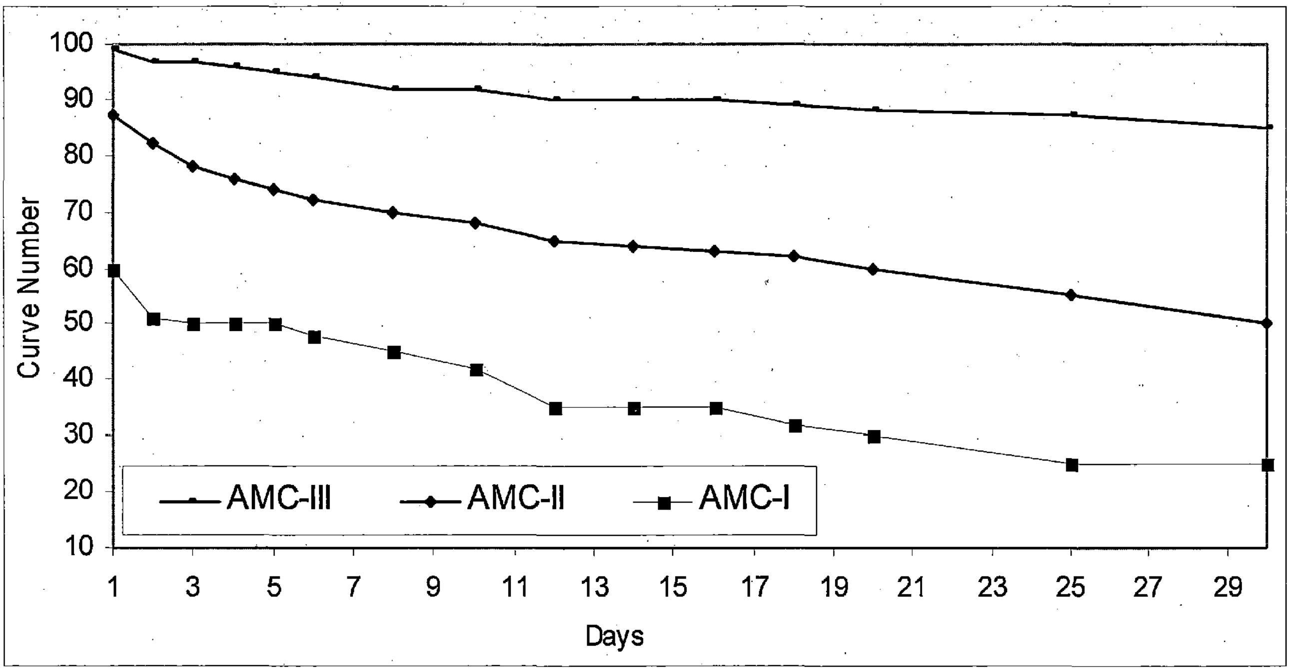

Figure 5.2 Relation between curve number (non-dimensional) and rain duration (day)

The following relations can be derived from the best fits of these curves for various AMCs as in Table 5.2. In this table, y 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.

Table 5.2 Relationship between CN rainfall and duration for AMC III, II and I condition

AMC	Relation	R^2
III	y = 97.407e-0.0049x	0.94
II	y = 82.167e-0.0167x	0.96
I	y = 56.284e-0.0305x	0.96

The above three relations actually represent the relation between CN and rainfall duration, which formed to be a major objective of this study.

To enhance the field utility, the above work is further extended to the derivation of design curve numbers for different return periods. To this end, similar to the above, annual P-Q data series were prepared for all 23 years and following the above procedure, CN values for three AMCs were derived for different durations, but for each of 23 years. The results are shown in Tables 5.3 a & b for 1 through 5 days durations and for AMC I through AMC III, respectively.

Now, for a given duration and AMC, considering the above annual CN-series a random series, different frequency distributions were employed for deriving CN-values corresponding to different return periods. Five frequency distributions namely, normal, log-normal, extreme-value, Pearson type III, and Log Pearson type III, were employed and, based on standard error and the criteria of CN <100, the results of Log Pearson type III distribution were adopted and these are shown in Table 5.4. As seen from the table that for a given AMC and return period, as rain duration increases, CN decreases. It is consistent with the expectation as describe earlier. For a given AMC and duration, as return period increases, CN increases. This is also consistent with the expectation that as return period increase the runoff usually increases or CN decreases, for example, for duration =

1 day, CN increases from 71.19 to 75.39 for AMC I, from 88.19 to 90.47 for AMC III, and from 96.5 to 98.13 for AMC III. This is a unique feature of this study not attempted in the past.

The above design CN-values for different AMCs, durations, and return periods derived using Log Pearson type III distribution for Tawang Renjeni watershed, upper Brantas Basin, for AMC I as shown in Figures. 5.3a &b for AMC I. It is seen from these figures that, for a given return period (Figure. 5.3a) as duration increases the quantum CN-value decreases, and vice versa. The reverse trend is apparent (Figure. 5.3b) with return period, but for a given duration. These inferences are the same as derived from Table 5.4 above. The other figure of design CN-values for AMC III and II are shown in Figures. 5.5 through 5.8.

Table 5.3a: Annual curve number for different rain durations for Tawang Renjeni watershed, upper Brantas Basin.

Data time	1-day			2-days			3-days			4-days			5-days		
	CURVE NUMBERS			CURVE NUMBERS			CURVE NUMBERS			CURVE NUMBERS			CURVE NUMBERS		
(year)	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I	AMC-III	AMC-II	AMC-I
1984	92	82	60	92	79	56	88	73	50	87	70	48	86	69	46
1985	92	82	60	91	78	55	90	77	51	89	74	50	89	73	48
1986	98	90	73	98	90	70	90	75	56	87	71	50	86	70	38
1987	96	86	67	91	81	67	90	80	65	89	75	56	88	74	55
1988	90	74	45	90	70	40	86	68	38	85	68	38	83	65	35
1989	95	84	60	93	78	50	86	71	45	83	64	40	80	62	38
1990	95	80	55	90	75	41	85	70	38	85	68	37	85	66	37
1991	94	83	65	93	75	51	92	75	48	90	72	47	90	71	46
1992	92	79	60	90	70	50	90	70	50	89	69	48	86	67	47
1993	95	85	65	94	81	60	86	72	57	85	70	50	84	70	49
1994	95	85	65	94	81	60	86	72	57	85	70	50	84	70	49
1995	94	85	65	93	77	57	90	75	55	88	74	54	87	72	53
1996	95	84	58	95	82	56	95	82	55	92	76	54	90	74	52
1997	93	86	72	93	83	65	92	81	63	91	80	63	89	74	60
1998	95	80	50	90	72	43	85	65	40	85	63	38	84	62	38
1999	94	85	65	93	80	57	90	73	50	90	70	48	88	66	47
2000	94	85	65	90	77	60	87	73	56	84	70	53	84	68	50
2001	85	72	55	85	72	54	84	68	50	82	65	47	81	64	46
2002	94	80	54	91	74	50	87	71	48	86	70	47	84	67	46
2003	94	85	65	91	76	57	85	70	52	84	68	50	83	66	47
2004	94	85	64	90	75	50	85	70	45	84	66	43	82	65	42
2005	94	85	65	92	79	57	87	73	52	85	70	50	84	68	48
2006	88	77	60	86	74	58	85	72	56	84	69	52	82	66	49
average	93.39	82.57	61.43	91.52	77.35	54.96	87.87	72.87	51.17	86.48	70.09	48.39	85.17	68.22	46.35

Table 5.3b :Annual curve number for different rain durations for Tawang Renjeni watershed, upper Brantas Basin.

Data time	CURVE NUMBERS					CURVE NUMBERS					CURVE NUMBERS				
	AMC III					AMC II					AMC I				
(year)	1-D	2-D	3-D	4-D	5-D	1-D	2-D	3-D	4-D	5-D	1-D	2-D	3-D	4-D	5-D
1984	92	92	88	87	86	82	79	73	70	69	60	56	50	48	46
1985	92	91	90	89	89	82	78	77	74	73	60	55	51	50	48
1986	98	98	90	87	86	90	90	75	71	70	73	70	56	50	38
1987	96	91	90	89	88	86	81	80	75	74	67	67	65	56	55
1988	90	90	86	85	83	74	70	68	68	65	45	40	38	38	35
1989	95	93	86	83	80	84	78	71	64	62	60	50	45	40	38
1990	95	90	85	85	85	80	75	70	68	66	55	41	38	37	37
1991	94	93	92	90	90	83	75	75	72	71	65	51	48	47	46
1992	92	90	90	89	86	79	70	70	69	67	60	50	50	48	47
1993	95	94	86	85	84	85	81	72	70	70	65	60	57	50	49
1994	95	94	86	85	84	85	81	72	70	70	65	60	57	50	49
1995	94	93	90	88	87	85	77	75	74	72	65	57	55	54	53
1996	95	95	95	92	90	84	82	82	76	74	58	56	55	54	52
1997	93	93	92	91	89	86	83	81	80	74	72	65	63	63	60
1998	95	90	85	85	84	80	72	65	63	62	50	43	40	38	38
1999	94	93	90	90	88	85	80	73	70	66	65	57	50	48	47
2000	94	90	87	84	84	85	77	73	70	68	65	60	56	53	50
2001	85	85	84	82	81	72	72	68	65	64	55	54	50	47	46
2002	94	91	87	86	84	80	74	71	70	67	54	50	48	47	46
2003	94	91	85	84	83	85	76	70	68	66	65	57	52	50	47
2004	94	90	85	84	82	85	75	70	66	65	64	50	45	43	42
2005	94	92	87	85	84	85	79	73	70	68	65	57	52	50	48
2006	88	86	85	84	82	77	74	72	69	66	60	58	56	52	49
average	93.39	91.52	87.87	86.48	85.17	82.57	77.35	72.87	70.09	68.22	61.43	54.96	51.17	48.39	46.35

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

T (year)	CN I					CN II					CN III				
	1-d	2-d	3-d	4-d	5-d	1-d	2-d	3-d	4-d	5-d	1-d	2-d	3-d	4-d	5-d
25	71.19	66.86	63.31	59.21	57.01	88.19	84.22	79.87	77.56	74.85	96.50	95.91	93.02	91.56	90.39
50	72.21	68.60	65.24	61.49	58.95	88.82	85.23	81.33	79.15	76.10	96.93	96.37	93.95	92.58	91.38
100	72.99	70.10	66.92	63.61	60.70	89.32	86.11	82.69	80.65	77.23	97.29	96.75	94.79	93.52	92.30
200	73.62	71.40	68.41	65.63	62.31	89.73	86.87	83.98	82.08	78.29	97.58	97.07	95.57	94.41	93.15
1000	75.39	74.65	70.76	68.78	65.68	90.47	88.72	86.78	85.24	80.53	98.13	97.67	97.21	96.32	94.97

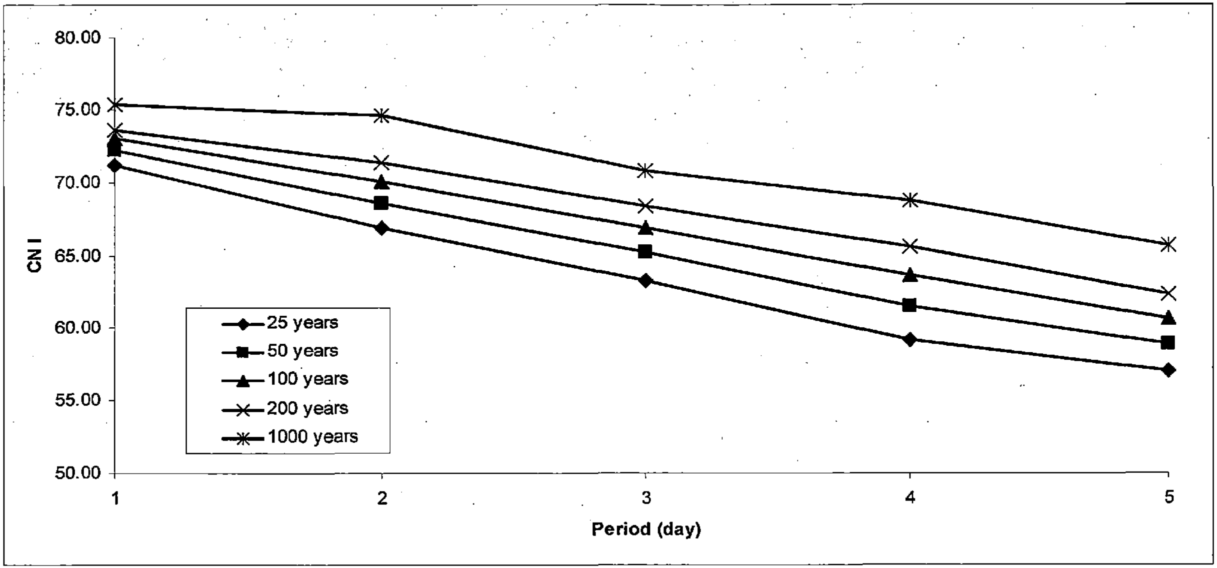

Figure 5.3 Design curve numbers for AMC I and different durations. Third parameter = return period.

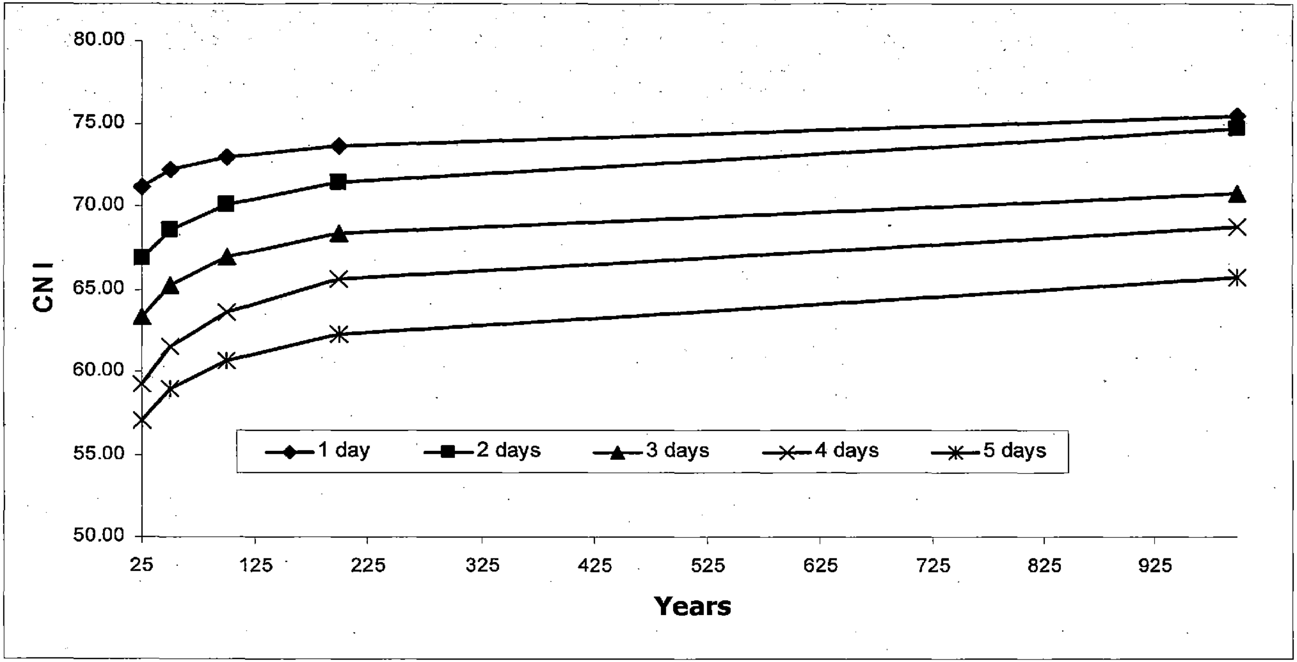

Figure 5.4 Design curve numbers for AMC I and different return periods. Third parameter = duration

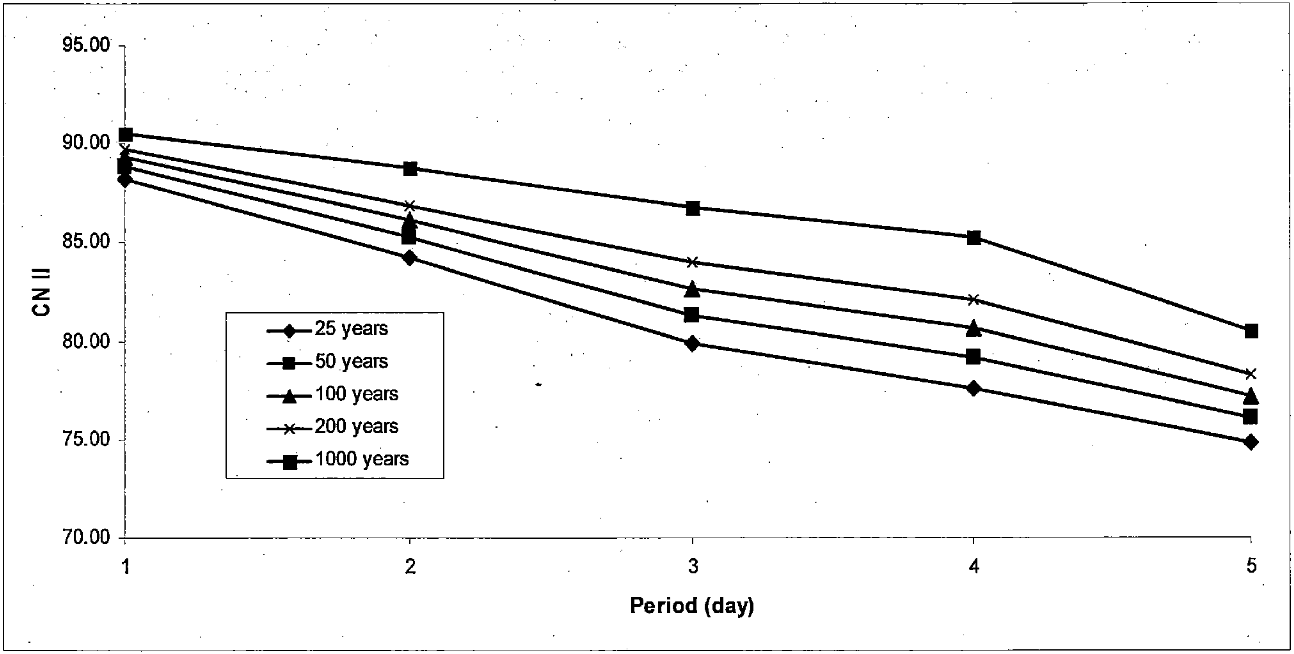

Figure 5.5 Design curve numbers for AMC II and different durations. Third parameter = return period.

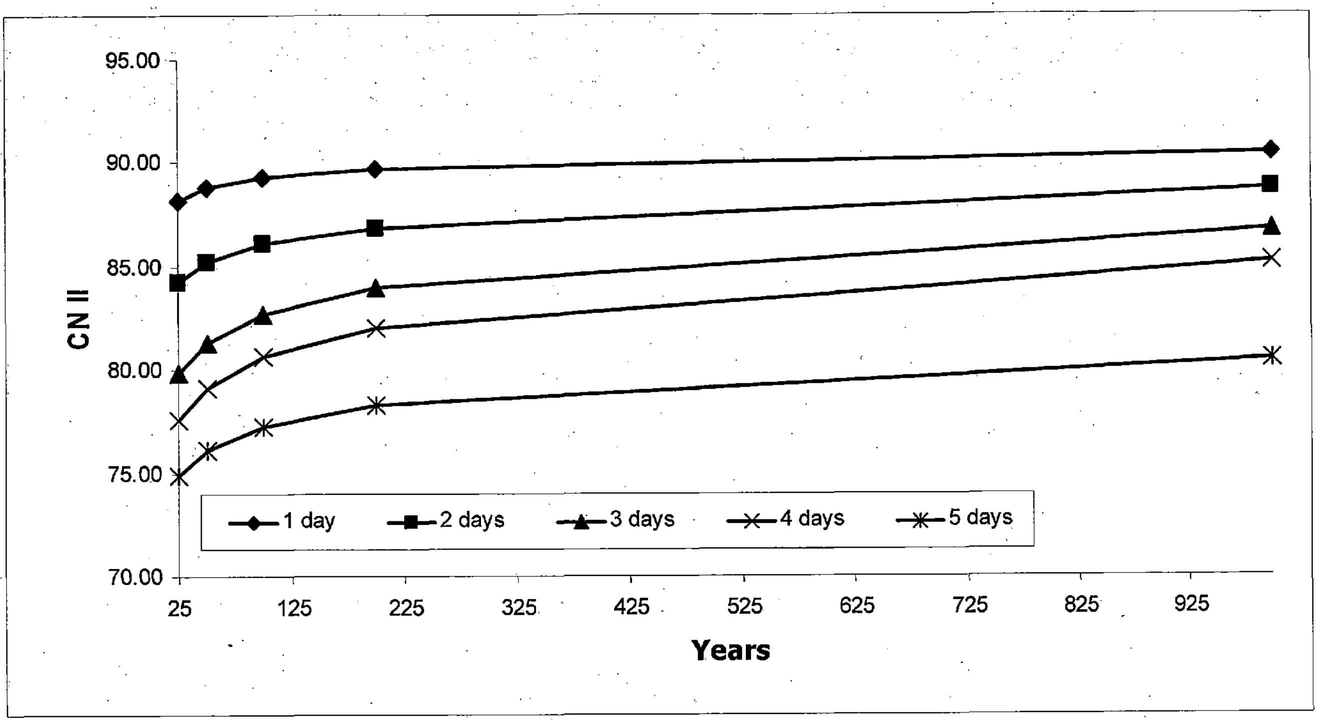

Figure 5.6 Design curve numbers for AMC II and different return periods. Third parameter = duration

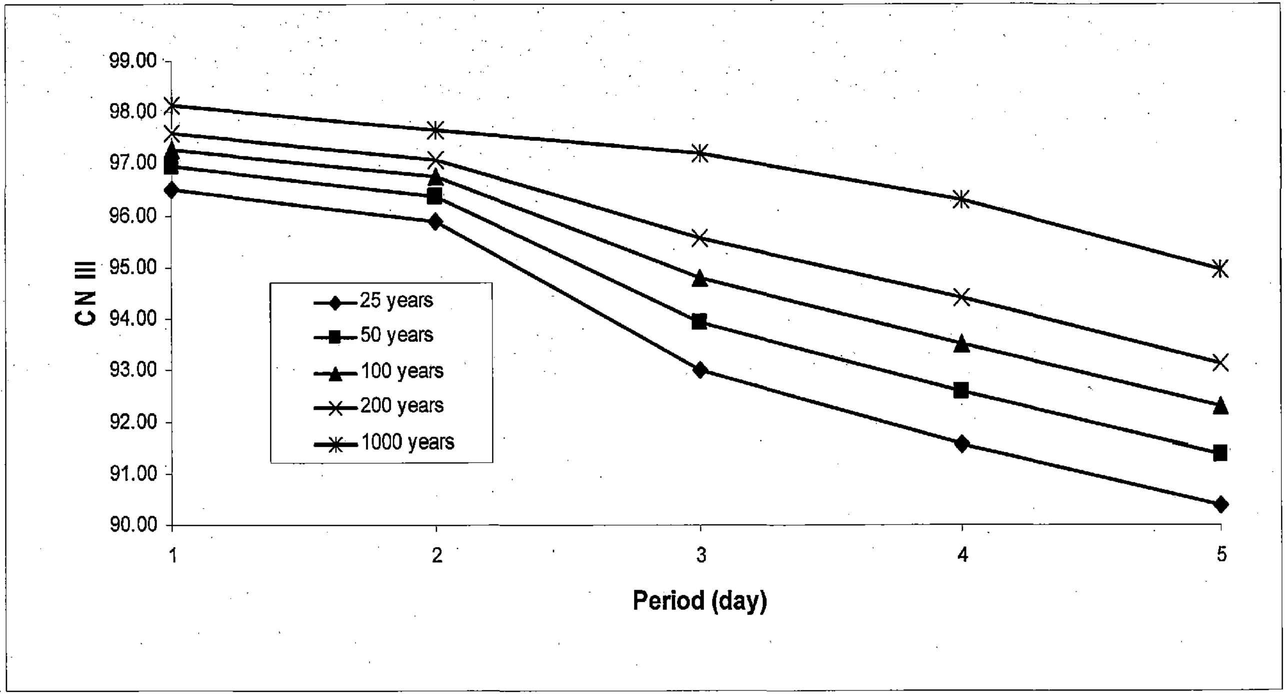

Figure 5.7 Design curve numbers for AMC III and different return periods. Third parameter = duration

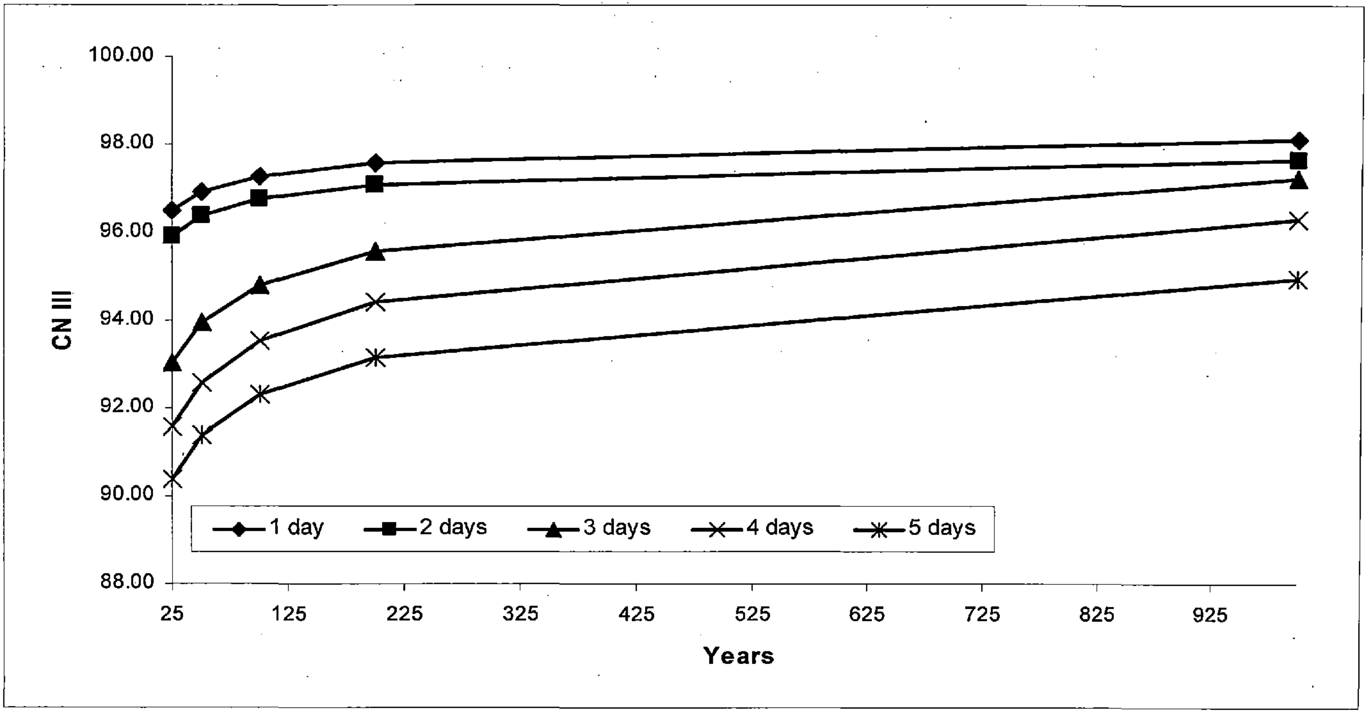

Figure 5.8 Design curve numbers for AMC III and different return periods. Third parameter = duration

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. The CN-duration relationships derived for different AMCs for the studied watershed are given below:
   - $CN = 97.407\ e^{-0.004*t}$ for AMC I
   - AMC II $CN=82.167\ e^{-0.0167*t}$ for AMC II
   - AMC III $CN = 56.284\ e^{-0.0305*t}$ for AMC III

   where t is the rain duration (day). These relations were fitted with R^2 ranging from 0.94 – 0.96, indicating reasonably satisfactory fits.
2. For a given AMC and return period, CN decreases as rain duration increases, and vice versa
3. For a given AMC and duration, CN increases as return period increases.
4. For a given duration and return period, CN increases as AMC level increases for AMC I to AMC III.

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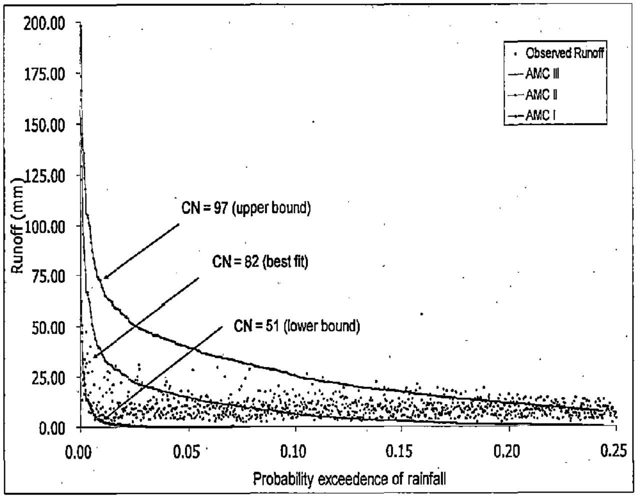
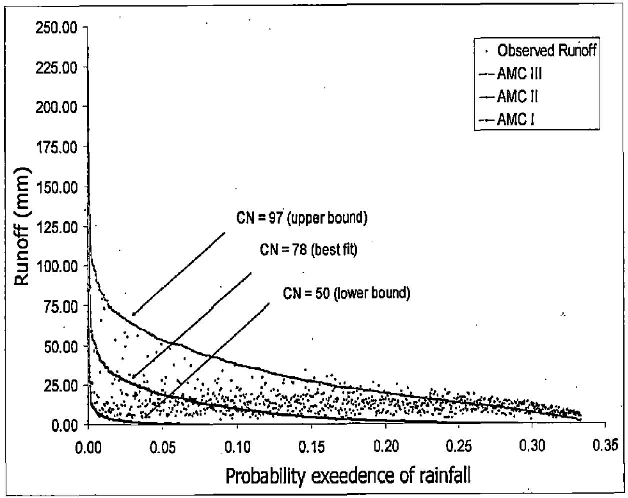
APPENDIX – I



CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 2 days duration for three level AMC, AMC I through AMC III



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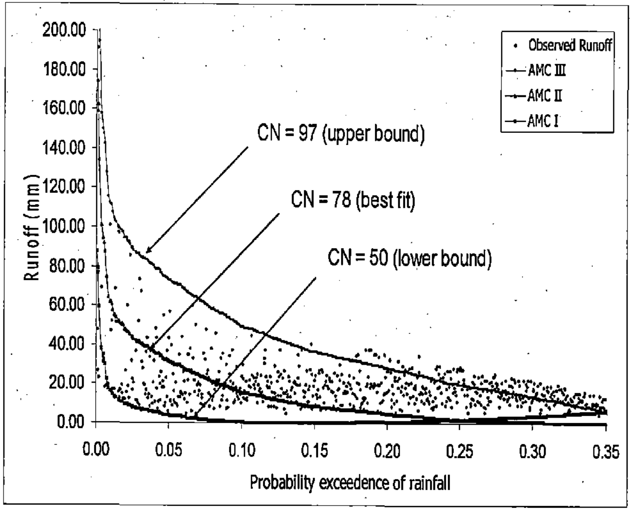
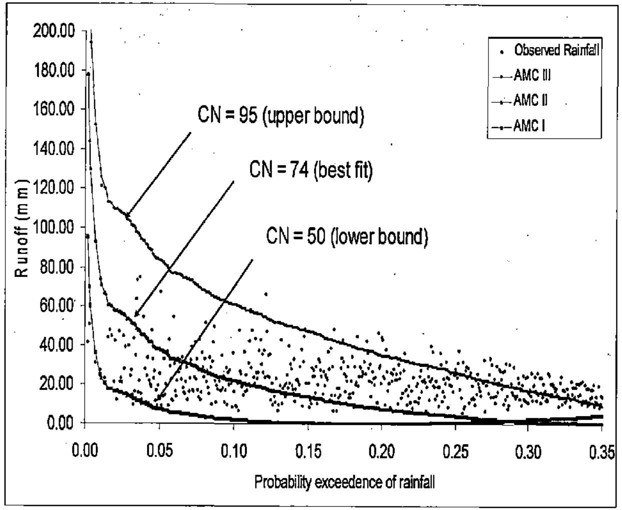
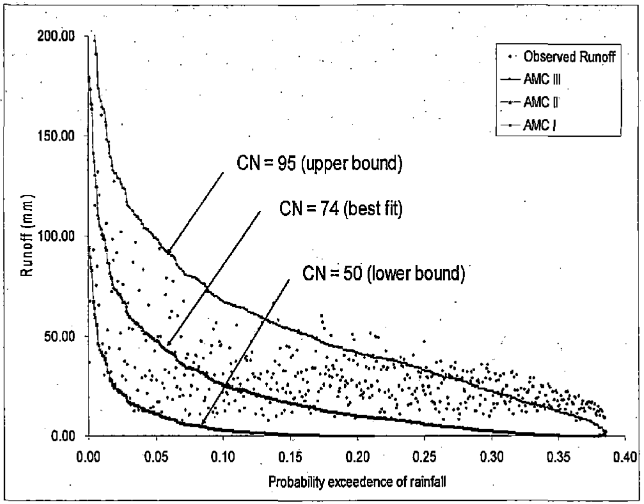


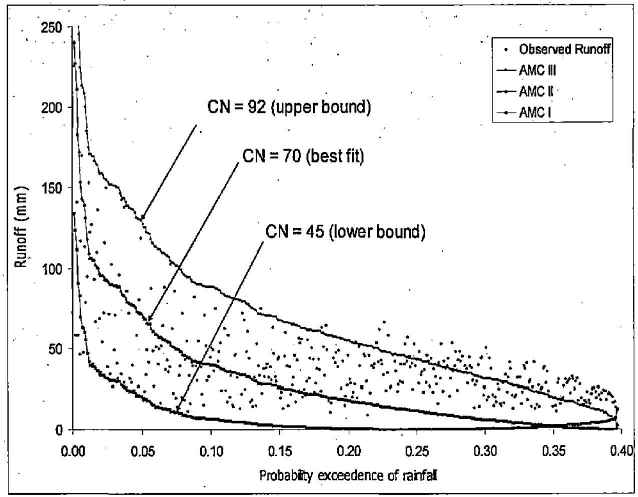
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 4 days duration for three level AMC, AMC I through AMC III



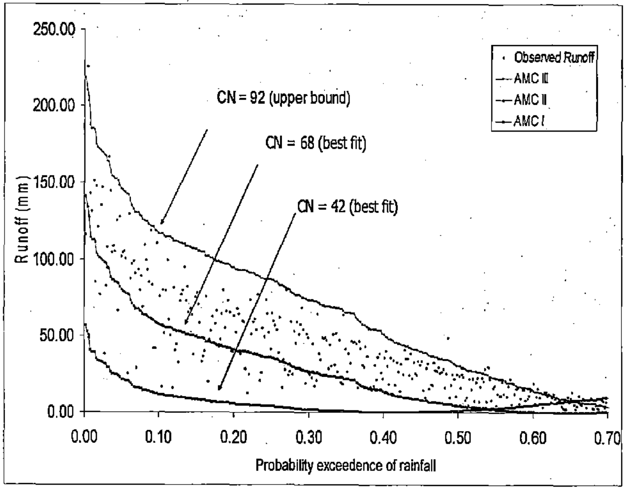
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 5 days duration for three level AMC, AMC I through AMC III



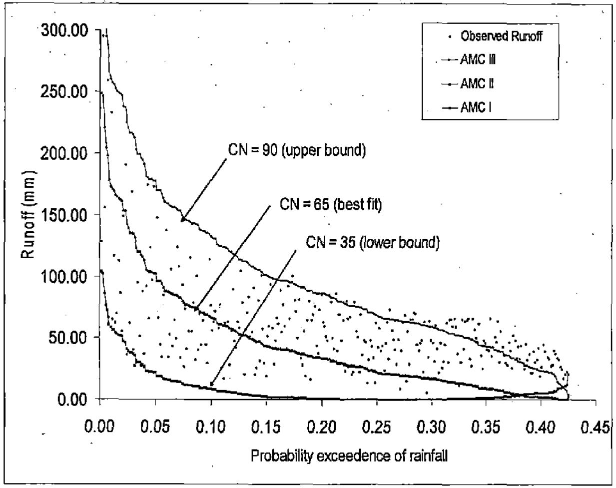
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 6 days duration for three level AMC, AMC I through AMC III



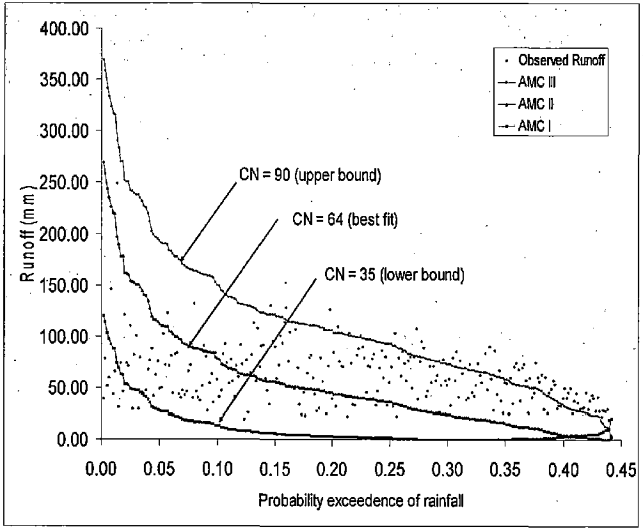
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 8 days duration for three level AMC, AMC I through AMC III



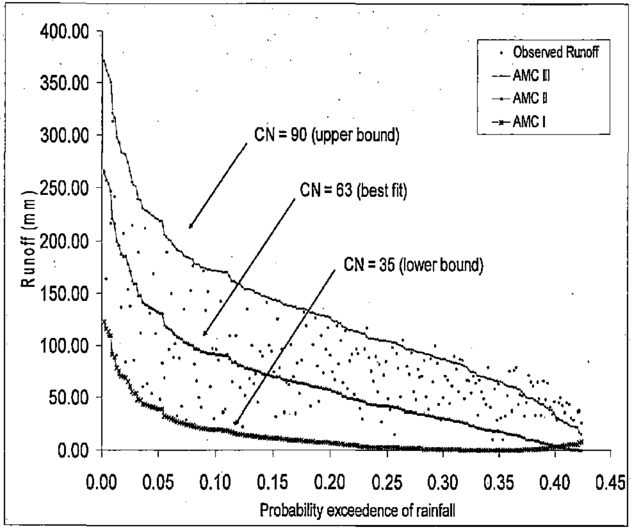
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 10 days duration for three level AMC, AMC I through AMC III



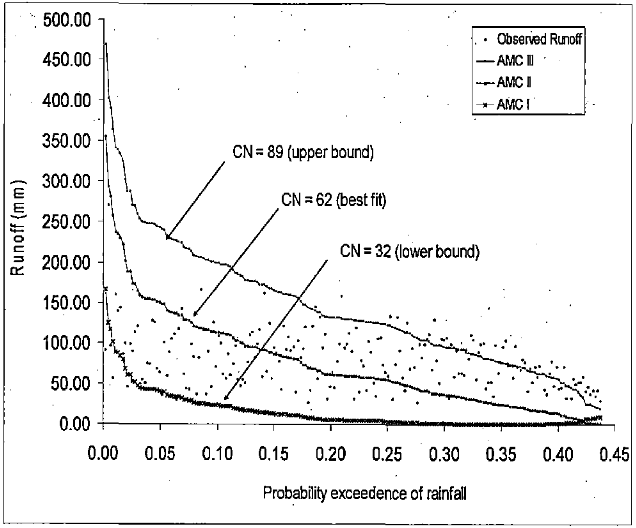
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 12 days duration for three level AMC, AMC I through AMC III



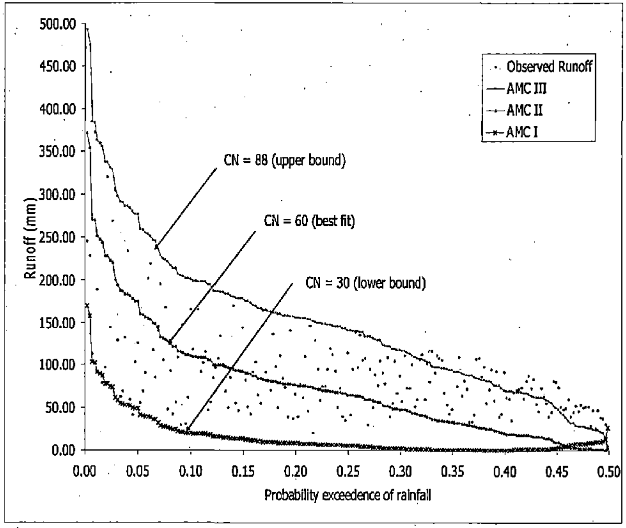
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 14 days duration for three level AMC, AMC I through AMC III



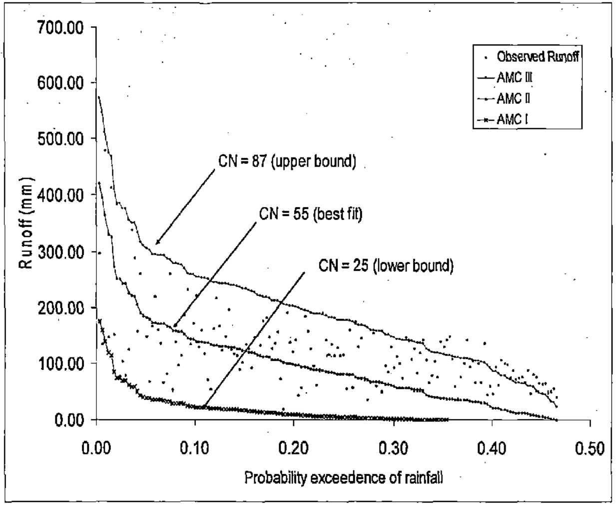
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 16 days duration for three level AMC, AMC I through AMC III



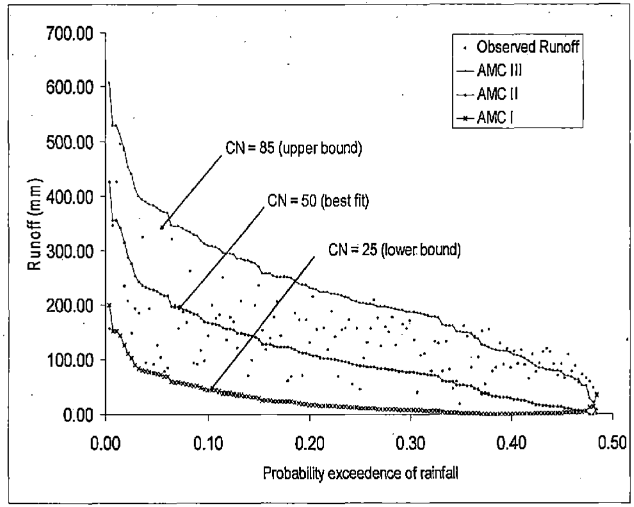
CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 18 days duration for three level AMC, AMC I through AMC III



CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 20 days duration for three level AMC, AMC I through AMC III



CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 25 days duration for three level AMC, AMC I through AMC III



CN-Value Derivation of Tawang Rejeni watershed of upper Brantas basin, for 30 days duration for three level AMC, AMC I through AMC III