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ASYMPTOTIC ESTIMATION OF RUNOFF CURVE NUMBER FOR SMALL HARD ROCK WATERSHEDS FROM RAINFALL-RUNOFF DATA

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PREFACE

Hydrologists are frequently concerned with the estimation of runoff from rainstorms for the purpose of structural design, environmental impact assessment, water resources and land management, etc. Presently, there are various methods available for this purpose. Many computer models in water resources use SCS curve number methodology to determine rainfall excess from rainfall events. This method is, developed by the U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS), for small watersheds in 1954. Curve Number (CN) is a dimensionless coefficient which reflects runoff potential and it depends on hydrologic soil group, land cover type, and antecedent moisture condition. This factor is used for evaluating effects of changes in land use and land treatment on direct runoff.

In small catchments, where sufficient historical P-Q data is available, curve number values can be estimated from selected P-Q pairs. These calculated CN values tend to approach an asymptotic value for larger ranges of rainfall value and this asymptotic curve number can be assumed as the curve number for the catchment (Hawkins, 1993).

In the present study, runoff curve number have been estimated for three small hard rock catchments, Barchi, Dandavathi, and Melumalai, from rainfall-runoff events by asymptotic fitting of curve numbers calculated from data. Validity of this methodology has been tested, by computing the curve number for Barchi watershed using the conventional SCS method. This study has been carried out by, Sh.Chandramohan T., Scientist C, of NIH Regional Centre, Belgaum, as a part of the work programme for the year 1999-2000.

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ABSTRACT

One of the major activities in applied hydrology is the estimation of storm event runoff from ungauged small watersheds. Such estimates are often required in the design of small hydraulic structures and formulation of watershed management strategies. USDA, Soil Conservation Service (SCS) Curve Number method is a well accepted tool in Hydrology for the estimation of design floods for small hydraulic structures and for other rainfall-runoff analyses. This is a simple, predictable, and stable conceptual method. The curve number (CN) is a measure of retention by a given combination of soil and vegetation and varies from 0 (no runoff) to 100 (all rainfall becomes runoff). Curve number values for different combinations of soil, land use and treatment classes are given in SCS National Engineering Handbook (SCS, 1985). These tables were derived from the analyses of data from small experimental watersheds in USA. So it is preferable to have an alternate method to estimate curve number of the selected catchment. Method suggested by Hawkins (1993), where an average curve number for a watershed is estimated from observed rainfall-runoff data set, used in the present study.

Observed rainfall-runoff event data has been used to estimate the average curve number for three small hard rock catchments, namely, Melumalai, Barchi, and Dandavathi. Natural and frequency matched data sets were used for the analysis. Sensitivity of computed curve number, with rainfall and runoff values, has been tested by forcing 10 % error in data set. In order to check the applicability of this method, curve number was estimated for Barchi watershed by the conventional SCS method using the soil and land use data.

1.0 INTRODUCTION

Water is one of the most important natural resources of a country, which controls the human developmental activities. Planning and execution of water resources projects require runoff estimates from storm events. Generally, in a river basin, number of raingauges are always more than the number of stream gauges which results in a longer rainfall records than the streamflow records. This leads to a situation in which it will be necessary to evolve some methodology to calculate runoff from the available rainfall records. A review of the literature reveals that there are many methods available to derive runoff from the rainfall records. In the absence of direct measurement of runoff, rainfall-runoff relationships, developed for a hydrologically homogeneous region can be used for the estimation of yields.

One of the simplest rainfall-runoff models is the linear model correlating runoff to rainfall. But important runoff producing mechanisms such as rainfall intensity, infiltration rate, antecedent moisture condition, etc., are not reflected in this type of model. There is a wide variety of other models where effect of these factors have been taken into account. SCS runoff curve number method is one of those models, which has wide acceptance in many hydrologic applications.

In 1954, the USDA Soil Conservation Service (SCS) proposed the curve number method to determine outflow hydrographs for use in small structural design and appraisal of land use changes. This procedure is based on a non-linear rainfall-runoff relation that uses a land condition factor called 'the curve number' to calculate depth of rainfall excess, and uses a triangular unit hydrograph to route rainfall excess to produce an outflow hydrograph. The curve number is a function of hydrologic soil type, land use and treatment, ground surface condition, and antecedent moisture. This method has been described in the SCS National Engineering Handbook, Section 4: Hydrology (NEH-4). It is a well established method in hydrological engineering and environmental impact analysis. Its popularity is rooted in its convenience, simplicity, authoritative origin, and responsiveness to four major catchment properties; soil type, land use/ land treatment, surface condition, and antecedent moisture condition.

The curve numbers (CN) associated with the soil cover complexes are median values, roughly representing average conditions on a watershed. These values are evolved based on the data from research watersheds, where experiments were conducted to determine the runoff for different soil and cover conditions.

The fundamental hypotheses of the SCS CN method are as follows;

(i) Runoff starts after an initial abstraction has been satisfied. This abstraction mainly consists of interception, surface storage, and infiltration, and

(ii) The ratio of actual retention of rainfall to the potential maximum retention S is equal to the ratio of direct runoff to rainfall minus initial abstraction.

The method is based on proportionality between retention and runoff in the following form;

$$F/S = Q/P \qquad (1)$$

where, F is actual retention (P - Q); and S = potential retention. This relation states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff. For practical applications, the above equation can be improved by incorporating initial abstraction. The initial abstraction consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins. Then the above equation can be rewritten as:

$(P - Ia - Q)/S = Q/(P - Ia)$, or

$$Q = (P - Ia)^2/(P - Ia + S) \qquad (2)$$

where, Q is the runoff volume uniformly distributed over the drainage basin, and P is the mean precipitation over the drainage basin.

The initial abstraction Ia can be expressed as a function of S, and SCS have recommended, Ia = 0.2 S from their field experiences. Physically, this means that for a given storm, 20 % of the potential maximum retention is the initial abstraction before runoff begins. Presumably, 0.8 S represents other retention losses including interception, infiltration, evapo-transpiration, and depression storage after runoff started.

Therefore, SCS rainfall-runoff relation becomes:

$$Q = (P - 0.2S)^2/(P + 0.8S) \qquad (3)$$

Evidently, this is a one parameter model with S as the parameter. This parameter depends upon characteristics of the soil-vegetation-land use (SVL) complex and antecedent soil moisture condition on a watershed.

SCS developed three antecedent moisture conditions and labeled them as AMC-I, II, and III. AMC-I represents dry condition of soil, AMC-III represents saturated soil and AMC-II is the average condition.

The watershed storage index S, is conveniently expressed in terms of a dimensionless index, runoff curve number as:

$CN = 1000/(10 + S)$, where S is in inches

or $CN = 25400/(254 + S)$, where S is in mms. (4)

Curve numbers are dimensionless, and can vary from 0 (no runoff) to 100 (all rainfall becomes runoff). Design estimates of CN based on soil, and land use are given in SCS National Engineering Handbook, Section IV (NEH-4).

Even though this methodology has been developed for small agricultural watersheds in USA, its simplicity attracted many researchers in India and other countries. This method has been subjected to large number of improvements and changes, to suit the conditions prevalent in the user country. The runoff curve number for different hydrologic soil cover complexes for Indian conditions are given in Handbook of Hydrology (1972), Soil Conservation Division, Ministry of Agriculture, Govt. of India.

Vandersypen et al. (1972) developed the following relationship between initial abstraction and potential maximum retention, for Indian conditions.

For black soil region (AMC I) and for all other regions, Ia = 0.3 S.

Therefore the SCS rainfall-runoff relationship becomes:

$$Q = (P - 0.3S)^2 / (P + 0.7S) \qquad (5)$$

and for black soil region (AMC-II and III), Ia = 0.1 S and the rainfall-runoff equation becomes:

$$Q = (P - 0.1S)^2 / (P + 0.9S) \qquad (6)$$

This equation is used with the assumption that the cracks, which are typical of black soil, when dry are filled.

So, for an event rainfall and curve number estimated from the SCS tables, the corresponding runoff can be calculated using equation (4) and (2). It is found that the calculated runoff values are sensitive to the CN values than to the observed rainfall values (Hawkins, 1975). Also it is found that selection of CN is difficult, for soil and land use/land cover types which are not mentioned in the SCS tables. So, the curve number values estimated using the conventional SCS method has to be verified using local real data on rainfall and runoff, for better application of SCS methodology.

In the present study, three small catchments are selected for the estimation of curve number from the historical rainfall-runoff data set. These catchments are: Melumalai in Dharmapuri district of Tamil Nadu, Barchi in North Kanara district of Karnataka, and Dandavathi in Shimoga district of Karnataka.

2.0 SCS CURVE NUMBER METHOD

The SCS curve number method is an infiltration loss model, although it may also account for interception and surface storage losses through its initial abstraction feature. This method is not intended to account for long term losses such as evaporation and evapo-transpiration.

The curve number methodology was originated as the result of a large number of infiltration tests carried out by SCS in late 1930s and 1940s. These tests were conducted to evaluate the effects of watershed treatment and soil conservation measures on the rainfall-runoff process. Sherman (1942, 1949) had proposed plotting direct runoff versus storm rainfall. Based on this idea, Mockus (1949), suggested that surface runoff estimates for ungauged watersheds could be made using the information on soils, land use, antecedent rainfall, storm duration, and average annual temperature. He combined all these factors into an empirical parameter 'b' characterising the relationship between rainfall depth P and runoff depth Q; $Q = P(1 - 10^{-bP})$ (Rallison, 1980). Andrews (1954), using infiltration data from Texas, Oklahoma, Arkansas, and Louisiana, developed a graphical procedure for estimating runoff from rainfall for several combinations of soil texture, type and amount of cover, and conservation practices. The combination was referred to as 'soil-cover complex' (Miler and Croshney, 1989).

Mockus' empirical rainfall-runoff relationship and Andrews' soil-cover complex were the basics of the conceptual rainfall-runoff relationship put forward by SCS. This method, since then referred to as the runoff curve number method, had the following significant features (Ponce, 1996):

1. The runoff depth Q is bounded in the range $0 \leq Q \leq P$, assuring its stability.

2. As rainfall depth P grows unbounded ($P \rightarrow \infty$), the actual retention ($P - Q$) asymptotically approaches a constant value S. This constant value, referred to in NEH-4 as potential maximum retention or potential retention, characterises the watershed's potential for abstracting and retaining water and therefore its runoff potential.

3. A runoff equation relates Q to P, and a curve number parameter CN, in turn, relates to S.

4. Estimates of CN are based on hydrological soil group, land use and treatment classes, hydrologic surface condition, and antecedent moisture condition.

The SCS rainfall-runoff relationship, $Q = (P - Ia)^2/(P - Ia + S)$, has two parameters; S and Ia. To remove the necessity for an independent estimation of initial abstraction, a linear relationship between Ia and S was suggested by SCS; $Ia = \lambda S$, where λ is the initial abstraction ratio. From the experiments conducted in watersheds less than 10 acres in size, it is found that 50 % of the data points were lying within the limits of $0.095 \leq \lambda \leq 0.38$. From this analysis, SCS adopted a standard value for initial abstraction ratio as

0.2. However, values varying in the range of 0.0 - 0.3 have been documented in a number of studies encompassing various geographical locations.

Potential retention is a measure of the ability of a given site to abstract and retain storm rainfall, provided the level of antecedent moisture has been factored into the analysis. In other words, potential retention and its corresponding curve number are intended to represent the capacity of a given site to abstract and retain storm rainfall. It also reflects (i) the recent history of antecedent rainfall, or lack of it, which may have caused the soil moisture to depart from an average level, (ii) seasonal variation in runoff properties, and (iii) unusual storm conditions.

The major factors that influence CN value are the hydrologic soil group, land use/treatment class, hydrologic condition, and antecedent moisture condition.

The SCS has classified all soils into four hydrologic soil groups (A, B, C, and D) according to their infiltration rate, which is obtained for bare soil after prolonged wetting. Among these, the group A is having the lowest runoff potential and high infiltration rates and group D soils are having highest runoff potential with lowest infiltration rates.

Treatment is a cover type modifier used in the SCS table to describe the effect on CN of the management of cultivated agricultural lands. It includes mechanical practices, such as contouring and terracing, and management practices, such as crop rotations and reduced or no tillage.

Hydrologic condition indicates the effect of cover type and treatment on infiltration and runoff and is generally estimated from density of plant and residue cover on sample areas. A good hydrologic condition indicates that the soil usually has a low runoff potential for the given hydrologic soil group, cover type, and treatment.

Antecedent moisture condition is an index of runoff potential for a storm event. The AMC is an attempt to account for the variation in CN at a site from storm to storm.

As any other conceptual model, the curve number method also works in the mean, implying that there is room for some variability. Due to this, the same watershed can have more than one curve number or a set of curve numbers. Among the likely sources of this variability are:

1. The effect of spatial variability of storm and watershed properties
2. The effect of temporal variability of the storm, ie., the storm intensity
3. The quality of the measured data, ie., the P-Q sets
4. The effect of antecedent rainfall and associated soil moisture

The latter was recognised very early as the primary or tractable source of the variability, and thus, the concept of antecedent moisture condition (AMC) originated.

The NEH-4 runoff curve numbers were developed from recorded rainfall-runoff data, where hydrologic soil group, land use/treatment class, and surface condition were known. The P-Q data was plotted and the CN corresponding to the curve that separated half of the plotted data from the other half was taken as the median curve number for the given site. The natural scatter of points around the median curve number was interpreted as a measure of the natural variability of soil moisture and associated rainfall-runoff relation.

To account for this variability, the P-Q plots were used to define enveloping or near-enveloping CN values for each site. These enveloping curve number values are considered as the practical upper and lower limits of expected CN variability for the given combination of soil cover complex. Thus, antecedent moisture condition was used as a parameter to represent the experienced variability. The curve number lying in the middle of the distribution is the median curve number, corresponding to AMC 2 (average runoff potential). This is the standard curve number given in the SCS tables. The low value is the dry curve number, of AMC 1 (lowest runoff potential) and the high value is the wet curve number, of AMC 3 (highest runoff potential).

Hjelmfelt et al. (1982) found that the AMC conversion table described the 90 % (AMC 1), 50 % (AMC 2), and 10 % (AMC 3), cumulative probabilities of exceedence of runoff depth for a given rainfall. In other words, they found that AMC 2 represented the central tendency, while AMC1 and AMC 3 accounted for dispersion in the data. Hawkins et al. (1985) interpreted the AMC categories as error bands or envelopes indicating the experienced variability in rainfall-runoff data.

To decide about the level of AMC to be used in a given case, NEH-4 has given a table based on total 5-day antecedent rainfall, for dormant and growing season. However, the table does not account for regional differences or scale effects. An antecedent period longer than 5 days would probably be required for larger watersheds. By considering this, SCS has deleted the table in the new version of Chapter 4, NEH, released in 1993. So in practice, the determination of AMC is left to the user, who must evaluate whether a certain design situation warrants AMC 1, AMC 2, or AMC 3.

Ponce (1996), enumerated the advantages and disadvantages of the method as:

The advantages are:

1. It is a simple, predictable, and stable conceptual method for the estimation of direct runoff depth based on storm rainfall depth.

2. It relies on only one parameter, the runoff curve number, which varies as a function of four major runoff producing watershed properties; hydrologic soil group, land use and treatment class, hydrologic surface condition, and antecedent moisture condition.

3. It is the only methodology that features readily grasped and reasonably well documented inputs.

4. It is a well established method, having been widely accepted for use in various countries.

The disadvantages are:

1. The method was originally developed using regional data, mostly from the midwestern USA. So some caution is necessary when it is applied to other geographic or climatic regions.

2. For lower curve numbers and/or rainfall depths, the method is very sensitive to curve number and antecedent moisture condition.

3. The method is best suited for agricultural sites, for which it was originally intended, and has since been extended to urban sites. The method rates fairly in applications to range sites, and generally does poorly in application to forest sites. The implication here is that the method is best suited for storm rainfall-runoff estimates in streams with negligible baseflow, ie., those for which the ratio of direct runoff to total runoff is close to one.

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

5. The method fixes the initial abstraction ratio at 0.2. In general, however, this ratio could be interpreted as a regional parameter.

3.0 STUDY AREA

For the estimation of curve number from the rainfall and runoff data set, three small catchments were selected. The description of each watershed is given below.

3.1 MELUMALAI WATERSHED

This watershed is located at Melumalai village, in Sulagiri block of Hosur taluk in Dharmapuri district of Tamil Nadu. It is in North-West direction of Krishnagiri at a distance of 19 km from Krishnagiri on Krishnagiri-Bangalore road. The watershed lies between North latitude 12°36'40" and 12° 40'00" and East longitudes 78°04'15" and 78°07'15". It covers an area of 16.5 sq.km.

This watershed is surrounded by hillocks on the eastern side, high level ground on northern side and low level ground on southern side. The upstream end of the watershed is at an elevation of 848 m and the mouth of the watershed is at an elevation of 590 m. The main stream runs at the centre of the watershed and it is a 4th order stream. This stream crosses Krishnagiri-Bangalore road at the outlet of the watershed, where the gauge readings are being taken and the flow is being measured. A full fledged meteorological observatory is located at Samalapallam, near to the outlet, which measures rainfall (daily and hourly), evaporation, humidity, minimum-maximum temperature, wind velocity and direction, and sunshine hours. The stream joins Ponnaiyar river about 3 km downstream of the gauge site. The study area and its location is shown in Figure 1.

Average annual rainfall for the watershed is 680 mm.

3.2 BARCHI WATERSHED

The Barchi watershed upstream of Barchi is located in the leeward side of western ghat and is a sub-basin of Kali river as shown in Figure 2.

Barchi nala originates from Thavargatti in Belgaum District at an altitude of about 734 m, 20 km north of Dandeli and flows through North Kanara district of Karnataka State. The catchment is relatively short in width and river flows on a southerly direction and joins the main Barchi river near the gauging site. The geographical area covered by Barchi watershed is 21.26 sq. km. The watershed lies between 74°36' and 74°39' East longitudes, and 15°18' and 15°24' North latitudes.

High land region consists of dissection of high hills and ridges forming part of the foot hills of western ghats. It consists of steep hills and valleys intercepted with thick

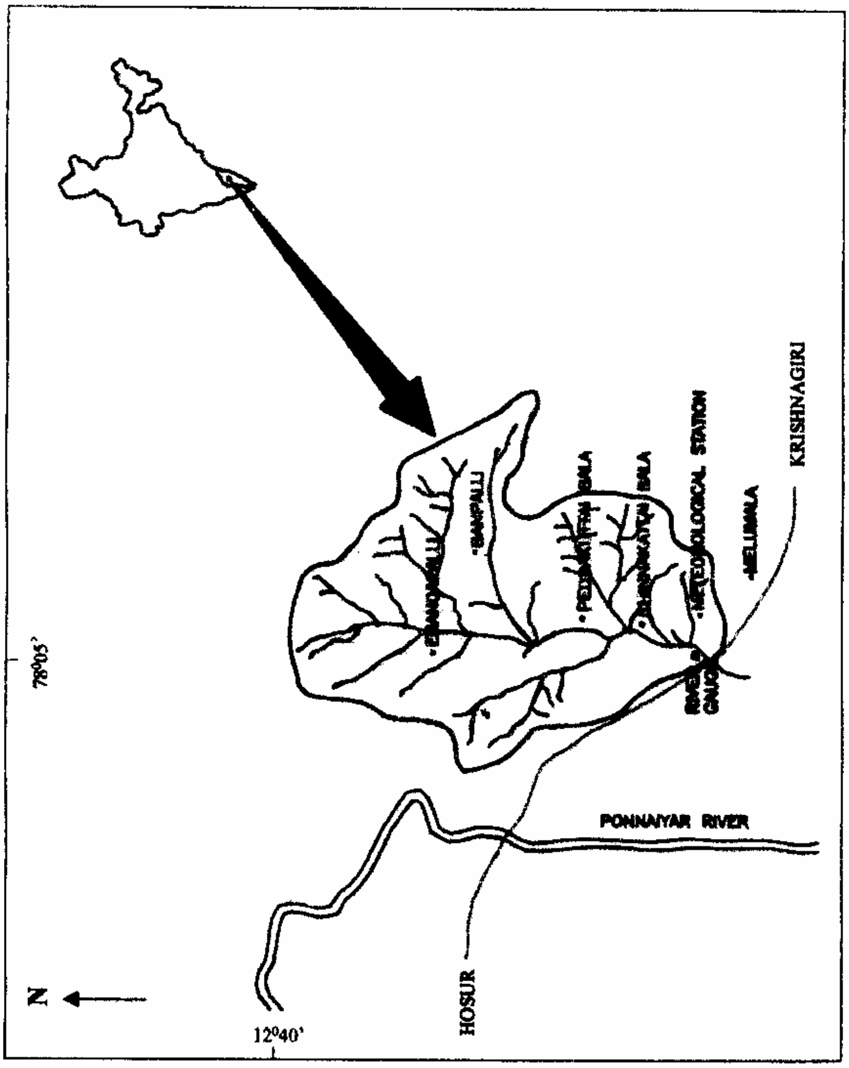


Fig. 1. Melumalai Watershed

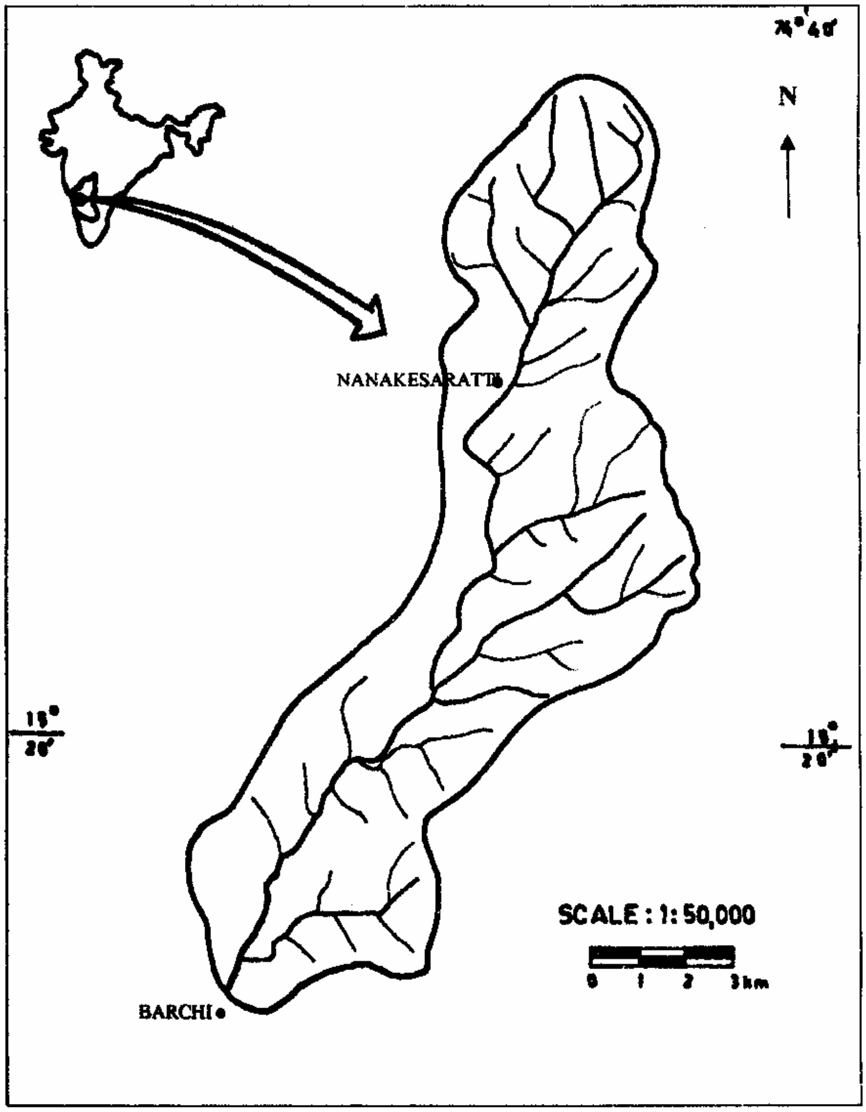


Fig. 2. Barchi Watershed

vegetation. The slopes of the ghats are covered with dense deciduous forest. The brownish and fine grained soils are the principal types of soils found in this area.

The stream gauge site is located at an elevation of 480 m, where the nala crosses Dandeli-Thavargatti road, about 5 km from Dandeli. The stream is a 4th order stream. This stream joins main Barchi river downstream of the gauge site. A full fledged meteorological station, maintained by WRDO, is located near the gauging site. Average annual rainfall for the watershed is 1500 mm and the area receives majority of this rainfall during south-west monsoon period.

3.3 DANDAVATHI CATCHMENT

The Dandavathi catchment upstream of Sorab is situated in the Western Ghats and is a sub-basin of Krishna river. The catchment and its location is shown in Figure 3.

Dandavathi originates from Karjikoppa in the foot hills of western ghat at an altitude of about 2775 ft and 16 km south of Sorab in Shimoga district of Karnataka State. The river flows in a northerly direction and joins the Varada river which is a tributary of Krishna. The total catchment area of the basin is 118.88 sq. km. The catchment area lies between 74°58' and 75°16' East longitudes and 13°45' and 14°00' North latitudes along the border of Sorab and Sagar taluk.

The catchment has four distinct seasons in an year, such as, cold weather, hot weather, southwest monsoon and post monsoon. The red and gravely soils are the principal soils found in the study area. The stream gauge site maintained by WRDO is located at Sorab at an elevation of 1950 m. Rainfall records are available from raingauges stations situated at Sorab and Kuppe. Average annual rainfall for this area is 1800 mm.

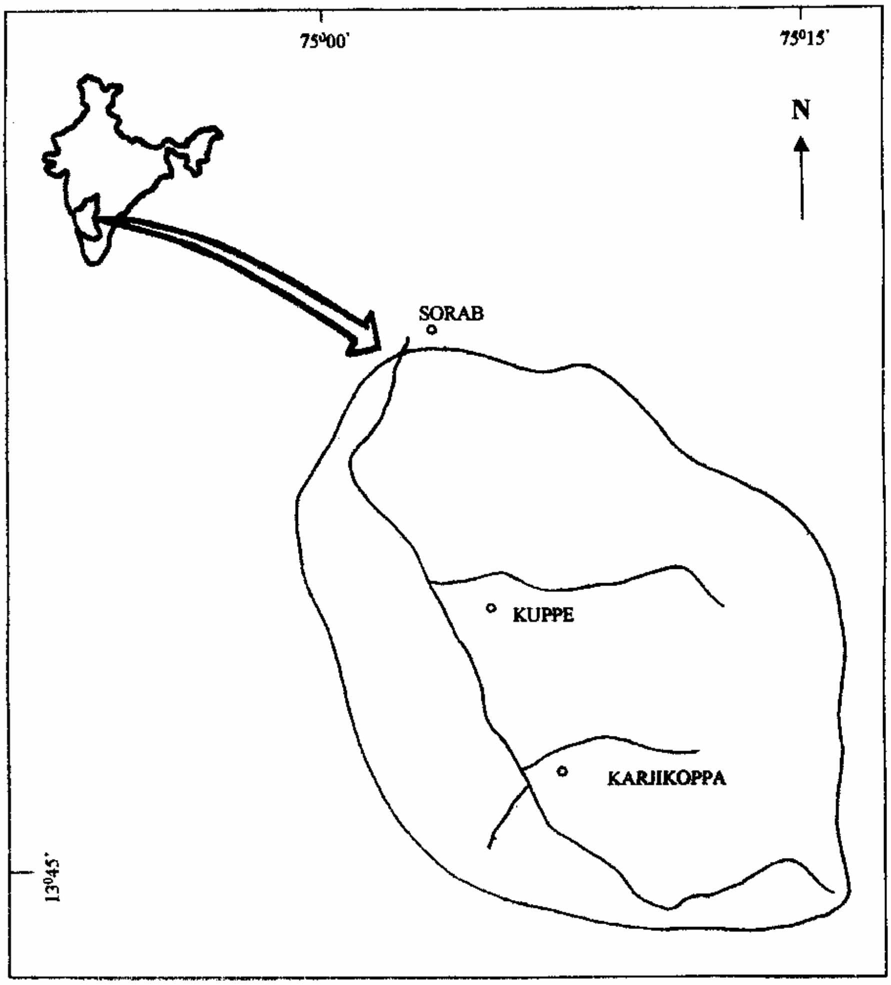


Fig. 3. Dandavathi Catchment

4.0 METHODOLOGY

Curve numbers given in the SCS tables (NEH-4) were derived from analysis of data from small experimental watersheds in USA. So, use of the same tables in our conditions, will lead to erroneous estimation of curve numbers and in turn runoff depths. Hence, it is advantageous to have some alternate method for the estimation of runoff curve number. The objective is either to verify the curve number values given in the standard SCS tables, or, to extend the methodology to soil cover complexes and geographic locations not covered by the NEH-4. Because of the sensitivity of the method to CN values and the unreliability of CN estimates from standard tables, reassurance and safe reference should be taken from local real data situations, ie., by determining curve number for local watersheds from recorded storm rainfall-runoff.

Since the method's inception, several investigators have attempted to determine runoff curve numbers from small watershed rainfall-runoff data, which can be used for homogeneous regions. An established procedure to estimate CN values from rainfall-runoff data is to solve for S from SCS rainfall-runoff equation, which results in:

$$S = 5(P + 2Q - \sqrt{4Q^2 + 5PQ}), \text{ for Ia} = 0.2\text{ S} \qquad (7)$$

For a given P and Q pair, the potential retention S can be calculated using the above equation, and the corresponding CN can be calculated using, $CN = 1000/(10 + S)$.

For areas where Ia = 0.1 S or 0.3 S, the expressions for the calculation of S from the observed rainfall-runoff pairs are as follows;

for Ia = 0.1 S,

$$S = 5(2P + 9Q - \sqrt{81Q^2 + 40PQ}) \qquad (8)$$

for Ia = 0.3 S,

$$S = 0.56(6P + 7Q - \sqrt{49Q^2 + 120PQ}) \qquad (9)$$

There are several ways to select the P-Q pairs for analysis. The standard method, referred to as the annual flood series, is to select daily rainfall and its corresponding runoff volume for the annual floods at a site. When the annual flood series is not available for a larger period, it is possible to select storm event data. This incorporates rainfall-runoff events with return period less than one year. This procedure has the advantage that it results in a considerable range of rainfall and runoff values for analysis.

Another approach is the frequency matching method. The storm rainfall and direct runoff depths are sorted separately, and then realigned on a rank basis to form desirable P-Q pairs of equal return period. The individual runoff values are not necessarily associated with the original rainfalls. For all return periods, the CN is taken to be consistent. Thus, when treating rainfall and runoff data, the N-year return period rainfall should be paired with N-year return period runoff. Here, the CN method may be seen as a transformation between a rainfall-depth distribution and a runoff depth distribution.

When curve numbers are calculated from real storm data, a secondary relationship emerges between CN and the storm rainfall depth. Different watersheds with varying rainfall-runoff relationship show different types of variation of curve number values with increasing precipitation values. The first variation is the Complacent behaviour, in which the observed CN values decline steadily with increasing rainfall depth and show no appreciable tendency to achieve a stable value. In this case, curve number cannot be safely determined from data, because no constant value is clearly approached.

The second variation is the standard behaviour, which is the most common scenario. Here, observed CN declines with increasing storm size and approaches and/or maintain a near constant value with increasingly larger storm. The runoff itself may arise from a variety of source process, including overland flow and rapid subsurface flows.

The third variation is violent behaviour, in which the distinguishing feature is that the observed curve numbers rise suddenly and later asymptotically approach a constant value. There is often accompanying complacent behaviour at lower rainfalls. From a source-process standpoint, this could be a threshold phenomenon at some critical rainfall depth value. The above three types of variations are shown in Figure. 4.

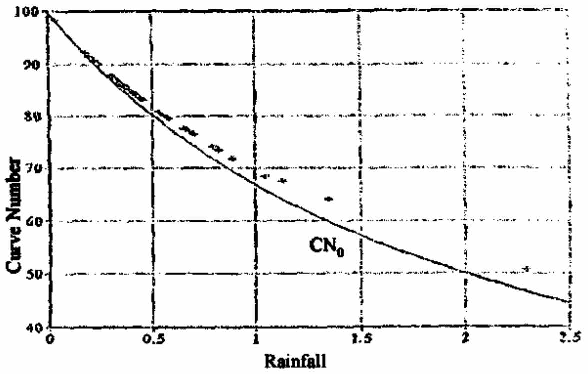
In the P-CN variations as shown in figure 4, there is a CN value for which any rainfall value less than a threshold P will yield no runoff. This is denoted as CN_0 curve, where $CN_0 = 100 / (1+ 0.5 P)$, for $Ia = 0.2S$. CN_0 is defined for a given P for which the initial abstraction is just satisfied. Any smaller P for that CN will give no runoff and likewise any CN smaller than CN_0 will give no runoff for the same P. The area below CN_0 line is considered as domain of no runoff (Hawkins 1979).

In most of the cases, these calculated CNs approach a constant value with increasing rainfall. This asymptotic constant value CN_∞ is used to identify the curve number for a watershed. The equation;

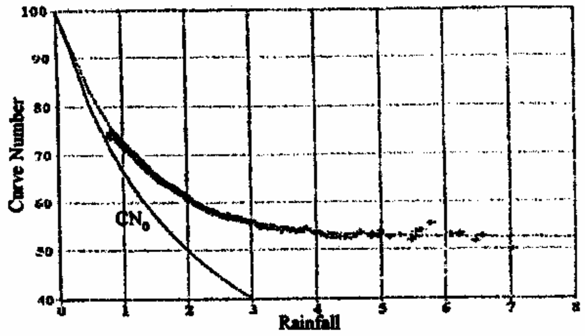
$$CN(P) = CN_\infty + (100 - CN_\infty)\exp(-kP) \qquad (10)$$

has been found to fit (P-CN) data set, where CN_∞ is the constant curve number value as $P \rightarrow \infty$ and k is a fitting constant. This equation may be fitted by a least square procedure to calculate CN_∞ and k. Although, this is an entirely curve fitting approach, it has been found to be appropriate for a wide array of watershed data sets.

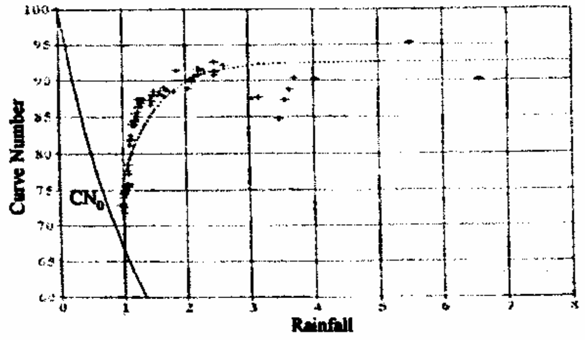
The asymptotic constant value is used in identifying the CN for a watershed. Thus, where no constant value is approached, as in complacent situations, no CN_∞ can be determined. The problem is then reduced to an objective determination of that asymptote for the standard and violent situations. When the data exhibit complacent behaviour, asymptotic fit can still be possible by assuming that the data set is merely the lower rainfall



Complacent Behaviour



Standard Behaviour



Violent Behaviour

Fig. 4. Different variations of CN with P (Hawkins, 1993)

end of the standard behaviour pattern. Then the watershed may perform in the extrapolated standard pattern when larger storms are eventually encountered. By considering this, a value of CN_∞ may indeed be calculated, but it will be much lower than any CN experienced in the data set. Complacent behaviour can also be a beginning of the violent behaviour, since there is no way of knowing which response path might be active at higher rainfalls. So, it is advisable that the complacent data set should not be extrapolated to assume constant CNs in the standard pattern. This situation suggests that the watershed does not respond in accord with the CN equation, at least not within the range of the data set encountered.

The violent pattern applies to the observed CNs, that suddenly increase and then approach a constant value with increasing storm size. In this case, the equation,

$$CN(P) = CN_\infty\{1 - \exp(-kP)\} \qquad (11)$$

has been found to fit P-CN data set. This pattern is sometimes preceded with a complacent pattern at lower rainfall, but only the non-complacent data points should be used in the above equation.

5.0 ANALYSIS AND RESULTS

5.1 ASYMPTOTIC ESTIMATION OF CURVE NUMBER

As mentioned in previous sections, SCS curve number methodology is the simplest and most popular methodology for the estimation of storm runoff. In this method, selection of proper curve number for a particular watershed is of utmost importance since the runoff output is sensitive to the curve number value. The asymptotic estimation of curve number is advantageous over the conventional method, as it uses the real rainfall-runoff data sets. There are also ways to check the stability of the fit and to assess the degree of accuracy of the results obtained.

In the present study, three watersheds falling under the hard rock region of the country were selected to estimate the average curve number for each watershed. Rainfall-runoff records were collected for a reasonably long period, so as to cover wide variations in the storm pattern. Using the hourly/daily rainfall records, various storms were separated and the corresponding runoff amounts were taken from the runoff records. Since the SCS method basically handles surface runoff, the base flow separation has been done by simple observation of the low flow values in the data set.

Once the rainfall-runoff events have been separated, the first step is to order the data, ie., sort the rainfall and runoff depths independently in descending order and rematch them. Since each of the ordered items is of the same return period, this assures frequency matching between rainfall and runoff. For this study, both natural and ordered P-Q data sets were used for the estimation of curve number. The second step is to determine curve numbers for different initial abstraction rates. Third step is the asymptotic definition, in which a classification is made and the average curve number is determined by least square fitting using a basic programme developed by Hawkins (1993).

Since it is difficult to properly determine the value of initial abstraction coefficient, the rainfall-runoff pairs were used to estimate curve numbers for three initial abstraction coefficients, 0.1 S, 0.2 S, and 0.3 S. The asymptotic curve numbers, for the three watersheds for these abstraction rates, are given in Table 1. From the table it can be seen that ordered data set is giving a higher CN value. This is because in ordered data set, higher rainfall is matched with a higher runoff which will give a larger CN value compared to natural data set in which the higher rainfall values may be matched with lower runoff values. It can also be seen from the table that an initial abstraction rate of o.3 S gives the larger CN_∞ value.

Table 1: Estimated Curve Numbers for the Watersheds for Different Ia Rates

Watershed	**BARCHI**		**MELUMALAI**		**DANDAVATHI**	
Ia	Natural	Ordered	Natural	Ordered	Natural	Ordered
0.1 S	31.3	36.8	37.9	41.8	52.2	54.9
0.2 S	37.9	42.2	45.7	50.9	56.2	58.9
0.3 S	42.6	46.2	50.0	56.6	59.0	61.6

Melumalai

26 storms and corresponding runoff values were selected from available daily data series for 1981 - 1991. All the storms were from monsoon season. Base flow was separated from individual runoff by simple judgment of low flow values.

For the selected rainfall-runoff values, CN_∞ values were calculated for both natural and ordered data set. Curve number values for this data set shows a standard behavior, as can be seen from Figures 5 and 6 (variation of natural and ordered data set for Ia = 0.2 S). The variation of curve numbers, calculated for all the initial abstraction rates, are similar to that shown in figure 5 and 6.

The results from the least square fit are shown in Table 2. The factor k is the fitting coefficient in the asymptotic equation (10). Other parameters given in the table will be explained in succeeding discussions. It can be seen from the table that the ordered data set yields better r-squared value. In the ordered data set, the rainfall and runoff pairs are matched as per the return period. This will reduce the scatter in the calculated CN values and results in a better fit.

Table 2: Results from Standard Asymptotic Fit for Natural and Ordered Data Set for Melumalai

	NATURAL			**ORDERED**		
	0.2 S	0.1 S	0.3 S	0.2 S	0.1 S	0.3 S
CN∞	45.66	37.89	50.03	50.88	41.83	56.57
k (1/inch)	0.60	0.82	0.48	0.88	1.17	0.74
R-squared %	53.39	46.87	57.78	94.00	92.22	94.78
CNP (90)	47.12	38.33	52.82	51.12	41.88	57.08
Stability %	97.20	99.30	94.41	99.50	99.91	98.83
dQ/dP %	38.14	25.70	43.94	49.61	34.07	58.05

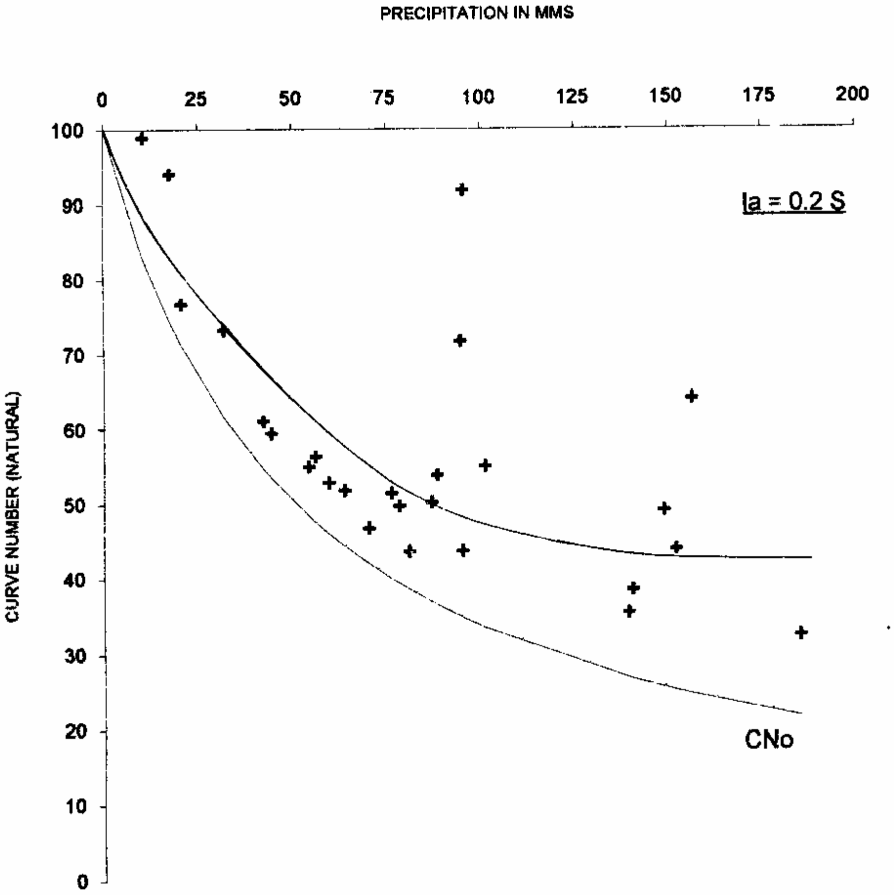


Fig. 5. Variation of Curve Number (Natural) With Rainfall for Melumalai

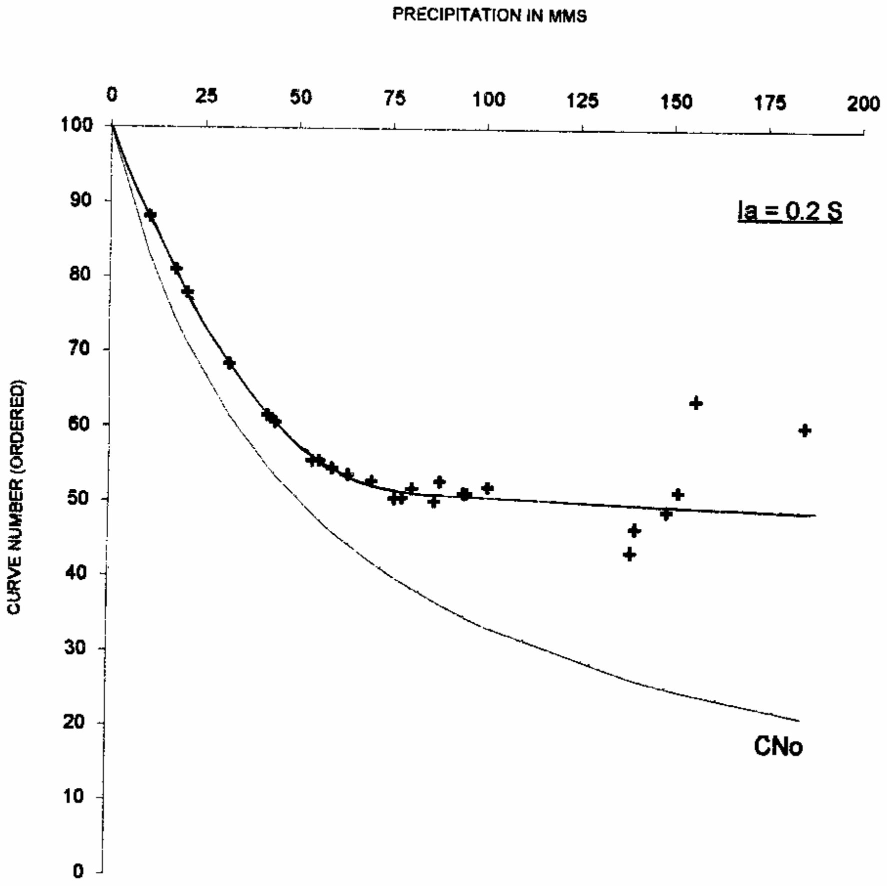


Fig. 6. Variation of Curve Number (Ordered) With Rainfall for Melumalai

Barchi

For the analysis, 32 rainfall-runoff combinations were selected from the hourly rainfall-runoff data series of 1988 - 1997. Variation of CN with the rainfall values is a standard variation, as shown in the Figure 7 and 8. From these figures, it can be seen that there is a gap between rainfall data set between 200-350 mms. If the last point was not available for the analysis, it could be inferred that the data set assumes a complacent behaviour. So, this example illustrates the necessity of incorporating all the possible ranges of rainfall-runoff values in a basin to obtain a dependable value of CN_∞. The result from the asymptotic fit is given in Table 3.

Table 3: Results from Standard Asymptotic Fit for Natural and Ordered Data Set for Barchi

	NATURAL			ORDERED		
	0.2 S	0.1 S	0.3 S	0.2 S	0.1 S	0.3 S
CN∞	37.90	31.29	42.59	42.20	36.79	46.23
k (1/inch)	0.30	0.37	0.26	0.35	0.44	0.30
R-squared %	84.92	79.31	87.55	97.92	96.78	98.31
CNP (90)	46.52	37.38	52.78	48.24	40.33	53.97
Stability %	86.13	91.14	82.25	89.54	94.41	85.61
dQ/dP %	26.69	15.80	34.62	33.19	24.80	39.62

Dandavathi

Daily data for raingauge stations at Sorab and Kuppe was considered for the analysis. 44 storms and the corresponding runoff recorded at Sorab, were selected for the period of 1988 to 1996.

In the case of Dandavathi also, P-CN relationship shows a standard behaviour as shown in Figures 9 and 10. The curve number for the watershed and other parameters of the fit for both natural and ordered data sets are shown in Table 4.

Table 4: Results from Standard Asymptotic Fit for Natural and Ordered Data Set for Dandavathi

	NATURAL			ORDERED		
	0.2 S	0.1 S	0.3 S	0.2 S	0.1 S	0.3 S
CN∞	56.14	52.19	59.00	58.84	54.91	61.63
k (1/inch)	0.28	0.33	0.25	0.34	0.40	0.30
R-squared %	60.59	53.44	64.93	93.68	92.63	94.27
CNP (90)	57.70	53.12	61.10	59.61	55.31	62.76
Stability %	96.44	98.04	94.89	98.14	99.13	97.06
dQ/dP %	76.30	73.55	78.11	80.83	78.25	82.33

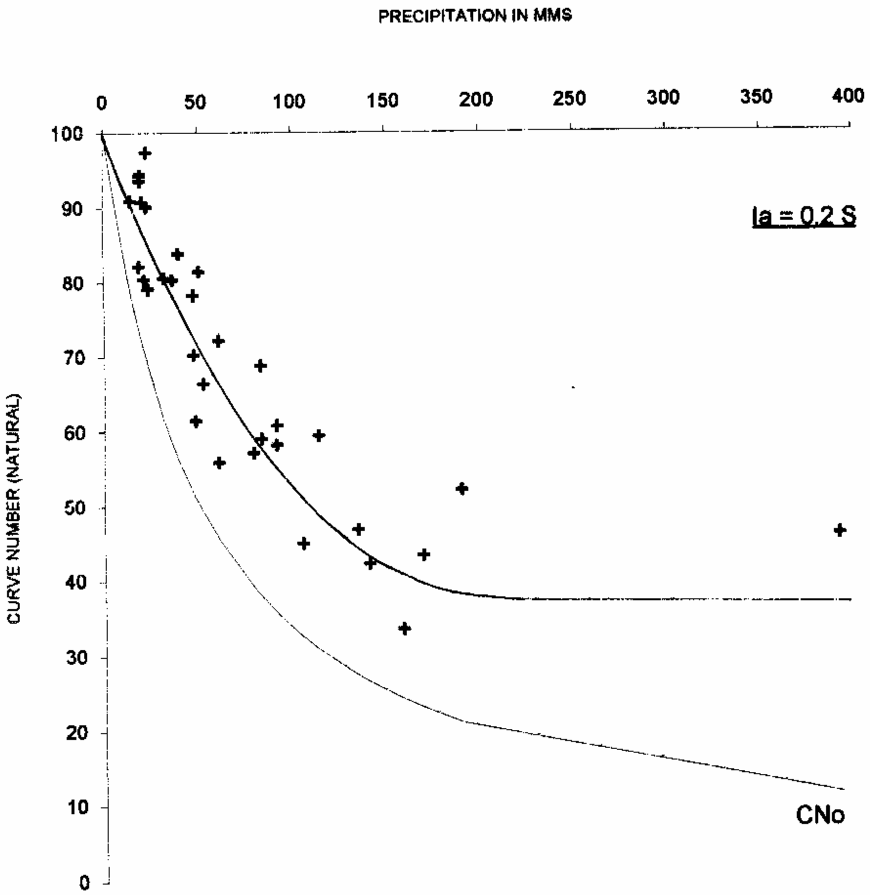


Fig. 7. Variation of Curve Number (Natural) With Rainfall for Barchi

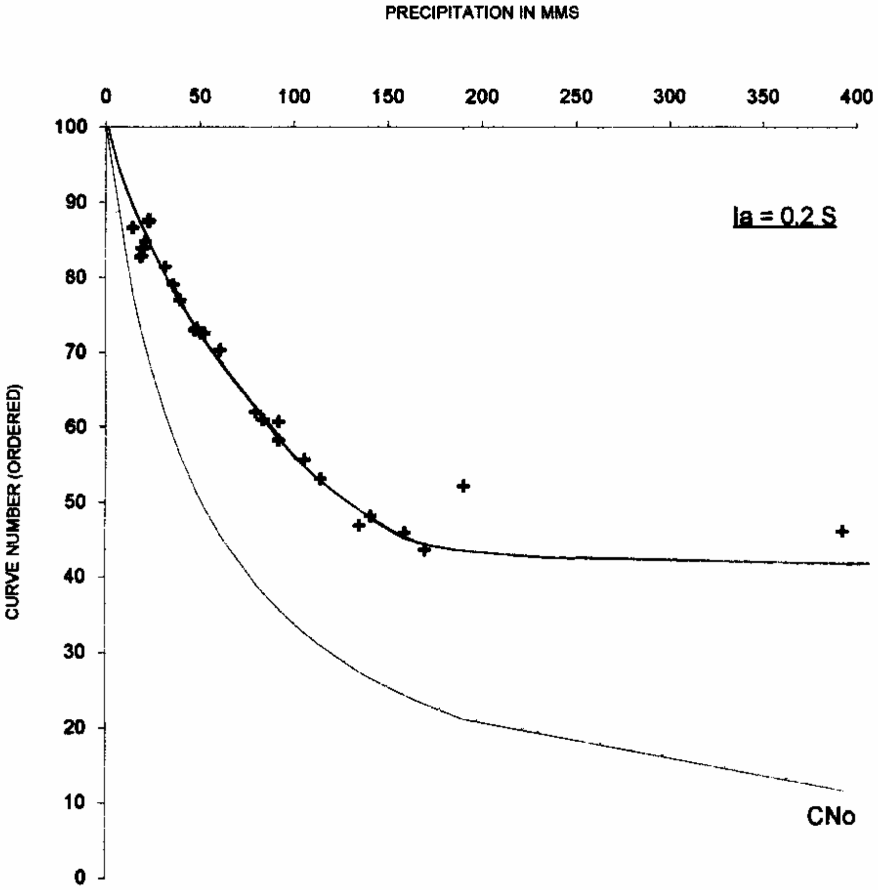


Fig. 8. Variation of Curve Number (Ordered) With Rainfall for Barchi

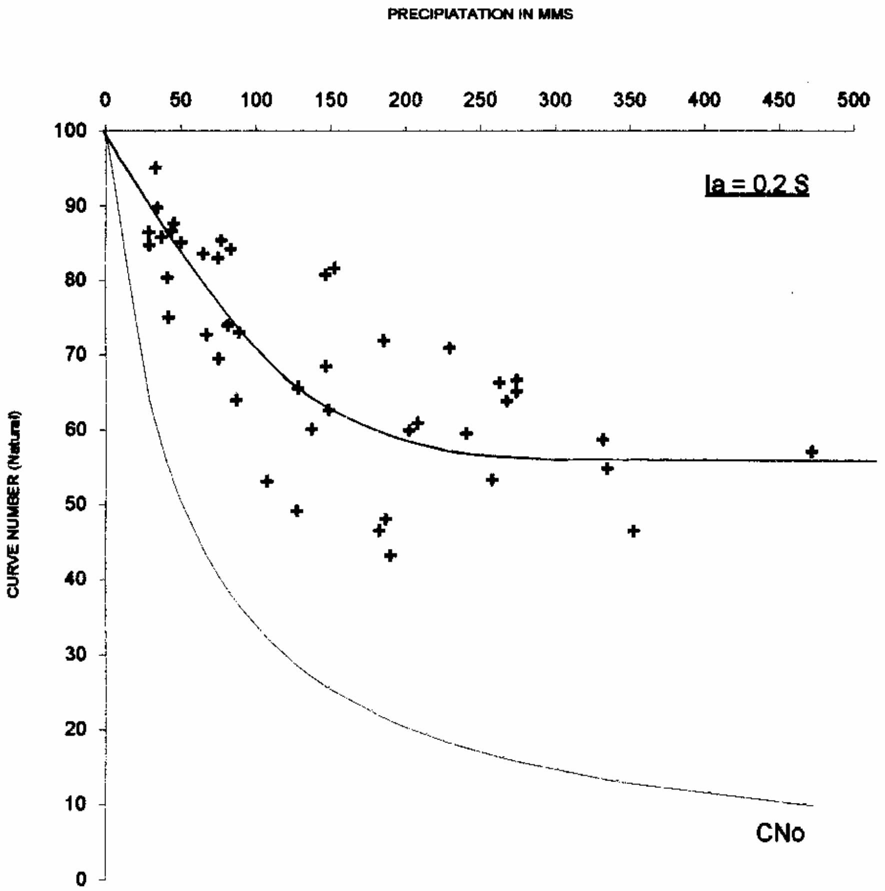


Fig. 9. Variation of Curve Number (Natural) with Rainfall for Dandavathi

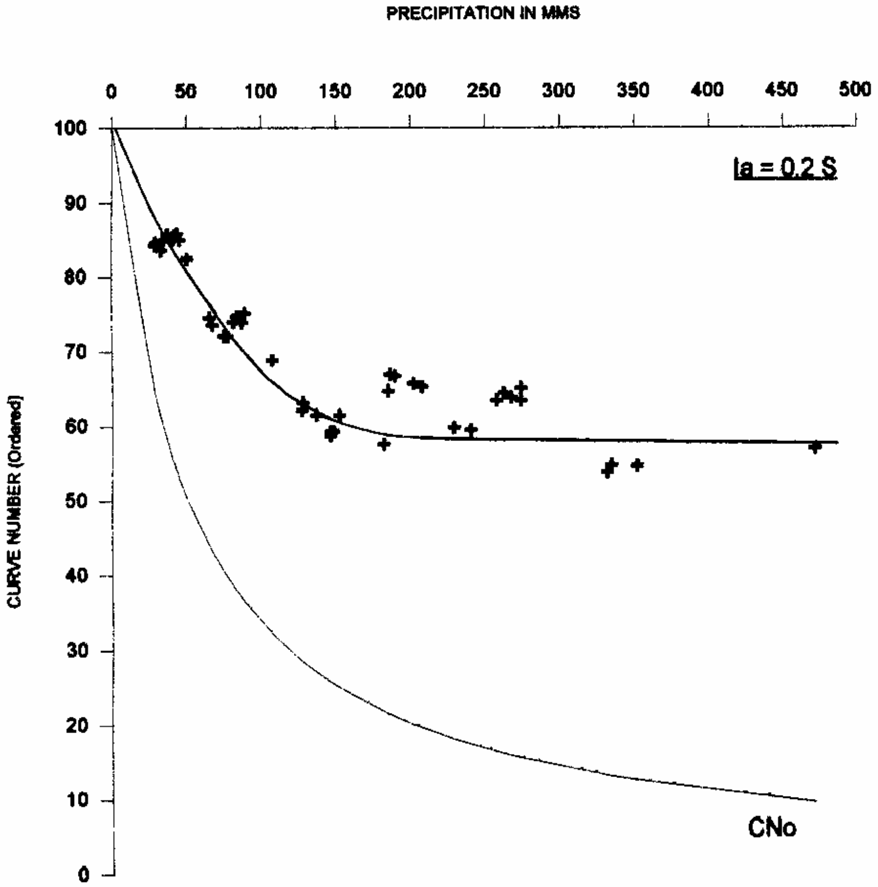


Fig. 10. Variation of Curve Number (Ordered) With Rainfall for Dandavathi

5.2 STABILITY ANALYSIS

Using CN_∞ as the curve number of reference in design work assumes that the constant CN (= CN_∞) is approached closely for the large extreme events. Since most data sets cover periods of record much less than design return periods, safe extrapolation of the fitted P-CN relations must be a concern. This is a general problem in extending model results beyond measured data. However, a stability criteria can be used as a measure of confidence. There are two methods to check the stability of the asymptotic fit; (i) using curve number for 90th percentile rainfall depth, and (ii) slope of the P:Q line. These are described below.

The degree of closeness of the upper range of the sample data to the CN_∞ index defines the stability of the fit. The relative closeness of fitted CN to the 90th percentile sampled rainfall depth is used to indicate the stability of the CN_∞ estimate. Here, the 90th percentile was determined by, rank ordering and interpolation with the rainfall data. Stability analysis is to check the extend of flattening of CN curve, and is defined as,

$$\text{Stability} = (100 - CN90) / (100 - CN_\infty)$$

The slope of the P:Q line is also a measure of hydrologically defined stability of the fit. The idea here is that the ultimate possible slope is 1:1 or 100 %. The fitted slope dQ/dP is calculated for the 90th percentile rainfall point and used as a measure of the relative development of the watersheds' hydrologic process for the upper ranges of the data set. This will vary from 0 to 100 %, with 100 % indicating a completely defined event hydrology, where the process of conversion of rainfall to runoff is completely explained by the asymptotic fit or the calculated CN value completely satisfies the SCS rainfall-runoff relation.

Stability of the asymptotic fit for the three watersheds was checked using the above mentioned criteria. The results are listed below.

Melumalai

For Melumalai watershed, 90th percentile rainfall is 15.34 cm. at which point the calculated CN is 51.12. This is very close to the CN_∞ estimate (50.88) which indicates high confidence level of the data set. Stability is calculated using the above formula as 99.05 % which shows the high degree of asymptotic attainment of CN_∞ in the data set.

For this watershed, slope of the fitted line (dQ/dP) is calculated as 49.61 %, which shows that about 50 % of the possible hydrological behaviour of the watershed is known.

Barchi

The 90th percentile rainfall for the watershed is 16.61 cm. and the corresponding curve number is found to be 48.24. The CN_∞ for the area obtained from the fit is 42.20. This gives a stability of 89.54 % which shows that the data set is poorly responding to the fit, as compared to that of Melumalai watershed, and the use of calculated CN_∞ in further applications may result in some degree of errors. This is further shown in the second stability criteria where the slope of the P-Q line is 33.19 %, which shows that only about 33 % of the path taken by rainfall to runoff is known.

Dandavathi

Dandavathi falls in high rainfall region of the western ghat and the 90th percentile rainfall value is 30.28 cm. The curve number corresponding to this rainfall is 59.61 which is very close to the asymptotic curve number 58.84. This results in a high stability of 98.14 %, which shows a high confidence level of the data set. This is further proved from the second stability criteria in which the slope of the P-Q line is found to be 80.83 %.

5.3 SENSITIVITY ANALYSIS

Storm runoff, as calculated by the SCS runoff curve number method is shown to be of varying sensitivity to both input rainfall and curve number. Although it is possible to calculate curve number from field data, such practice is not widespread since even when precipitation data are available, gauged small watersheds are rare. Clearly, an accurate estimate of curve number is the weak input link for this method.

The poor matching of curve number value estimated from the standard tables and using P-Q data, could arise from a number of sources, ie., (i) inability of the user to apply the estimation technique correctly, (ii) poor input soils and vegetation data, (iii) incorrect hydrologic analysis of field data to calculate CN, and (iv) basic error inherent in the methodology in either runoff model or the estimation procedure.

Hawkins (1975) studied the effect of fractional errors in the precipitation data and estimation of CN on the calculated Q values. He found that errors from curve number sources are more serious than precipitation source errors. It implies that the runoff calculation efforts should devote intense attention to accurate and representative curve number estimation.

To study the effect of errors in the values of measured P and Q on CN values, a ± 10 % error was forced on the rainfall-runoff data set and CN_∞ was estimated for different combinations of P-Q. These values were used to plot isolines for different percentage errors in P and Q. The results for $Ia = 0.2\ S$, are listed below.

Melumalai

The variation of curve number with the errors in rainfall and runoff values is as shown in Figure 11. Table 5 shows the asymptotic curve numbers for different combinations of P and Q. The CN values ranges from 46 to 56.1.

Table 5: Asymptotic Curve Number for Different Combinations of P & Q for Melumalai

	90 P	**P**	**110 P**
90 Q	53.3	49.5	46.0
Q	54.8	50.9	47.4
110 Q	56.1	52.2	48.7

From the figure, it can be seen that the curve number values are more sensitive to errors in precipitation between -5 to +5 % range. It shows the importance of accurate estimation of CN_∞ and good quality of rainfall-runoff data.

Barchi

The variation of curve number with various combinations of rainfall and runoff values is as shown in Figure 12. Table 6 shows the asymptotic curve numbers for different combinations of P and Q. The asymptotic curve number value varies between 36.3 to 49.3.

Table 6: Asymptotic Curve Number for Different Combinations of P & Q for Barchi

	90 P	**P**	**110 P**
90 Q	44.3	39.8	36.3
Q	47.0	42.2	38.3
110 Q	49.3	44.2	40.0

Figure shows that the curve number contours for Barchi are denser than the contours for Melumai. It indicates that the variation of curve number with the percentage error is more, compared to that for Melumalai. Here also, the variation is more in the middle portion of the graph.

Dandavathi

The variation of curve number with the errors in rainfall and runoff values is as shown in Figure 13. Table 7 shows the asymptotic curve numbers for different combinations of P and Q. The variation in CN values is considerable, between 48.9 to 70.3, as can be seen from the table. The curve number is sensitive to all ranges of errors, which can be seen from the similar spacing of the contour lines.

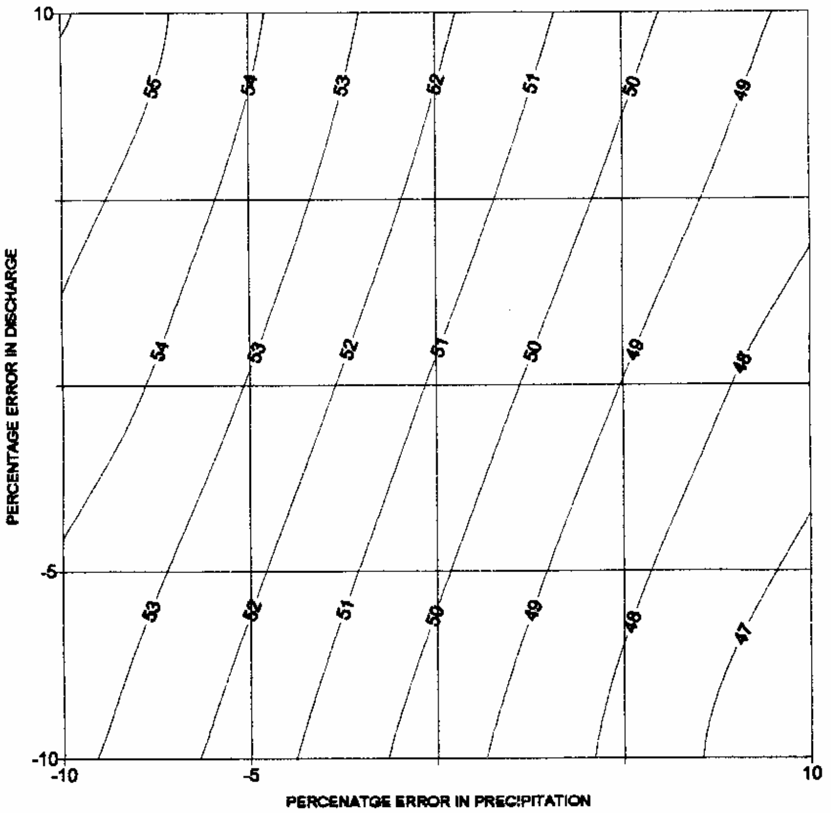


Fig. 11. Sensitivity of CN Values to P-Q Data Set for Melumalai

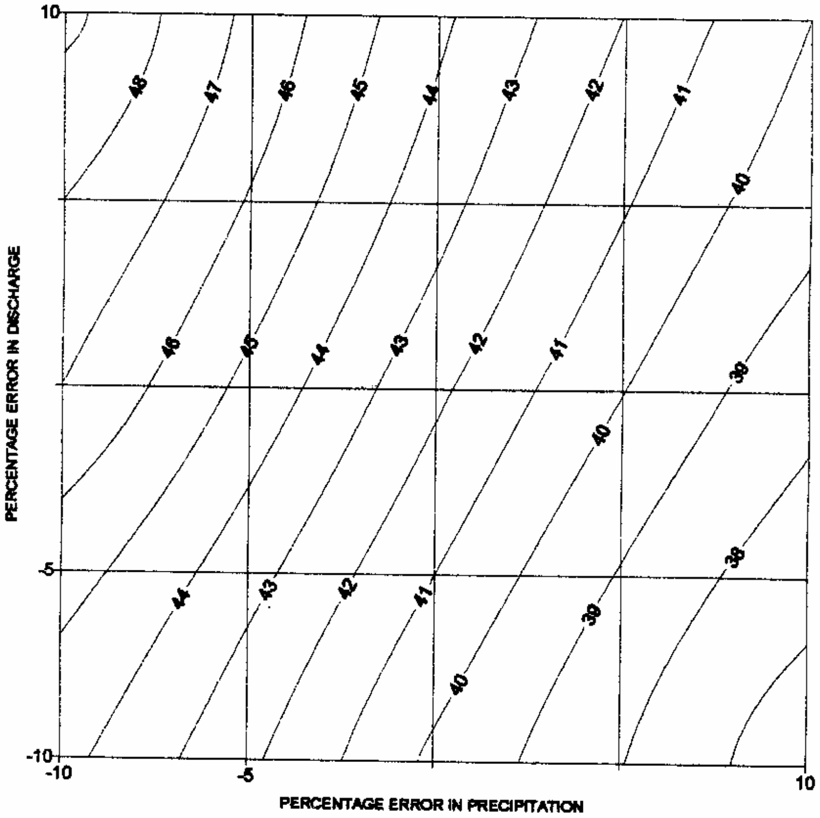


Fig. 12. Sensitivity of CN Values to P-Q Data Set for Barchi

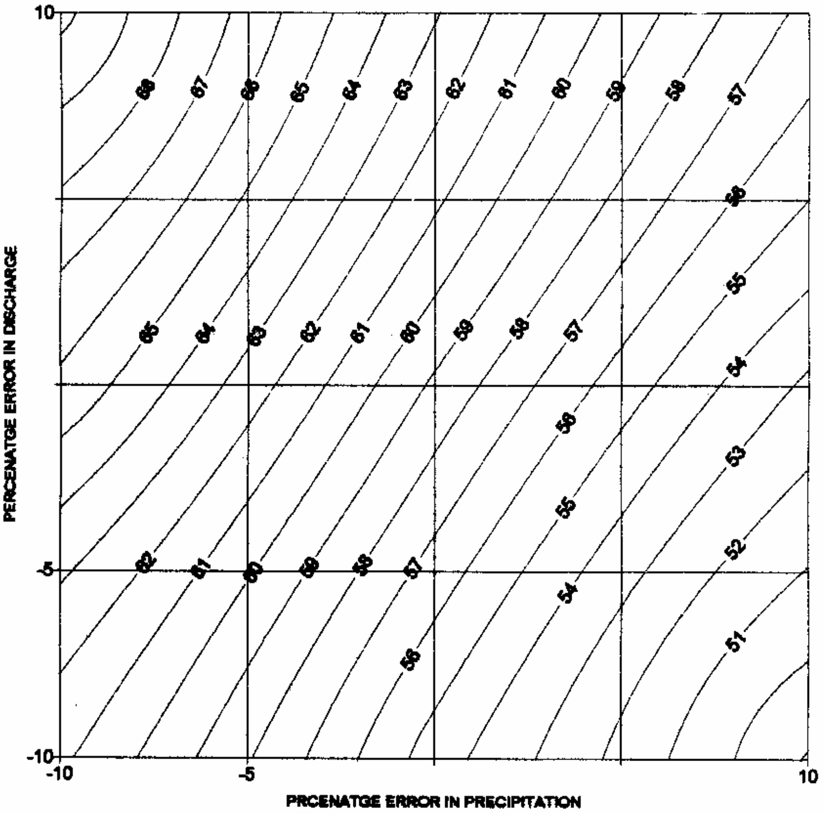


Fig. 13. Sensitivity of CN Values to P-Q Data Set for Dandavathi

Table 7: Asymptotic Curve Number for Different Combinations of P & Q for Dandavathi

	90 P	P	110 P
90 Q	61.2	54.5	48.9
Q	65.8	58.8	52.8
110 Q	70.3	63.1	56.7

5.4 ESTIMATION OF CN USING CONVENTIONAL SCS METHOD

The estimation of curve number using the conventional SCS methodology requires the details of soil hydraulic classification, and land use types for the study area. An extensive field investigation has been conducted in the Barchi watershed to collect the information regarding the prevailing soil and land use types. Infiltration tests were conducted at 8 sites, widely spread over the watershed, to differentiate the various classes of soil as per the USDA classification. Major portion of the watershed is covered with natural forest and mixed plantation, with patches of agricultural land. The forest surface is mostly covered with 50-80 % humus. Soils are fine grained with generally brownish to dark brownish colour. Infiltration is generally low to moderate.

Using the information collected from field investigations and field tests, soil and land use maps have been prepared. By overlaying procedure, different SVL (Soil-Vegetation-Land use) complexes were separated. The SVL complexes, for the Barchi watershed is as shown in Figure 14. From the figure, it can be seen that the area consists of about 30 such complexes with different combinations of land use and hydraulic groups. Curve numbers for these individual complexes were estimated from the standard tables (prepared by Indian Soil Conservation Division, Ministry of Agriculture) and averaged over the entire watershed. The CN value for individual complexes vary between a high value of 90 (for a combination of agricultural land and soil hydraulic group C) and a low value of 26 (for a combination of disturbed forest and soil group A). For an initial abstraction of 0.3 S and AMC II, the average curve number for the watershed was calculated as 49.

For the above AMC and initial abstraction conditions, the CN value obtained through asymptotic fitting is 46.2, as can be seen from Table 1. The higher value from the conventional method may be due to the following reasons:

(a) While using the conventional method, thick humus cover is not taken into consideration. But during the actual runoff process, this plays an important role by increasing the retention and lesser runoff. This effect will be reflected in the actual measured data.

(b) From the literature (Hawkins, 1984 and Hossein et al., 1989), it can be seen that the experiences with the use of SCS method for forested watersheds are least successful and no comparisons have been reported between the estimated CNs and the data defined CNs.

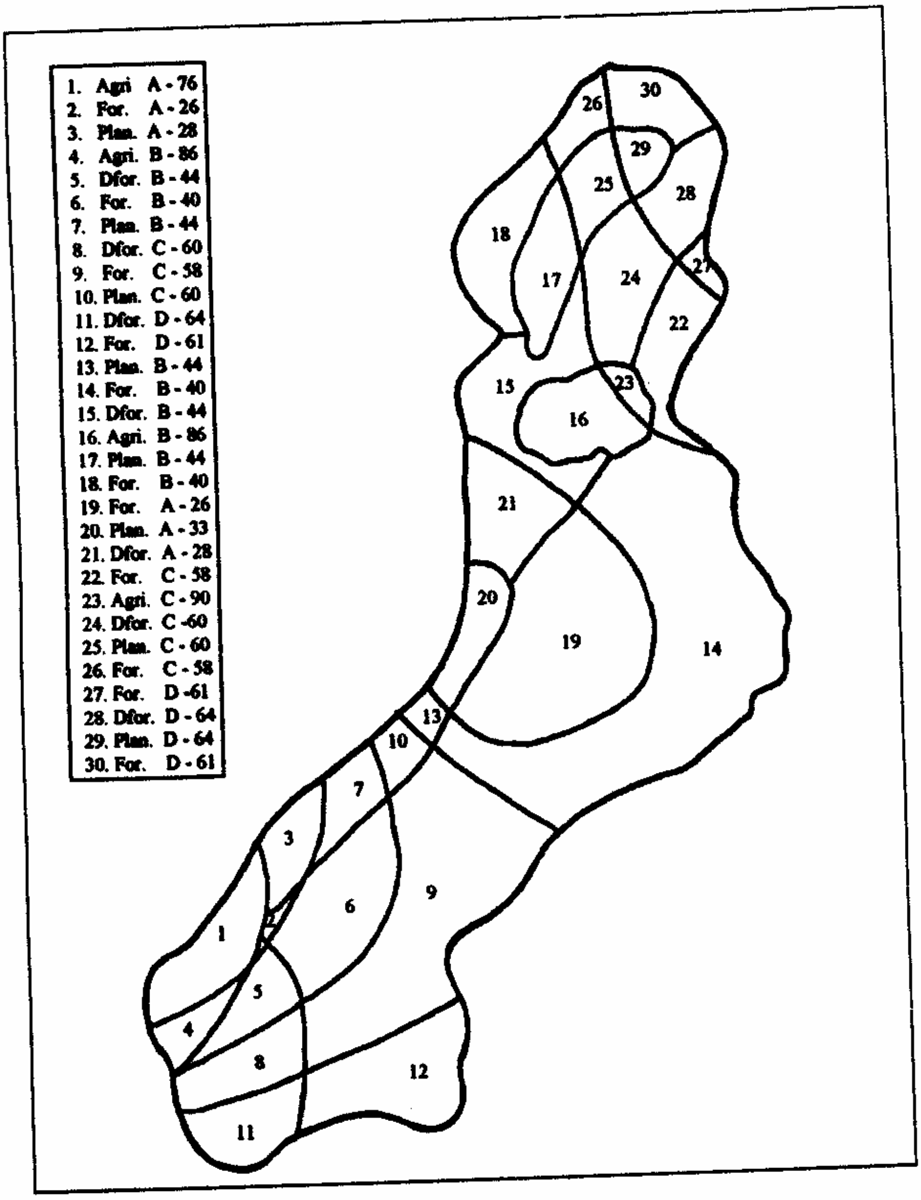


Fig. 14. SVL Complexes for Barchi Watershed

6.0 CONCLUSIONS

The advantages of the SCS curve number method are its simplicity, reliance on only one parameter, and responsiveness to major runoff producing watershed properties. However, it does have some major disadvantages like, its sensitivity to the choice of curve number, fixing the level of antecedent moisture condition, and the selection of initial abstraction ratio.

In the present study, event rainfall-runoff data are used to estimate curve number for three watersheds of hard rock region and average curve number value has been determined for each catchment by asymptotic fitting of the estimated curve number values for different rainfall-runoff events. To verify the applicability of the method to hard rock watersheds, curve number for Barchi was calculated using the conventional SCS method using soil and land use data.

In the absence of an appropriate CN table for Indian conditions, it is desirable to estimate curve numbers from available P-Q data set or to use P-Q data set of homogeneous basins. This method also can be used as a check on the values estimated using the conventional SCS method and in a broader sense, can be used to revise the standard CN tables for land use conditions and soil characteristics which are not covered by the tables. But the consistency of the data set used is an important factor, which controls the accurate estimation of curve number.

Rainfall-runoff data can effectively be used for the estimation of runoff curve number. Since actual field data are involved, this method is more reliable. This method does not require information on the three levels of antecedent moisture condition. But, the selected data set should cover a wide range of AMC conditions, from dry to wet, in order to have reasonable results. However, this method is also not free from assuming suitable initial abstraction parameter, which affects the output (curve number/runoff). So, further research effort should be applied to provide some guidelines for selecting initial abstraction coefficient for different agro-climatic regions and soil types.

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