3.1 Time Series Analysis of Floods and Low Flows

3.1.1 General

The history of land use in the hills of Bhavani shows that its dense tropical forest were in the past used only by a few thousand scattered habitants of hill tribes of Thodas, Kotas, Irulas, Kurumbar, Kattanaickan, Paniyar and Badagas. The habitation in the hilly region began to increase at a fast rate, from 1850 onwards, when the Britishers and others from plains started settling in these hills. Natural forests were indiscriminately converted into tea and coffee plantations, agricultural and urban lands. Agriculture took a rapid stride because of green revolution and urbanisation increased after independence. The conversion of land use from forest to agriculture and then to urban had a great impact on the hydrologic characteristics of the basin. The human influence, coupled with mismanagement of lands affected the watersheds of the basin, causing very high peak floods, very low dry weather flow, high sediment loads in streams and frequent land slides and landslips.

Heavy soil erosion was recorded in agricultural watersheds during the 1st and 2nd world war resulting in complete siltation of Katery reservoir. Soil conservation works were taken up in sporadic pockets including Katery watershed.
after independence between 1955 and 1962 and between 1962 and 1970 in Kundha watershed. Due to inadequate maintenance staff and lack of interest for soil and water conservation by the farmers, soil conservation measures were neglected and terraces and bunds got obliterated, resulting in full erosion hazard. Once again, the soil conservation work was started in 1972-73 but it was slow and mainly limited to constructing terraces and building of stone walls to a limited extent.

All the watersheds in the basin are under transition due to land use changes by human influence and have been in a dynamic condition due to economic development in this region (Fig. 3.1.3). The land use changes of these basins are as follows:

i. Natural forest/grasslands are undergoing transition to man-made forest of bluegum, blackwattle and pine e.g., Wenlock downs, Avalanche etc..

ii. Natural forest/grasslands/man-made forest are undergoing transition to agricultural lands (tea/coffee/orchards/banana/potato/tapioca) e.g., Kateri, Kundha etc.

iii. Agricultural watersheds are undergoing transition to urban lands e.g., Coonoor and Ootacamund.
iv. Forest and agriculture mixed watersheds are undergoing transition to urban lands eg. Gudalore and Kotagiri.

Among the many watersheds in Nilgiris, which are in transition, two typical watersheds - Kateri and Coonoor were taken up for study as these underwent transition from forest to agriculture and to urban over a period of 25 years (Fig. 3.1, 3.2, 3.3). Kateri watershed underwent transition from forest to agriculture and that of Coonoor from agriculture to urban. Kateri and Coonoor watersheds were once covered with dense forest and were protected by well spread grass and forest tree canopy. The forest floors were covered with thick undergrowth. Leaf litter and humus zone in the top soil were well pronounced. The sub-soil acted as a good retention reservoir and released stored rain water slowly and thereby moderated the surface flow during high precipitation and augmented the dry weather flow.

Clearing of forests and introduction of agriculture as per local practice created a change in the hydrological regime of these watersheds. By clearing of forests, loss of complete top soil took place in 25 years and cultivation in sub-soil could absorb only very little precipitation due to badly managed tea and potato cultivation. Hence high magnitude floods occurred for moderate precipitation and dry weather flow reduced to the barest minimum (23, 24, 27, 33, 49, 54, 65).
REFERENCE

- D.R.G.
- S.R.G
- SYMONS (PRIVATE)
- MEASURING WEIR
- ROAD METALLED
- CART TRACK
- FOOT PATH

SCALE 1:21 MILE

FIG. 3-1

KATERI
(a) Stages of Natural Forest 150 to 200 Years Ago

- Canopy
- Leaf Litter & Humus
- Roots Underlying Subsoil
- Top Soil
- Under Growth

(b) Stage 2: Land Use after Clearing Forest to 50 Years Ago and at Present

- Potato
- Tea
- Top Soil Absent (Eroded)
- Exposed Subsoil 'Badly Managed Tea and Potato

Proper Land Use (Recommended)

(c) Stage 3: Land Use 15 to 20 Years Ago

- Contour Furrow
- Drop Pits & Drain
- Grass on Embankment
- Terraces for Potato
- Sub Soil (Top Soil Absent)
- Trenches for Tea
- Mulch for Tea

Proper Land Use (Recommended)

3-Stages of Watershed Transition in Kateri
3.1.2 Methodology

Available rainfall data of 31 years and 25 years for Kateri (1943-1979) and Coonoor (1954-1979) respectively and streamflow data of 23 years (1957-79) for both the watersheds were subjected to regression analysis, to study their trend. Rainfall, low monthly flows, basin runoff and peak floods were analysed using linear regression, curvi-linear regression, semi-averages and moving averages.

3.1.3 Results and Discussions

From the original data of rainfall, basin runoff and low dry weather flow, twelve year moving averages, linear and curvi-linear regression were carried out for Kateri and Coonoor watersheds. The results are given in Table 3.1, (Figs. 3.4, 3.5, 3.6). The equation are given below.

<table>
<thead>
<tr>
<th>Description</th>
<th>1948-57 Curvilinear Semi-Average Time-series base data</th>
<th>C</th>
<th>K</th>
<th>C</th>
<th>K</th>
<th>C</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual rainfall</td>
<td>100</td>
<td>96</td>
<td>97</td>
<td>91</td>
<td>87</td>
<td>97</td>
<td>91</td>
</tr>
<tr>
<td>Annual basin runoff</td>
<td>100</td>
<td>46</td>
<td>45</td>
<td>35</td>
<td>22</td>
<td>57</td>
<td>54</td>
</tr>
<tr>
<td>Monthly low dry weather flow</td>
<td>100</td>
<td>32</td>
<td>28</td>
<td>41</td>
<td>1</td>
<td>52</td>
<td>36</td>
</tr>
<tr>
<td>Annual peak flow</td>
<td>100</td>
<td>363</td>
<td>237</td>
<td>1060</td>
<td>358</td>
<td>363</td>
<td>182</td>
</tr>
</tbody>
</table>

C - Coonoor watersheds (A = 44.02 Km²)
K - Kateri watershed (A = 54.76 Km²)
TWELVE YEARS MOVING AVERAGES — KATERI

FIG. 3.5

RAIN FALL

\[\text{cm} \]

0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20 YEARS

LOW MONTHLY DRY WEATHER FLOW

\[\text{cm} \]

0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18 YEARS

\[Q_{\text{max}} \text{ (m}^3\text{sec)}\]

BASIN RUNOFF (cm)

\[\text{m}^3\text{sec} \]

0  10  20  30  40  50

\[\text{cm} \]

0  10  20  30  40  50

4  5  6  7  8  9  10  11  12  13  14  15  16  17  18 YEARS

TWELVE YEARS MOVING AVERAGES — KATERI

FIG. 3.5
RAINFALL
\[ Y = 125.04 - 0.11x - 0.04x^2 \]

BASIN RUNOFF
\[ Y = 32.9 - 1.5x + 0.09x^2 \]

LOW MONTHLY DRY WEATHER FLOW
\[ Y = 1.00 - 0.06x + 0.001x^2 \]

\[ Q_{\text{max}} \]
\[ Y = 27.1 + 1.69x + 0.15x^2 \]

FIG. 3.6 CURVILINEAR REGRESSION - KATERI
Coonoor watershed (Linear regression)

Rainfall \[ Y = 139.5 - 0.22x \] \hspace{1cm} (3.1)
Basin runoff \[ Y = 35.1 - 1.91x \] \hspace{1cm} (3.2)
Low monthly runoff \[ Y = 1.6 - 0.07x \] \hspace{1cm} (3.3)
Peak floods \[ Y = 183.9 + 35.7x \] \hspace{1cm} (3.4)

Coonoor watershed (Curvilinear regression)

Rainfall \[ Y = 138.44 - 0.22x + 0.54x^2 \] \hspace{1cm} (3.5)
Basin runoff \[ Y = 57.07 - 1.91x + 0.02x^2 \] \hspace{1cm} (3.6)
Low monthly runoff \[ Y = 1.706 - 0.07x + 0.002x^2 \] \hspace{1cm} (3.7)
Peak floods \[ Y = 107.3 + 35.74x + 6.6x^2 \] \hspace{1cm} (3.8)

Kateri watershed (Curvilinear regression)

Rainfall \[ Y = 125.04 - 0.11x - 0.04x^2 \] \hspace{1cm} (3.9)
Basin runoff \[ Y = 32.9 - 1.5x + 0.09x^2 \] \hspace{1cm} (3.10)
Low monthly runoff \[ Y = 1.00 - 0.06x + 0.001x^2 \] \hspace{1cm} (3.11)
Peak floods \[ Y = 27.01 + 1.69x + 0.15x^2 \] \hspace{1cm} (3.12)

where \( x \) refers to year.

It is very striking from the Table 3.1 that though the reduction of rainfall in both the watersheds was the same i.e., 3 to 9 percent, dry weather flow decreased by 3 to 10 fold in Kateri (rural) and only 2 to 3 fold in Coonoor (urban). This shows that in drought years, irrigated
agriculture for potato in rural watershed (Kateri) has an adverse effect on dry weather flow compared to urban watershed (Coonoor). Basin runoff was reduced by 2 to 5 fold in the case of Kateri and 2 to 3 fold in the case of Coonoor. The increase of peak floods by 4 fold shows the impact of urbanisation coupled with bad planning in Coonoor, while it is increased by 2 to 4 fold in Kateri due to bad agricultural management and insufficient soil and water conservation measures.

3.2 Rainfall-runoff Characteristics of Experimental Watersheds in Transition

3.2.1 General

Two experimental watersheds in the Bhavani basin were considered for a detailed investigation of their transitional characters. The two aspects to which this study is directed are:

i. To propose a method of quantifying the transitional effect of a watershed in terms of suitable hydrologic variables.

ii. To select an appropriate rainfall-runoff model which would be capable of accounting the time variant watershed characteristics.
3.2.2 Model Used

3.2.2.1 Details of the Model

For the conversion of rainfall excess into surface runoff, many deterministic models were reviewed and finally the 3-coefficient surface runoff model by Chow and Kulandaaiswamy (32) was selected. Babu Rao (5) has made detailed investigation of the coefficients in the model (5, 31,32,46,48,54).

Kulandaissamy (46) considered the rainfall-runoff by system analysis. Starting with the general functional relationship between storage, inflow and outflow, he proposed a general storage equation for storage as follows:

\[ S = \sum_{n=0}^{N} a_n(Q,i) \frac{d^n Q}{dt^n} + \sum_{m=0}^{M} b_m(Q,i) \frac{d^m i}{dt^m} \]  \hspace{1cm} (3.13)

where \(a_n\)'s and \(b_m\)'s are parameters depending upon \(Q\) and/or \(i\). From a detailed study of equation (3.13), it has been shown (5) that satisfactory results are obtained if values of \(N\) and \(M\) are limited to 1 and 0 respectively.

In the present study, the following simplified case of the Equation (3.13) is considered.

\[ S = a_0 Q + a_i \frac{dQ}{dt} + b_0 i \]  \hspace{1cm} (3.14)
Equation (3.14) is then coupled with the lumped form of continuity equation

\[
\frac{dS}{dt} = i - Q
\]  \hspace{1cm} (3.15)

This constitutes the 3-coefficient model, where \(a_0\), \(a_1\) and \(b_0\) are the three coefficients. Substituting the storage Equation (3.14) in the continuity Equation (3.15) the following model for surface runoff is obtained.

\[
Q(t) = \left[ \frac{-b_0D + 1}{a_1D^2 + a_0D + 1} \right] i(t)
\]  \hspace{1cm} (3.16)

where \(Q(t)\) is the surface runoff hydrograph ordinate \((m^3/\text{day} \text{ or cm/day})\),

\(i(t)\) is the effective rainfall rate \(\text{(cm/day)}\),

\(a_0, a_1,\) and \(b_0\) are the model parameters \((\text{day}, \text{day}^2 \text{ and day respectively})\)

\(D\) is the differential operator \((\frac{d}{dt})\).

The model parameters \(a_0, a_1\) and \(b_0\) were estimated for each storm by the method of least squares from the known data by taking the time unit as 0.1 day. For known rainfall excess and the surface runoff for a storm, storage is determined at 0.1 day interval; and different equations are formed by substituting the values of \(S, Q \frac{dQ}{dt}\), and \(i\) in Equation (3.14) for the entire period of surface runoff. These equations are reduced to three normal equations and they are solved for the values of \(a_0, a_1\) and \(b_0\).
The surface runoff computed in Equation (3.16) was compared with the observed surface runoff by a statistical measure called special correlation coefficient ($R_s$) given by:

$$Rs = \frac{2 \sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} y_i^2}{\sum_{i=1}^{N} x_i^2} \quad \ldots \quad (3.17)$$

where $R_s$ is the special correlation coefficient

$x$ is the known variable

$y$ is the corresponding estimated value

$N$ is the number of observations of $x$ and $y$

Further details of this model are given by Babu Rao, Jebaraj et al (5,44).

3.2.2.2 Description of Watersheds

In the Bhavani basin, two typical experimental watersheds (A and B) located at latitude $11^\circ23'30"$ N and longitude $76^\circ39'50"$ E in the high hills of Nilgiris were selected. The two watersheds have an equal area of about 33 hectares and lie side by side (Fig. 3.7). They have the same geologic, geomorphic and regulative characteristics. The mean annual rainfall of 1540 mm occurs during both the south-west and the North-east monsoons. The streams in both the watersheds are perennial.
FIG. 3.7  LOCATION MAP OF GLENMORGAN
Hydrologic measurements by the Central Soil and Water Conservation Research Centre, Ootacamund were started in the year 1970, in both the watersheds with shola forest and natural grasslands as natural vegetative cover. At the end of 1972, the natural grasslands in one of the watersheds (B) were converted into bluegum (*Eucalyptus globulus*) plantations. The other watershed (A) was kept as it was, and hydrologic measurements were continued. The hydrologic regime of the watershed B was undergoing change with the growth of bluegum trees and change in vegetative covers. From the data collected, data of three years were analysed. These data pertain to one year of calibration period (1970) and two years of post calibration period (1973 and 1976). The daily rainfall-runoff data for each basin were plotted separately for each year. The base flow was separated from the total runoff. The surface runoff and the corresponding effective rainfall for each storm were computed. Totally 230 storms were selected for the two watersheds for the 3 year period. Most of the storms were complex and extend more than one day. The rainfall excess is determined by $\theta$ - index method. The correlation coefficient of the computed hydrographs was above 0.99 for 222 storms and between 0.95 and 0.99 for the remaining 8 storms. Thus the performance of the model was found to be excellent (Fig. 3.8.) (5, 30, 31, 32, 44, 46, 54, 64, 65).
SURFACE RUNOFF: cm / hour

WATERSHED-A; STORM OF 10, JUNE, 1973; OBSERVED AND COMPUTED HYDROGRAPHS

MODEL PARAMETERS

\[ a_0 = 0.5 \text{ DAY} \]
\[ a_1 = 0.08 \text{ DAY}^2 \]
\[ b_0 = -0.01 \text{ DAY} \]

WATERSHED-A; STORM OF 10, JUNE, 1973; OBSERVED AND COMPUTED HYDROGRAPHS

FIG.3·8
3.2.3 Results and Discussions

3.2.3.1 Computation of Transition Factor

The annual rainfall excess for the years 1970, 1973 and 1976 were worked out for both watersheds A and B and are given in Table 3.2.

**TABLE 3.2: ANNUAL RAINFALL EXCESS**

<table>
<thead>
<tr>
<th>Year</th>
<th>Watershed</th>
<th>Annual Rainfall Excess Volume in cm</th>
<th>Annual Rainfall Excess Volume in B compared with that in A in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>A</td>
<td>8.0704</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5.8312</td>
<td>72.25</td>
</tr>
<tr>
<td>1973</td>
<td>A</td>
<td>10.8816</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>10.1653</td>
<td>95.17</td>
</tr>
<tr>
<td>1976</td>
<td>A</td>
<td>5.5320</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4.6988</td>
<td>84.94</td>
</tr>
</tbody>
</table>

When the annual rainfall excess volumes in watershed B are compared with those in A, it indicates that in the year 1970, when the watersheds were alike, the annual rainfall excess volume in B is 72.25 percent of the annual rainfall excess volume in A. In 1973, the trees were cleared in B and the land was prepared for afforestation. In 1976, there has been a growth of afforested plants. The annual rainfall excess in B over that of A in the years 1973 and 1976 are 95.17 percent and 84.94 percent respectively. The above Table indicates that the transition of a watershed...
is reflected in a systematic manner in its rainfall excess volumes and can be used for quantification of transition.

The percentage increase in annual rainfall excess in B in 1973 over that in 1970 is 32 percent, which is due to the land preparation for afforestation, whereas for the year 1976 it is 18 percent. The reduction in increase of annual rainfall excess in 1976 from that of 1973 is attributed to the growth of the plant in the three year period. This change in rainfall excess volume, has been mainly attributed to transition of the watershed. The changing conditions of the watershed called transitional effect has been quantified by a factor known as transition factor with 1970 as base year. Assuming a factor of 1.0 as a base for the year 1970 for B, the transition factor for the years 1973 and 1976 are 1.32 and 1.18 respectively. The same trend can also be seen in Table 3.3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual rainfall cm</th>
<th>NRD</th>
<th>Annual runoff cm</th>
<th>Annual surface runoff cm</th>
<th>Annual Base Flow cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>155.5</td>
<td>160</td>
<td>44.3</td>
<td>28.5</td>
<td>5.8</td>
</tr>
<tr>
<td>1973</td>
<td>198.2</td>
<td>141</td>
<td>52.2</td>
<td>26.3</td>
<td>10.2</td>
</tr>
<tr>
<td>1976</td>
<td>96.2</td>
<td>126</td>
<td>20.7</td>
<td>21.5</td>
<td>4.7</td>
</tr>
</tbody>
</table>

NRD = Number of rainy days
3.2.3.2 Quantification of Rainfall Excess

From the above discussions, it is seen that the rainfall excess is being affected by the transitional character of the watershed. In order to quantify the rainfall excess, the concept of Antecedent Precipitation Index (API) was related to the rainfall excess. The API for each day for the years 1970, 1973 and 1976 was computed by the following equation:

\[(API)_i = 0.85 (API)_{i-1} + P_i \quad \ldots (3.18)\]

where \((API)_i\) is the Antecedent Precipitation Index for the \(i\)th day (cm/day)

\((API)_{i-1}\) is the Antecedent Precipitation Index for the previous day (cm/day)

\(P_i\) is the precipitation on the \(i\)th day (cm/day)

Graphs of percentage rainfall excess versus API were plotted for the watersheds separately for the years 1970, 1973 and 1976 considering only the ascending portions of the API (Fig. 3.9). It is observed from the graphs that the watershed A has not undergone any change. The watershed B has undergone changes due to the transition. For a known API the percentage rainfall excess in 1973 is more than in the years 1970 and 1976. The percentage rainfall excess in 1976 is more than the year 1970 but less than the year 1973. Equations of the form \(y = ax^n\) were formed for
GRAPHS OF PERCENTAGE RAINFALL EXCESS Vs. API FOR VARIOUS TRANSITION FACTORS FOR WATERSHED - B

FIG. 3.9

LEGEND
2. B (1973)
3. B (1976)

T.F. = TRANSITION FACTOR

GRAPHS OF PERCENTAGE RAINFALL EXCESS Vs. API FOR VARIOUS TRANSITION FACTORS FOR WATERSHED - B

FIG. 3.9
the three curves for watershed B by making log-log plots of percentage rainfall excess versus API (Fig. 3,10). The equations for the years 1970, 1973 and 1976 are:

\[
\begin{align*}
Y(1970) &= 0.26 x^{1.55} \\
Y(1973) &= 0.32 x^{1.57} \\
Y(1976) &= 0.29 x^{1.56}
\end{align*}
\] .. (3.19)

where \( y \) is the percentage rainfall excess, and \( x \) is the API.

The coefficients \( a \) and \( n \) in the above equations of the form \( y = ax^n \), are related to the transition factor \((t_r)\) by the following equations.

\[
\begin{align*}
a &= 0.26 t_r^{0.7439} \\
n &= 1.55 t_r^{0.04634}
\end{align*}
\] .. (3.20)

The values of \( a \) and \( n \) can be computed from the above equations for a known value of transition factor and hence the percentage rainfall excess can be obtained for a known API. Once the transition factor and API are known, the rainfall excess for a storm can be computed and from it the surface runoff hydrograph can be predicted by using the 3-coefficient model.
LOG-LOG PLOT OF PERCENTAGE RAINFALL EXCESS Vs. API FOR VARIOUS TRANSITION FACTORS FOR WATERSHED-B

LEGEND
1. B (1970): \( Y = 0.26 x^{1.55} \)
2. B (1973): \( Y = 0.32 x^{1.57} \)
3. B (1976): \( Y = 0.29 x^{1.56} \)
3.2.3.3 Analysis of Runoff Model Parameters

The model parameters $a_0$, $a_1$, and $b_0$ are generally assumed to be functions of a parameter $g$ representing the rainfall characteristics, transition factor $t_r$ of the watershed and delay time $\tau$, the time from the end of effective rainfall to the end of surface runoff (5). Functionally, they can be represented as:

$$a_0 = f(g, t_r, \tau)$$
$$a_1 = f(g, t_r, \tau)$$
$$b_0 = f(g, t_r, \tau)$$

...(3.21)

$$\theta = t_g R_{ev}$$

where $t_g$ is the time in days to the centre of area of the rainfall excess (day), and

$R_{ev}$ is the rainfall excess volume (cm).

A plot of $a_0$, $a_1$, and $b_0$ against $g$ and $t_r$ for 230 storms in watershed A and B in Fig. 3.11 did not indicate any variation either with respect to $g$ or $t_r$, whereas, $a_0$, $a_1$ and $b_0$ vary linearly with delay time, $\tau$ as shown in Fig. 3.12. To eliminate the effect of delay time on model parameters, storms having a fixed delay time (in this case 1 day) were chosen from among the 230 storms. One day delay time was selected primarily because it gave a large number of storms (185 in numbers) for further analysis. For these storms, the model parameters can be considered constant with values
Fig. 3.11 Graph of $a_0$, $a_1$, $b_0$ vs. $\theta$: (a) for storms in watershed A - during 1970; 1973; 1976
(b) for storms in watershed B - during 1970; 1973; 1976
FIG. 3-12  GRAPH OF $a_0, a_1, b_0$ Vs. DELAY TIME
for $a_0$, $a_1$ and $b_0$ as 0.5000 days, 0.6900 day$^2$ and -0.0100 day respectively. The correlation coefficient of the computed hydrographs with the above constant model parameters for 185 storms with delay time, $\tau = 1$ day was above 0.99 for all the storms. From this study, it is concluded that the transitional effect of a small watershed can be represented by the change in the rainfall excess of the watershed and that the storms having same delay time can be represented by a deterministic 3-coefficient runoff model with constant parameters. From the above analysis it is observed that:

i. The watershed transition introduces a change in the rainfall excess volume and can be quantified by a transition factor

ii. For the watershed studied, there is an increase in rainfall excess by 32 percent immediately after land preparation for afforestation and it decreases with the increase in the growth of the vegetation

iii. The 3-coefficient model reproduces the surface runoff hydrograph of a watershed in transition fairly well

iv. The parameters of the 3-coefficient surface runoff model are sensitive only to the delay time.
3.3 Modelling of Surface Runoff Characteristics

3.3.1 General

In the previous section an experimental watershed in transition (Area = 30 hectares) was studied using the 3-coefficient model. The same model is now applied to three large watersheds in the same region, having respectively urban, rural and forest land uses. The method presented can also be extended to a mixed watershed consisting of all the three land uses mentioned above.

3.3.2 Model Used

3.3.2.1 Description of Watersheds

Three watersheds lying in the high hills of Bhavani between 1600 and 2700 m above MSL (N.Lat 10° 55' - 11° 45' and E.Long. 76° 30' - 77° 45') and having daily rainfall and runoff data for more than 30 years were selected for the study. One of the watersheds - Mukurthy - is purely a forest watershed, the second - Coonoor - an urban watershed and the third - Kateri - an agricultural watershed.

Mukurthy watershed has an area of 25.25 Km² situated at an elevation of 2150 m to 2700 m above MSL (Fig. 3.13). The area is covered with natural and man-made forests and grasslands. Kateri watershed has an area of 54.753 Km² situated at an elevation of 1800m to 2200m above MSL (Fig. 3.1). It consists of potato growing agricultural lands and tea estates. Coonoor watershed has an area
of 44.03 km² situated at an elevation ranging from 1600m to 2150m above MSL (Fig. 3.2). More than 50 percent of the area is under urban set up.

3.3.2.2 Data Base

Based on the hydrologic feature of the Bhavani basin the year is divided into non-monsoon (January to May) and monsoon (June to December) periods. Five years of daily rainfall and flow data for the three watersheds were subjected to analysis by the 3-coefficient model. In each watershed, 20 storms in monsoon period (including multi-peaks) and 10 storms in non-monsoon period were analysed. The separation of baseflow and a definition sketch for the rainfall characteristics are shown in Figs. 3.14 and 3.15 respectively. A typical plot of daily rainfall, total runoff surface runoff and base flow for 16th May to 30th September 1933 for Mukurthy basin is presented in Fig. 3.16. The coefficients of the model were determined by the method of least squares and then they were expressed as functions of rainfall characteristics and antecedent precipitation index by stepwise regression analysis. The regression analysis was carried out for the monsoon and non-monsoon seasons separately.

The steps involved in the rainfall-runoff modelling using the 3-coefficient model by digital simulation are
Fig. 3.14
Separation of baseflow
TG — TIME TO CENTRE OF GRAVITY OF RAINFALL EXCESS
DIAGRAM
TR — DURATION OF RAINFALL
TE — DURATION OF RAINFALL EXCESS
DT — DURATION BETWEEN TWO RAINFALL ORDINATES

FIG.3·15 RAINFALL CHARACTERISTICS
Fig. 3.16 Plotting of daily rainfall and flows - Mukurthy
as follows:

i. Plotting of daily total runoff and rainfall for each season and identifying the storms with their corresponding runoff.

ii. Separation of baseflow and surface runoff from the plotted daily runoff.

iii. Computation of daily API and runoff characteristics such as surface runoff volumes, equivalent depth of runoff and baseflow volume for each storm in each season.

iv. Computation of rainfall characteristics, such as rainfall volumes, ratio of mean rainfall to maximum rainfall, rainfall excess by \( I \) - index method, time to centre of gravity, duration of rainfall excess and ratio of time to e.g. to duration of rainfall excess for each storms in each season.

v. Obtaining the parameters \( a_0, a_1 \) and \( b_0 \) in the 3-coefficient model from the rainfall excess and surface runoff of each storm obtained in steps (iii) and (iv).

vi. Performing stepwise multiple regression for the three dependent parameters \( a_0, a_1, b_0 \) and five independent variables of rainfall characteristics and initial condition of the basin considering the storms in monsoon and non-monsoon periods separately. The five independent variables used are \( X_1, X_2, X_3, X_4 \) and \( X_5 \). where \( X_1 = \) Rainfall excess volume, \( \text{Rev}, X_2 = \) Ratio of time to centre of gravity of rainfall excess diagram to duration of rainfall excess \( T_g/T_e \), \( X_3 = \eta = \text{Rev} \ T_g/T_e \),
Reproduction of flood hydrographs is made either by using constant coefficients or the coefficients obtained from regression equations. The selection of the coefficients is based on the analysis of variance of correlation coefficients of the observed and computed flood hydrographs. For Mukurthi, the model parameters were computed from the regression equation. For Kateri constant parameters were used for monsoon period. For non-monsoon period the parameters were computed from the regression equations. In the case of Coonoor, constant parameters were used for continuous reproduction of flood hydrograph for both the seasons. The observed and computed hydrographs by the above procedure are shown in Fig. 3.17.

For predicting the daily flood hydrograph due to a given storm in a watershed, the following curves are made use of:

\[
X_4 = \text{API before the start of the storm and} \\
X_5 = \text{ratio of mean rainfall to maximum rainfall}
\]
FIG. 3.17 Plotting of observed and computed runoff for three Watersheds.
i. Log-Log plot of API Vs % Rainfall excess volume (Rev)

ii. Log-Log plot of % Rev Vs τ

iii. Log-Log plot of API Vs baseflow

The above curves were prepared from the analysis of the past storm and flow data for both the monsoon and non-monsoon periods for the three basins. The plots indicate that a linear regression equation of the form \( y = a + b \log x \) can be fitted. Such an equation is fitted and the regression coefficients for different basins are furnished in Table 3.4.

Having obtained the foregoing information, the following steps are followed in obtaining the outflow hydrograph due to a storm in a given basin for a given season and API.

i. For the known API, percentage rainfall excess volume is obtained from the plot of API Vs % Rev.

ii. Knowing the percentage rainfall excess volume, τ is obtained from the plot of % Rev Vs τ.

iii. With the rainfall excess volume, τ and rainfall hyetograph as input the surface runoff is computed by the 3-coefficient model choosing the model parameter as discussed in section 3.3.2.

iv. In Table 3.5 regression coefficients in the equation for base flow Vs API are presented for different basins. Using this equation baseflow is computed and added to the surface runoff to get the total runoff.
TABLE 3.4: REGRESSION COEFFICIENTS FOR RELATIONSHIPS FOR REV Vs API AND Vs Rev

General equation
\[ \log y = a + b \log x \]

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Period</th>
<th>X</th>
<th>Y</th>
<th>a</th>
<th>b</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mukurthy (Forest)</td>
<td>Monsoon API Rev</td>
<td>2.9312</td>
<td>0.4865</td>
<td>0.810</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3952</td>
<td>0.2557</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>Monsoon Non-monsoon API Rev</td>
<td>2.119</td>
<td>1.4736</td>
<td>0.921</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3435</td>
<td>0.5319</td>
<td>0.610</td>
</tr>
<tr>
<td>2. Kateri (Rural)</td>
<td>Monsoon API Rev</td>
<td>1.9653</td>
<td>0.6058</td>
<td>0.740</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8758</td>
<td>0.4358</td>
<td>0.1520</td>
</tr>
<tr>
<td></td>
<td>Monsoon Non-monsoon API Rev</td>
<td>2.350</td>
<td>0.5535</td>
<td>0.791</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.6282</td>
<td>1.0224</td>
<td>0.834</td>
</tr>
<tr>
<td>3. Coonoor (Urban)</td>
<td>Monsoon API Rev</td>
<td>2.1941</td>
<td>0.0379</td>
<td>0.767</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0109</td>
<td>0.8347</td>
<td>0.725</td>
</tr>
<tr>
<td></td>
<td>Monsoon Non-monsoon API Rev</td>
<td>1.8962</td>
<td>0.7094</td>
<td>0.848</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9964</td>
<td>0.5022</td>
<td>0.5645</td>
</tr>
</tbody>
</table>
TABLE 3.5: REGRESSION COEFFICIENTS FOR BASEFLOW EQUATION
\[ \text{LOG } Q_b = C + m \text{ log } A_p \]

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Period</th>
<th>C</th>
<th>m</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mukurthy</td>
<td>Monsoon</td>
<td>-0.5541</td>
<td>0.7231</td>
<td>0.7628</td>
</tr>
<tr>
<td></td>
<td>Non-monsoon</td>
<td>-0.8711</td>
<td>0.5070</td>
<td>0.651</td>
</tr>
<tr>
<td>2. Kateri</td>
<td>Monsoon</td>
<td>-1.8782</td>
<td>0.8248</td>
<td>0.810</td>
</tr>
<tr>
<td></td>
<td>Non-monsoon</td>
<td>-0.2302</td>
<td>0.5708</td>
<td>0.5706</td>
</tr>
<tr>
<td>3. Coonoor</td>
<td>Monsoon</td>
<td>-1.8735</td>
<td>0.6240</td>
<td>0.824</td>
</tr>
<tr>
<td></td>
<td>Non-monsoon</td>
<td>-1.8071</td>
<td>0.3837</td>
<td>0.6754</td>
</tr>
</tbody>
</table>

Various steps in the mathematical model are indicated in the master flow diagram (Fig. 3.18). For the storms studied the correlation coefficient (R) for the predicted hydrographs with the observed for the three basins varied between 0.8762 and 0.9912. A typical plot of the computed hydrographs by the above method along with the observed ones for the three watersheds are shown in Fig. 3.17.

3.3.4 Effect of Urbanisation or Afforestation of a Rural Watershed

So far, the emphasis has been on modelling the watersheds having three typical land uses namely rural, urban and forest. As stated earlier, these watersheds are undergoing transition and are likely to change from one land use to the other and become watersheds having mixed
START

READ $\Delta t \: R_s(t) \: Q(t)$ FOR MUKURTHI SUB-BASIN (MONSOON PERIOD)

COMPUTE API

CALL SUBROUTINE
$\log (\%_{\text{Rev}}) = 2.9312 + 0.4868 \log API$

CALCULATE $\%_{\text{Rev}}$

CALL SUBROUTINE $\log \left( \frac{TD}{\%_{\text{Rev}}} \right) = 0.3952 + 0.2657 \log \left( \frac{\%_{\text{Rev}}}{TD} \right)$

CALCULATE TD

CALL SUBROUTINE RAINFALL CHARACTERISTICS

CALL SUBROUTINES FOR MODEL PARAMETERS
$a_0 = 3.39 - 0.00024x_1 - 1.57x_2 - 0.014x_3 - 0.045x_4 - 0.47x_5$
$a_1 = 3.02 - 0.0058x_1 - 1.31x_2 - 0.002x_3 - 0.05x_4 - 1.79x_5$
$b_0 = 0.20 - 0.004x_1 - 0.95x_2 + 0.017x_3 - 0.01x_4 + 1.23x_5$

CALCULATE $a_0, a_1, b_0$

CALL SUBROUTINE FOR 3-COEFFICIENT MODEL
FIG. 3.18 MASTER FLOW DIAGRAM FOR MUKURTHY

A

CALCULATE $q_c(t)$

CALL SUBROUTINE $\log q_b = -0.5541 + 0.7231 \log A_p$

CALCULATE $q_b(t) = q_b$

CALCULATE $Q_c(t) = q_c(t) + q_b(t)$

END
land uses in due course. One of the questions for which answer is sought from this investigation is what happens to the hydrologic characteristics of a rural watershed when it is completely urbanised or afforested. Specifically, what are the effects of urbanisation or afforestation of a rural watershed on the following characteristics of a hydrograph.

3.3.4.1 Effect of urbanisation or afforestation on Rainfall Excess (the surface runoff volume)

The rainfall excess of a given storm is intimately related to the storm characteristics as well as to the infiltration characteristics of the watershed. The infiltration characteristics are mainly related to the witness of the soil prior to the storm, the type of soil and the land use to which the watershed is subjected to. The above concept can be expressed by the following functional relationship.

$$\frac{F_Y}{R_Y} = F \left( \frac{S_{MI}}{r_a}, \frac{T_G}{T}, \text{type of land use} \right) \quad (3.22)$$

where $F_Y$ represents abstractions, $R_Y$ is the volume of rainfall, $S_{MI}$ is the soil moisture index, $r_a$ is the average rainfall rate, $T_G$ is the time to the centre of gravity of the rainfall area and $T$ is the duration of rainfall.

From the observed data, curves were drawn between

$$\frac{F_Y}{R_Y} \quad \text{versus} \quad \frac{T_G}{T} \quad \text{with} \quad \frac{S_{MI}}{r_a}$$
as parameters for all the three
watersheds. Subtracting $F_Y$ from $R_Y$, the volume of rainfall excess is arrived at. In the case forest watershed (Mukurthy) a single set of curves were obtained (Fig. 3.19) while in the case of urban (Coonoor) and rural (Katari) watersheds two sets of curves, for monsoon and non-monsoon separately, were prepared (Figs. 3.20 to 3.23). Assuming that the rainfall excess curves obtained for one watershed can be inter-changed with the others, depending on the land use to which the watershed is subjected to, the rainfall excess of the rural watershed when it is completely urbanised or afforested can be computed. For an assumed rainfall excess of 5 cm in the rural watershed, such computations were made and the results are presented in Figs. 3.24 and 3.25. It is observed that there is an increase of 49 percent in rainfall excess of the watershed is urbanised and a decrease of 20 percent in rainfall excess if the watershed is afforested as indicated in Fig. 3.26.

3.3.4.2 Effect of urbanisation or afforestation on
Time distribution of the runoff and time to peak

For obtaining the time distribution of the surface runoff, the 3-coefficient model (Eq. 3.16) is used. The coefficients $a_0$, $a_1$ and $b_0$ were estimated for the rural watershed for a number of storms and average values of these coefficients are computed. For studying the effect of urbanisation or afforestation on the model parameters $a_0$, $a_1$ and $b_0$, the following functional relationships were assumed
FIG. 3.19  FOREST WATERSHED (MUKURTHY); GRAPH OF $F_Y/R_Y$ Vs. $SMI/r_a$ AND $T_G/T$

FIG. 3.20  AGRICULTURAL WATERSHED (KATERI); GRAPH OF $F_Y/R_Y$ Vs. $SMI/r_a$ AND $T_G/T$
FIG. 3.21 AGRICULTURAL WATERSHED (KATERI) GRAPH OF Fv / Rv Vs. θ / T

A = 54.753 sq. km.

MONSOON

0 = θ / T

SMI
FIG. 3.23 URBAN WATERSHED (COONOOR); GRAPH OF FV/RV VS. SMI/To

AND T6/1

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.

MONSOON

NON-MONSOON

SMI/To

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

FV/RV

0 1 2 3 4 5 6 7 8 9 10

A = 44.08 sq.km.
RAINFALL

\[ A = 54.753 \text{ sq.km.} \]
\[ L = 14 \text{ km} \]
\[ R = 751.8 \text{ m} \]
\[ d = 8.35 \text{ km} \]
\[ P = 35.42 \text{ km} \]
\[ L_b = 11.9 \text{ km} \]
\[ S = 0.0537 \]
\[ t_{da} = 5.65 \text{ DAYS} \]

--- EFFECT OF URBANISATION
--- NATURAL CONDITION
--- EFFECT OF AFFORESTATION

\[ R_v = 1.956 \text{ cm} \]
\[ R_{evu} = 0.2445 \text{ cm} \]
\[ R_{evn} = 0.163 \text{ cm} \]
\[ R_{evf} = 0.1076 \text{ cm} \]

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>(a_0) DAYS</th>
<th>(a_1) DAYS</th>
<th>(b_0) DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>URBAN</td>
<td>1.343</td>
<td>0.781</td>
<td>0.123</td>
</tr>
<tr>
<td>NATURAL</td>
<td>1.65</td>
<td>1.5</td>
<td>0.3743</td>
</tr>
<tr>
<td>AFFORESTATION</td>
<td>15.75</td>
<td>6.073</td>
<td>0.962</td>
</tr>
</tbody>
</table>

FIG. 3.24  KATERI; STORM OF 22nd APRIL 1956

STORM No.9
FIG. 3.25 KATERI; STORM OF 30th SEPTEMBER 1956
STORM No.14

RAINFALL

A = 54.753 sq.km.
L = 14 km
R = 151.8 m
d = 8.35 km
P = 35.42 km
Lb = 11.9 km
S = 0.0537
tda = 5.65 DAYS

--- EFFECT OF URBANISATION
--- --- NATURAL CONDITION
--- --- --- EFFECT OF AFFORESTATION

R = 11.735 cm
Revu = 3.5289 cm
Revn = 1.928 cm
Revf = 0.6362 cm

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>a0 DAYS</th>
<th>a1 DAYS</th>
<th>b0 DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>URBAN</td>
<td>1.7</td>
<td>0.680</td>
<td>0.091</td>
</tr>
<tr>
<td>NATURAL</td>
<td>2.34</td>
<td>2.5</td>
<td>0.0218</td>
</tr>
<tr>
<td>AFFORESTATION</td>
<td>12.583</td>
<td>5.97</td>
<td>1.976</td>
</tr>
</tbody>
</table>

FIG.3·25 KATERI; STORM OF 30th SEPTEMBER 1956
STORM No.14
FIG. 3.26 KATERI; EFFECT OF AFFORESTATION AND URBANISATION ON THE RAINFALL EXCESS
where $A$ is the area of the watershed, $L$ is the length of the main channel, $S$ is the average slope of the main channel, $Re$ is the elongation ratio of the basin and $t_{da}$ is the average time delay of the basin. By a study of $a_0$, $a_1$ and $b_0$ with the watershed characteristics and the time delay, the following relationships for the three watersheds were obtained.

\[
a_0 = k_0 \frac{A \cdot L}{Re \sqrt{S}} \cdot t_{da} \quad \ldots \quad (3.26)
\]

\[
a_1 = k_1 \frac{A \cdot L}{Re \sqrt{S}} \cdot t_{da} \quad \ldots \quad (3.27)
\]

\[
b_0 = k_2 \frac{A \cdot L}{Re \sqrt{S}} \cdot t_{da} \quad \ldots \quad (3.28)
\]

Knowing the values of $A$, $L$, $Re$ and $S$, $t_{da}$ and $a_0$, $a_1$ and $b_0$, the coefficients, $k_0$, $k_1$ and $k_2$ in the above equations can be computed for different types of land uses. Using the values of $k_0$, $k_1$ and $k_2$ of the urban watershed (Coonoor) the values of the parameters $a_0$, $a_1$ and $b_0$ were computed for the rural watershed (Kateri) in order to study the effect of urbanisation on the time distribution of surface runoff and time to peak. Similarly using the values of $k_0$, $k_1$ and $k_2$ of the forest watershed (Mukurthy).
the values of the parameters $a_0$, $a_1$ and $b_0$ were computed for the rural watershed (Kateri) to study the effect of afforestation. The model parameters so evaluated were used in Eq. 3.14 and the time distribution of surface runoff is computed. Totally 30 storms were used 18 from the monsoon period and 12 from the non-monsoon period of the rural watershed. From these studies, it is found that there is an increase of 107 percent in the surface runoff peak if the watershed is urbanised and 80 percent decrease in the surface runoff peak, if the watershed is afforested for an assumed peak of 1.0 cm/day in the natural condition (rural)(Figure 3.27). Further it is found that there is a decrease of 18 percent in time to peak ($t_p$) if the watershed is urbanised and increases by 28 percent if the watershed is afforested for an assumed $t_p$ of 2.5 days in the natural condition (Fig. 3.28).

By using the above procedure, any mixed watershed consisting of urban, rural and forest can be modelled and the effect of land use changes on the stream flow can be predicted.

3.3.5 Summary

In this study, a method for continuous runoff prediction for the non-monsoon and monsoon seasons, by the application of 3-coefficient model is presented. The proposed model predicts the flood hydrographs continuously, for the entire season fairly well for different types of land uses. The model lends itself for the application of runoff
FIG. 3.27 KATERI: EFFECT OF AFFORESTATION AND URBANISATION ON THE PEAKS OF SURFACE RUNOFF

A: 54.753 sq. km.

107% INCREASE IN PEAK

80% DECREASE IN PEAK
FIG. 3-28 KATERI; EFFECT OF AFFORESTATION AND URBANISATION ON $t_p$
prediction in watersheds having different land uses, such as forest, rural, urban etc. Further, the model can be used to quantify the effect of land use changes on the surface runoff characteristics of a mixed watershed.

3.4 Modelling of Base flow Characteristics

3.4.1 General

The rising limb of a hydrograph in a basin, is mainly influenced by the storm characteristics, whereas the falling limb below the point of inflection (recession curve) depends on the storage and land use characteristics of the basin (11,31,38,48). Using the method suggested by Burnash et al (11), the recession curves of Mukurthy (forest), Kateri (rural) and Coonoor (urban) watersheds for monsoon and non-monsoon periods were analysed to determine the primary, supplementary and interflow coefficients. The variation of these coefficients was analysed to study the land use effect on the base flow characteristics.

3.4.2 Methodology

The basic components of a general hydrologic model for modelling head-water portion of the hydrologic cycle are represented in Fig. 3.29. The soil mantle in this model, is divided into upper and lower zones each containing tension and free water zones. The rate of vertical drainage the percolation to deeper soils is controlled by the contents of the upper zone free water and the deficiency of lower
A GENERALIZED HYDROLOGIC MODEL

Fig. 3.29
zone moisture volumes. The preferred path for moisture in the upper zone free water, is considered to be downward as percolation. Horizontal flow in the form of interflow occurs only when the rate of precipitation exceeds the rate at which downward motion can occur from the upper zone free water. When the precipitation rate exceeds the percolation rate and the maximum interflow drainage capacity, then the upper zone free water capacity is filled completely, and the excess precipitation will result in surface runoff. The surface runoff is highly rate dependent volume, with the rate of runoff being determined by the rate of precipitation application and the degree of dryness of the lower zones.

The lower zone tension water capacity, is that depth of water held by the lower zone soils after wetting and drainage which is generally available for evapotranspiration. The two lower zone free water storages, primary and supplementary represent those volumes which are available for drainage as base flow or subsurface outflow not appearing in the channel. These free water storages fill simultaneously from percolated water and drain independently at different rates, generating a variable ground water recession.

The use of three free water components one in the upper zone and two in the lower zone, allows the generation of a wide variety of recessions, and is generally consistent with observed streamflow characteristics (11).
Fig. 3.30 depicts the utilization of a semi-logarithmic discharge plot in evaluating these three basic recession characteristics. Fig. 3.31 represents a semi-logarithmic discharge record in m$^3$ per sq.km, for the watersheds of Bhavani basin. Recession periods which produce similar straight line segments have been identified by letters A, B and C. Those periods, with similar slopes have been combined to produce a composite recession exhibiting average basin characteristics. By combining these slopes, Fig. 3.32 a master recession can be approximated which allows a reasonable estimate of the drainage characteristics and maximum free water storage volumes for the basin.

The primary base flow recession constant, $K_P$ is given by

$$K_P = \left( \frac{Q_P_{t_1}}{Q_P_0} \right)^{1/t_1} \quad \text{.. (3.29)}$$

where $Q_P_{t_1}$ is the sub-surface flow at the start of the primary base flow and $Q_P_0$ after time $t_1$ days. When we subtract the recession constant from one we get the depletion coefficient. That is $(1-K_P)$ gives the depletion coefficient for the primary zone. The supplementary base flow constant $K_S$ is

$$K_S = \left( \frac{Q_S}{Q_{smax}} \right)^{1/\Delta t} \quad \text{.. (3.30)}$$
FIG. 3.30 SEMI-LOGARITHMIC PLOT OF FLOW IN MUKURTHY AND COONOOR WATERSHEDS IN BHAVANI BASIN
FIG. 3.31  SEMI-LOGRITHMIC PLOT OF ALIGNMENT OF COMMON SLOPES

NON-MONSOON

ALIGNMENT OF COMMON SLOPES
STREAMFLOW SUPPLIED BY FREE WATER DRAINAGES
A = PRIMARY WITHDRAWAL
B = SECONDARY WITHDRAWAL
C = INTERFLOW SUPPLEMENTAL AND PRIMARY WITHDRAWAL
NON-MONSOON

COMPOSITE RECESSION

STREAMFLOW SUPPLIED BY FREE WATER DRAINAGES

A = PRIMARY WITHDRAWAL
B = SECONDARY WITHDRAWAL
C = INTERFLOW SUPPLEMENTARY AND PRIMARY WITHDRAWAL

FIG. 3.32 SEMI-LOG RITHMIC PLOT OF COMPOSITE RECESSION
where $Q_{g_{\text{max}}}$ is the supplementary base flow measured 1 or 2 days after peak runoff and $Q_{g_{1}}$ is the supplementary baseflow at $\Delta t = \left(\frac{2}{3} - t_{2}\right)$ where $t_{2}$ is the time of supplementary base flow in days. Similarly, the interflow recession constant $K_{I}$ is given by

$$K_{I} = \left( \frac{Q_{I}}{Q_{I_{\text{max}}}} \right)$$

(3.31)

$Q_{I_{\text{max}}}$ is the interflow measured 1 or 2 days after peak runoff and $Q$ is the interflow at $\Delta t = \frac{2}{3} - t_{3}$ where $t_{3}$ is the time of interflow in days.

From the available daily flow data of 25 years for Coonoor and Kateri, six years of data (1956, 61, 66, 71, 76 and 79) were used and for Mukurthy, all the available data of 4 years (1934, 35, 36 and 37) were used for the base flow analysis. Each year was divided into two seasons of monsoon (June-December) and non-monsoon (January-May). The discharge data was plotted on semi-log paper using time on x-axis and discharge on y axis (Figs. 3.33, 3.34, 3.35, 3.36, 3.37). Using the method outlined in the previous section, the recession constants for primary, secondary and inter flows were worked out for all the three watersheds for the monsoon and non-monsoon periods separately and presented in Tables 3.6, 3.7 and 3.8. The average values of the recession constants are presented in Table 3.9.
FIG. 3.33  SEMI-LOGARITHMIC PLOT: MUKURTHY

MUKURTHY

N-Monsoon

M-Monsoon

COMPOSITE RECESSION

N-Monsoon
FIG. 3.34  SEMI-LOGRITHMIC PLOT; KATERI
FIG. 3.36 SEMI-LOGRITHMIC PLOT; COONOOR

COMPOSITE RECESSION

NO OF DAYS

Q IN M³/SEC

1966 M
1966 N
1956 N
1961 M
1961 N
1956 M

0 50 100 150 200 214

Composite Recession

Fig. 3.37  Semi-logarithmic Plot; Coonoor
### TABLE 3.6: FOREST-MUKURTHY WATERSHED LOW FLOW COEFFICIENTS

<table>
<thead>
<tr>
<th>Year</th>
<th>NON-MONSOON</th>
<th>SBF</th>
<th>IF</th>
<th>MONSOON</th>
<th>SBF</th>
<th>IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1934</td>
<td>.9950897</td>
<td>.9753406</td>
<td>-</td>
<td>.9974647</td>
<td>.943694</td>
<td>.8377237</td>
</tr>
<tr>
<td>1935</td>
<td>.9952106</td>
<td>.9680029</td>
<td>-</td>
<td>.9828307</td>
<td>.921202</td>
<td>.8682209</td>
</tr>
<tr>
<td>1936</td>
<td>.9880754</td>
<td>.4343722</td>
<td>-</td>
<td>.9823713</td>
<td>.897804</td>
<td>.348597</td>
</tr>
<tr>
<td>1937</td>
<td>.9915248</td>
<td>.9480784</td>
<td>-</td>
<td>.9858558</td>
<td>.897285</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>.9924751</td>
<td>.8314487</td>
<td>-</td>
<td>.9871306</td>
<td>.914246</td>
<td>.684872</td>
</tr>
</tbody>
</table>

PBF - Primary base flow  
SBF - Supplementary base flow  
IF - Interflow

### TABLE 3.7: RURAL-KATERI WATERSHED LOW FLOW COEFFICIENTS

<table>
<thead>
<tr>
<th>Year</th>
<th>NON-MONSOON</th>
<th>SBF</th>
<th>IF</th>
<th>MONSOON</th>
<th>SBF</th>
<th>IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>.98891</td>
<td>.95212</td>
<td>-</td>
<td>.99241</td>
<td>.96582</td>
<td>.9100824</td>
</tr>
<tr>
<td>1961</td>
<td>.99761</td>
<td>.97634</td>
<td>-</td>
<td>.98915</td>
<td>.9180949</td>
<td>.221324</td>
</tr>
<tr>
<td>1966</td>
<td>.98907</td>
<td>.93105</td>
<td>-</td>
<td>.99227</td>
<td>.965739</td>
<td>.9127469</td>
</tr>
<tr>
<td>1971</td>
<td>.992149</td>
<td>.5782792</td>
<td>-</td>
<td>.9923042</td>
<td>.9621215</td>
<td>.8863772</td>
</tr>
<tr>
<td>1976</td>
<td>.9874929</td>
<td>.2421901</td>
<td>-</td>
<td>.9826358</td>
<td>.9162314</td>
<td>.8659142</td>
</tr>
<tr>
<td>1979</td>
<td>.9866941</td>
<td>.8934921</td>
<td>-</td>
<td>.9902612</td>
<td>.9524493</td>
<td>.5871774</td>
</tr>
<tr>
<td>Average</td>
<td>.990321</td>
<td>.7622452</td>
<td>-</td>
<td>.989835</td>
<td>.946365</td>
<td>.7307272</td>
</tr>
</tbody>
</table>

PBF - Primary base flow  
SBF - Supplementary base flow  
IF - Interflow
### TABLE 3.8: URBAN-COONOOR WATERSHED LOW FLOW COEFFICIENTS

<table>
<thead>
<tr>
<th>Year</th>
<th>PBF</th>
<th>NON-MONSOON</th>
<th>SBF</th>
<th>IF</th>
<th>PBF</th>
<th>MONSOON</th>
<th>SBF</th>
<th>IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>.98997</td>
<td>.34595</td>
<td>-</td>
<td>.98584</td>
<td>.93496</td>
<td>.54604</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1961</td>
<td>.99234</td>
<td>.97235</td>
<td>-</td>
<td>.99027</td>
<td>.95681</td>
<td>.25733</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1966</td>
<td>.98639</td>
<td>.89013</td>
<td>-</td>
<td>.97287</td>
<td>.82440</td>
<td>.78300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>.98867</td>
<td>.84724</td>
<td>-</td>
<td>.98773</td>
<td>.89712</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>.99137</td>
<td>.85838</td>
<td>-</td>
<td>.99111</td>
<td>.89341</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>.98062</td>
<td>.69045</td>
<td>-</td>
<td>.97993</td>
<td>.90836</td>
<td>.59383</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>.9882266</td>
<td>.7674166</td>
<td>-</td>
<td>.984625</td>
<td>.90251</td>
<td>.54505</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PBF - Primary base flow  
SBF - Supplementary base flow  
IF - Inter flow
TABLE 3.9: AVERAGE VALUES OF RECESSION CONSTANTS

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Season</th>
<th>RECESSION CONSTANTS (AVERAGE)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Primary base flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mukurthy (Forest)</td>
<td>NM</td>
<td>0.99</td>
<td>0.83</td>
<td>-</td>
</tr>
<tr>
<td>Kateri (Rural)</td>
<td>NM</td>
<td>0.99</td>
<td>0.76</td>
<td>-</td>
</tr>
<tr>
<td>Coonoor (Urban)</td>
<td>NM</td>
<td>0.99</td>
<td>0.76</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>NM</td>
<td>0.99</td>
<td>0.79</td>
<td>-</td>
</tr>
<tr>
<td>Mukurthy (Forest)</td>
<td>M</td>
<td>0.99</td>
<td>0.91</td>
<td>0.69</td>
</tr>
<tr>
<td>Kateri (Rural)</td>
<td>M</td>
<td>0.99</td>
<td>0.95</td>
<td>0.73</td>
</tr>
<tr>
<td>Coonoor (Urban)</td>
<td>M</td>
<td>0.99</td>
<td>0.90</td>
<td>0.54</td>
</tr>
<tr>
<td>Average</td>
<td>M</td>
<td>0.99</td>
<td>0.92</td>
<td>0.65</td>
</tr>
<tr>
<td>Annual Average</td>
<td></td>
<td>0.99</td>
<td>0.86</td>
<td>0.65</td>
</tr>
</tbody>
</table>

NM = Non-monsoon (January to May)
M = Monsoon (June to December)

3.4.3 Results and Discussions

Among the three recession constants, the primary base flow constant is mainly controlled by the depth and type of sub-soil which form the aquifer. The supplementary base flow constant, is controlled by the precipitation and infiltration characteristics of the watershed and the interflow. constant, is controlled by the vegetation, permeability, soil moisture, leaf litter, humus and organic matter of top soil as well as by the precipitation characteristics. On comparing the primary base flow recession constants in
Table 3.9, one finds that it is the same for both monsoon and non-monsoon periods for all the three watersheds. This indicates that the three watersheds have similar and identical geological formations and rocks. In fact, these areas are underlain by disintegrated charnockites, gneiss, granite and mixed gneisses to a considerable depth. The effect of land use and vegetation have negligible effect on the primary base flow constants.

On comparing the supplementary base flow recession constants, it is seen that the constants computed for monsoon period differ markedly from these computed for non-monsoon period. Fig. 3.38 indicates the typical variation of non-monsoon flow, as a function of time of year for urban, rural and forest watersheds. As one would expect, the contribution of non-monsoon runoff is least, in the case of urban watersheds, followed by rural and forest watersheds. Fig. 3.39 indicates the ratio of volume of non-monsoon runoff to the annual rainfall as a function of time. During the monsoon period, the supplementary recession constants for the three watersheds remained more or less constant, while during the non-monsoon period, the forest watershed, had the highest constant. This indicates that the release of water from the supplementary storage in forest watershed is more gradual than the other two watersheds. The infiltration tests carried out in the Bhavani basin indicate high rate of infiltration of 16.8 to 20.7 cm/hr in forest, 5.1 to 10.0 cm/hr in grassland, 11 to 15 cm per hour
FIG. 3.38 VARIATION OF NON-MONSOON FLOW AS A FUNCTION OF TIME FOR THREE WATERSHEDS IN BHAVANI BASIN

FIG. 3.39 RATIO OF VOLUME OF NON-MONSOON RUNOFF TO THE ANNUAL RAINFALL AS A FUNCTION OF TIME FOR THREE WATERSHEDS IN BHAVANI BASIN
in scrub forests and only 1.27 cm/hr in agricultural lands (62). The low infiltration rates in urban and rural lands affect the volume of supplementary base flow storages and in turn affect the supplementary base flow constants.

This is indicated by the fact that the depletion of supplementary storage which is equal to \((1-K_3)\) is more gradual during monsoon than that of non-monsoon.

The interflow constants are practically zero during the non-monsoon period. During the monsoon period, a low constant value of 0.54 was observed in urban land use (Coonoor) while forest and rural land uses (Kateri and Mukurthy) had higher interflow constants (0.73 and 0.69). The above figures indicate that interflow contribution to surface runoff is most, in the case of urban watershed followed by forest and agricultural watersheds.

3.4.4 Summary

The recession curve or depletion curve of the three typical watersheds with three different land uses were studied from the available hydrographs. The basins studied were Mukurthy (Forest), Kateri (Rural) and Coonoor (Urban) interflow, supplementary base flow and primary base flow coefficients were computed. It was observed that the primary base flow constants was the same (0.993) for all land uses. This is due to identical conditions of geological formation in all the three watersheds. Sub-
surface base flow and interflow recession constants were affected by land use of forest, rural and urban which influence the infiltration characteristics of the upper mantle of the basin. The change of forest to rural and urban land use, causes decreasing low flows over years making the perennial streams to become dry.

3.5 Curve Numbers for Flow Prediction

3.5.1 General

The concept of curve numbers has been evolved by the Soil Conservation Service, United States Department of Agriculture, USA to predict runoff from catchments under different land uses. In this method, a combination of hydrologic soil group and plant cover which is represented by land use and treatment class is used to determine the hydrologic soil cover complex. The effect of this complex on rainfall and runoff is represented by a runoff curve number referred to as CN. This method with a slight modification, was adopted and curve numbers were prepared for Mukurthy (forest), Kateri (rural) and Coonoor (urban) watersheds from the existing daily hydrographs. These curves are then used to predict runoff from a mixed watershed of the Bhavani basin.
3.5.2 Methodology

Land use has a predominant effect, in controlling the surface runoff, particularly the peak flow. A number of methods are available for estimating runoff hydrograph and peak flow of a watershed. However, there are only a few methods which take into account the land use effect explicitly in predicting either the peak flow or the volume of runoff. Such methods, if found suitable, can be used as a prediction tool for forecasting the hydrologic effect of a watershed undergoing land use changes. After critically analysing the suitability of other methods like rational method, unit hydrograph method etc., the curve numbers method is selected for this study which takes into account hydrologic soil-cover complex which is dynamic in any given land use. The soil-cover complex is governed by the following physical characteristics of the basin.

3.5.2.1 Soil cover Complex

The land use of a basin is classified into:

i. Cultivated land
ii. Fallow land
iii. Uncultivated land
iv. Forest
v. Tree crops
vi. Area not available for cultivation and urban.
The land treatment of a basin is as follows:

i. Straight row farming  
ii. Contour farming  
iii. Terracing

The hydrologic soil groups is broadly divided into:

A Low runoff potential - sands or gravels  
B Moderately low runoff potential - Sandy loam  
C Moderately high runoff potential - clay loam  
D High runoff potential - Clay, impervious rock or other strata.

The wetness or dryness of a soil is an important factor controlling the runoff. This parameter is difficult to determine directly and use it reliably. For practical purposes, it is expressed as an antecedent precipitation index representing the initial soil moisture condition which is easily measured.

3.5.2.2 Curve Numbers (CN)

The runoff curve number technique combines soil, plant cover, cultivation and soil conservation practices in a watershed and helps in predicting runoff not only under present land use but also under future changed land use condition.
Here the runoff relation was developed by assuming that
the surface runoff (Q) to rainfall excess (P) is equal to
the ratio of water retained during runoff (F) to the poten-
tial maximum retention (S) that could be retained during
an extremely large storm. Hence it is expressed as

\[ \frac{F}{S} = \frac{Q}{P} \]  \hspace{1cm} (3.32)

The potential maximum retention S, depends upon soil-
cover complex. The total rainfall P, loses some of its
amount as interception. This is termed as initial abstrac-
tions (Ia). The rainfall, falling on the basin after
initial abstractions, is termed as effective precipitation
Pe. Thus equation (3.32) is modified to

\[ \frac{Q}{P_e} = \frac{F}{S} \]  \hspace{1cm} (3.33)

where
- Q = total surface runoff in due to a storm in mm
- P_e = effective rainfall in mm of that storm
- F = actual retention excluding the initial abstrac-
tion in mm
- S = potential maximum retention in mm

The initial abstraction Ia is taken as a percentage
of the potential maximum retention. On an average an
initial abstraction of 0.2S is assumed. Thus Ia = 0.2S
The effective rainfall $P_e$ can now be expressed as $(P - I_a)$ i.e. $(P - 0.2S)$. The actual retention at any time is the difference between the effective precipitation and runoff i.e. $F = (P_e - Q)$.

Thus equation (3.33) can be written as

$$\frac{P_e - Q}{S} = \frac{Q}{P_e}$$  \hspace{1cm} (3.34)

or \hspace{1cm} $Q = \frac{P_e^2}{P_e + S}$  \hspace{1cm} (3.35)

Substituting $P_e = P - I_a = (P - 0.2S)$ equation 3.35 can be written as

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$  \hspace{1cm} (3.36)

The potential maximum retention is also given by the relationship. \hspace{1cm} $CN = \frac{25400}{254^2 + S}$  \hspace{1cm} (3.37)

in which $CN$, is called Curve Number. $CN$ is 0 as $S \to \infty$ and 100 at $S = 0$. Any watershed condition that can be defined by a value of $S$ can be described by a $CN$ with its value between 0 and 100.

The runoff curve number is used to estimate the volume of runoff or yield of a basin using the hydrologic soil cover complexes presented in Table 3.10. Having arrived
TABLE 3.10: RUNOFF CURVE NUMBERS FOR HYDROLOGIC SOIL COVER COMPLEXES

<table>
<thead>
<tr>
<th>LAND USE</th>
<th>Cover</th>
<th>Treatment Practice</th>
<th>Hydrologic Condition</th>
<th>Antecedent Moisture Condition II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( Ia 0.3S )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Cultivated</td>
<td>Straight flow</td>
<td></td>
<td></td>
<td>76</td>
</tr>
<tr>
<td>Cultivated</td>
<td>Contoured</td>
<td>Poor</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>Cultivated</td>
<td>Contoured</td>
<td>Poor</td>
<td></td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td>Cultivated</td>
<td>Bunded</td>
<td>Poor</td>
<td></td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td></td>
<td>59</td>
</tr>
<tr>
<td>Cultivated</td>
<td>Paddy</td>
<td></td>
<td></td>
<td>95</td>
</tr>
<tr>
<td>Orchards</td>
<td>-</td>
<td>with understory cover</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>without understory cover</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>Forest</td>
<td>Dense</td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Scrub</td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>Pasture</td>
<td>Poor</td>
<td></td>
<td></td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td></td>
<td></td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td></td>
<td></td>
<td>39</td>
</tr>
<tr>
<td>Tree Crops</td>
<td>(Non-agricultural)</td>
<td></td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>Wasteland</td>
<td></td>
<td></td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>Roads (Dirt)</td>
<td></td>
<td></td>
<td></td>
<td>77</td>
</tr>
</tbody>
</table>
at curve number the maximum quantity of runoff to be expected is obtained for different storms. The antecedent moisture conditions of the basin is taken into account by representing the dry, average and wet antecedent moisture condition of the basin by AMC I, II and III respectively. AMC II represents the average condition which can be converted to AMC I and III by multiplying by a factor given in Table 3.11.

<table>
<thead>
<tr>
<th>Curve Number for Condition II</th>
<th>Factor to Convert Curve Number for Condition II to Condition I</th>
<th>Factor to Convert Curve Number for Condition II to Condition III</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.40</td>
<td>2.22</td>
</tr>
<tr>
<td>20</td>
<td>0.45</td>
<td>1.85</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>1.67</td>
</tr>
<tr>
<td>40</td>
<td>0.55</td>
<td>1.50</td>
</tr>
<tr>
<td>50</td>
<td>0.62</td>
<td>1.40</td>
</tr>
<tr>
<td>60</td>
<td>0.67</td>
<td>1.30</td>
</tr>
<tr>
<td>70</td>
<td>0.73</td>
<td>1.21</td>
</tr>
<tr>
<td>80</td>
<td>0.79</td>
<td>1.14</td>
</tr>
<tr>
<td>90</td>
<td>0.87</td>
<td>1.07</td>
</tr>
<tr>
<td>100</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Based on the above technique, the CN for Bhavani basin was constructed. For this the basin’s landuse was broadly divided into urban, agriculture and forest. Three typical watersheds of the basin, having predominantly the above said land uses were selected and the curve numbers were constructed as detailed below:
The runoff curve number method made use of the equation (3.36) wherein an initial abstraction of 0.2S was used. Initial abstractions of 0.1S, 0.3S and 0.5S were also used and the equations were modified as under

\[ Q = \frac{(P-0.1S)^2}{(P+0.9S)} \quad \text{for } I_a = 0.1S \quad \ldots \quad (3.38) \]

\[ Q = \frac{(P-0.3S)^2}{(P+0.7S)} \quad \text{for } I_a = 0.3S \quad \ldots \quad (3.39) \]

\[ Q = \frac{(P-0.5S)^2}{(P+0.5S)} \quad \text{for } I_a = 0.5S \quad \ldots \quad (3.40) \]

In this study all the four initial abstractions were used and the one which gave a fairly satisfactory estimate of the runoff was selected for further analysis. It was found that the runoff prediction was quite high when the present method of converting the curve number to suit the moisture condition was used and therefore the existing technique of considering the antecedent moisture condition in the runoff curve number was modified by making use of the Antecedent Precipitation Index (API).

The API for each storm was computed using the equation.

\[ (API)_1 = 0.85 (API_{1-1}) + P_1 \quad \ldots \quad (3.41) \]
where $\text{API}_{i-1} = \text{Yesterday's API}$

$P_i = \text{Rainfall for today}$

After determining the runoff by the existing technique for the average condition, the ratio between observed runoff and the computed runoff ($Q_a/Q_c$) was calculated and termed as correction factor ($f$). Knowing the API index of storms, a plot of API Vs $f$ was made for the three watersheds of the Bhavani basin which represent urban (Coonoor), rural (Kateri) and forest (Mukurthy) land use (Figs. 3.40, 3.41, 3.42).

These curves were then made use of in predicting runoff for different land use patterns. Here knowing rainfall and the curve number of the basin, the runoff $Q_a$ is computed. From the API Vs $f$, plot the corresponding factor $f$ was determined for the known API of the storm. The previously computed $Q_c$ was multiplied by this factor $f$ to get the modified computed runoff $Q_{c1}$.

The curve numbers obtained for different watersheds in the Bhavani basin are as follows:

Mukurthy (forest watershed):

Here 15 storms over a period from 1936 to 1945 were used and was tested by ten storms selected from 1946 to 1955. Here an initial abstraction of 0.2S gave better estimate than the other initial abstractions (Fig. 3.43).
FIG. 3.43 CURVE NUMBER FOR MUKURTHY
FOR $I_a = 0.2S$

HYDROLOGY SOLUTION OF RUNOFF EQUATION

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

FOREST

DIRECT RUNOFF ($Q$) IN MILLIMETERS

RAINFALL ($P$) IN MILLIMETERS
Kateri (rural watershed):

A total of sixty storms covering a period of fifteen years were taken for constructing the rural curve number.

To find out which one of the initial abstraction gives a fairly close result to the observed, another ten storms were selected for which the curve numbers with different initial abstractions were applied. The computed and observed runoff were compared to select one of the initial abstractions. The results show that an initial abstraction of 0.5S predicts a better value than others (Fig. 3.44).

Coonoor (urban watershed):

A total of thirty storms over a period of eight years were taken for constructing urban curve number. Then ten storms spread over a period of five years were selected and tested for runoff prediction using different initial abstractions. From this analysis, an initial abstraction of 0.5S was found to predict a value nearer to actual (Fig. 3.45).

3.5.3 Results and Discussions

The curve numbers constructed for individual land uses were applied to Sigur (upper) of the Bhavani basin having a mixed land use with 31.95 percent forest, 9.64 percent urban and 58.41 percent rural (28.96 percent pasture and 29.45 percent farming) (Fig. 3.46). 22 storms were selected extending over a period of 15 years for the analysis.
FIG. 3.44  CURVE NUMBER FOR KATERI
FOR I = 0.5S

HYDROLOGY SOLUTION OF RURAL
RUNOFF EQUATION

\[ Q = \frac{(P - 0.5S)^6}{(P + 0.5S)} \]

DIRECT RUNOFF (Q) IN MILLIMETERS

RAINFALL (P) IN MILLIMETERS

40  60  80  100  120  140  160  180

RAINFALL (P) IN MILLIMETERS
FIG. 3.45

CURVE NUMBER FOR COONDOOR
FOR \( t_a = 0.5S \)

HYDROLOGY SOLUTION OF RUNOFF EQUATION

\[ Q = \frac{(P - 0.5S)^2}{(P + 0.5S)} \]

RAINFALL \((P)\) IN MILLIMETERS

DIRECT RUNOFF \((O)\) IN MILLIMETERS
The rainfall (P) for each storm was noted and the antecedent precipitation index was computed.

The curve number for each land use was determined as under (based on the curve numbers as determined for Mukurthy, Kateri and Coonoor, Table 3.12).

<table>
<thead>
<tr>
<th>Land use</th>
<th>Treatment</th>
<th>Soil group</th>
<th>Curve number</th>
<th>Area</th>
<th>Curve number used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>Open</td>
<td>B</td>
<td>44</td>
<td>31.95</td>
<td>44</td>
</tr>
<tr>
<td>Farming</td>
<td>Contour</td>
<td>C</td>
<td>85</td>
<td>29.45</td>
<td>80</td>
</tr>
<tr>
<td>Pasture</td>
<td>Fair</td>
<td>C</td>
<td>79</td>
<td>28.96</td>
<td>80</td>
</tr>
<tr>
<td>Non-Agricultural/Urban</td>
<td></td>
<td>C</td>
<td>91</td>
<td>9.64</td>
<td>91</td>
</tr>
</tbody>
</table>

From the rainfall volume P and curve numbers of respective land uses three runoff values were determined. These three runoff was corrected by the respective correction factor. The runoff computed under each land use is then proportionally reduced according to the percentage area covered by the respective land uses and the sum of these gives the net surface runoff for a watershed having mixed land use pattern. Observed and computed runoff of the Sigur (upper) with mixed land use is given in Fig. 3.47.

One of the objectives of constructing curve number for a basin having mixed land uses, is to predict the runoff pattern, when the land use is changed. Such a prediction becomes essential, especially when the basin is
FIG. 3.47 $Q_c$ vs. $Q_a$ for Sigur Upper

COMPUTED RUN OFF $Q_c$

OBSERVED RUN OFF $Q_a$
<table>
<thead>
<tr>
<th>Land use</th>
<th>Treatment</th>
<th>Soil group</th>
<th>Curve Number</th>
<th>Percentage Area</th>
<th>Weighted Curve Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Coonoor</td>
<td>Forest Open</td>
<td>B</td>
<td>44</td>
<td>4.20</td>
<td>184.8</td>
</tr>
<tr>
<td></td>
<td>Farming Contour</td>
<td>C</td>
<td>82</td>
<td>62.96</td>
<td>5162.72</td>
</tr>
<tr>
<td></td>
<td>Tea</td>
<td>C</td>
<td>76</td>
<td>21.19</td>
<td>1610.44</td>
</tr>
<tr>
<td></td>
<td>Non-agricultural</td>
<td>C</td>
<td>91</td>
<td>11.65</td>
<td>1060.15</td>
</tr>
<tr>
<td>2. Kateri</td>
<td>Forest Open</td>
<td>B</td>
<td>44</td>
<td>2.47</td>
<td>108.68</td>
</tr>
<tr>
<td></td>
<td>Farming Contour</td>
<td>C</td>
<td>82</td>
<td>58.75</td>
<td>4817.50</td>
</tr>
<tr>
<td></td>
<td>Tea</td>
<td>C</td>
<td>76</td>
<td>38.78</td>
<td>2947.28</td>
</tr>
<tr>
<td>3. Mukurthy</td>
<td>Forest Open</td>
<td>B</td>
<td>44</td>
<td>100</td>
<td>4400</td>
</tr>
</tbody>
</table>
undergoing transition from forest to rural and urban. The estimated runoff for Sigur upper for different combination of land uses is given in Table 3.13.

The determination of runoff for changing land uses reveals that a combination of rural and urban land use yield a better runoff than the other combinations. Another interesting factor is that for most of the storms the contribution from forest watershed is almost nil up to 100 mm of rainfall. In the case of storm ranging between 100 to 150 mm there is some contribution from forest. However for storms above 150 mm the forest watershed gives a runoff exceeding the precipitation while no such behaviour is observed in urban and rural watersheds.

3.5.4 Summary

The conventional method of constructing curve number did not reproduce the runoff volume satisfactorily. Hence a correction factor f which is the ratio of the observed runoff to the computed runoff by the conventional curve number technique is related to the antecedent precipitation index and made use of in runoff prediction. The modified runoff volume obtained after applying the correction factors reproduce the observed runoff volumes satisfactorily.

The curve numbers developed for individual land uses when applied to a mixed watershed reproduces the runoff volume fairly satisfactorily.
<table>
<thead>
<tr>
<th>Percentage Rural</th>
<th>Landuse Percentage Urban</th>
<th>Percentage Forest</th>
<th>Runoff for P=27.88 Q,in mm</th>
<th>Runoff for P=44.55 Q,in mm</th>
<th>Runoff for P=83.69 Q,in mm</th>
<th>Runoff for P=173.25 Q,in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.41</td>
<td>9.64</td>
<td>31.95</td>
<td>1.3</td>
<td>9.60</td>
<td>73.91</td>
<td>110.23</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>80</td>
<td>2.7</td>
<td>6.96</td>
<td>73.06</td>
<td>151.80</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>60</td>
<td>5.4</td>
<td>13.92</td>
<td>75.60</td>
<td>145.20</td>
</tr>
<tr>
<td>0</td>
<td>60</td>
<td>40</td>
<td>8.1</td>
<td>20.80</td>
<td>78.38</td>
<td>138.62</td>
</tr>
<tr>
<td>0</td>
<td>80</td>
<td>20</td>
<td>10.8</td>
<td>20.80</td>
<td>81.04</td>
<td>132.03</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>0</td>
<td>13.5</td>
<td>34.80</td>
<td>83.7</td>
<td>125.44</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>0</td>
<td>8.1</td>
<td>25.80</td>
<td>79.92</td>
<td>107.88</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>0</td>
<td>5.4</td>
<td>20.34</td>
<td>77.95</td>
<td>98.82</td>
</tr>
<tr>
<td>80</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>10.70</td>
<td>74.25</td>
<td>81.38</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>10</td>
<td>1.35</td>
<td>12.04</td>
<td>74.80</td>
<td>93.48</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>20</td>
<td>2.7</td>
<td>13.30</td>
<td>75.37</td>
<td>105.59</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>30</td>
<td>4.05</td>
<td>14.72</td>
<td>75.92</td>
<td>117.71</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>5.4</td>
<td>16.46</td>
<td>76.49</td>
<td>129.80</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>60</td>
<td>2.7</td>
<td>9.10</td>
<td>73.33</td>
<td>140.36</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>40</td>
<td>2.7</td>
<td>4.28</td>
<td>57.86</td>
<td>120.99</td>
</tr>
</tbody>
</table>
The curve numbers developed can be used to predict runoff volume of a mixed watershed when it undergoes land use changes. It can be concluded that the runoff curve number technique is a simple yet a useful technique for the prediction of runoff for any basin with different land uses. It combines within itself combination of land uses, treatment practices like soil and water conservation, hydrologic soil-cover complex and antecedent rainfall and can be profitably used for the prediction of runoff in a watershed where in land use has or likely to undergo certain changes.