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RAINFALL - RUNOFF RELATIONSHIPS

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1985-86

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ABSTRACT

For estimating dependable yield while planning and designing water resources development projects, long period series of stream flow are required. However, since the flow data are generally available for only short periods, the stream flow series are extended using rainfall data through use of rainfall-runoff relationships.

Rainfall is the single important parameter which influences runoff directly as overland flow or indirectly as sub-surface and ground water. In the absence of direct measurements of runoff, regional rainfall-runoff relationships developed over a hydrologically homogeneous region based on long period rainfall and runoff data should be used for estimation of yields from ungauged catchments in the region.

Starting with simple techniques like runoff-coefficients and empirical formulae, the later day developments included use of graphical relationships such as simple rainfall-runoff plots, coaxial graphical techniques using antecedent precipitation index and statistical techniques such as bivariate and multivariate regression equations between rainfall and runoff.

The study and analysis of rainfall-runoff process has attained further sophistication with the introduction of high speed computers making it possible to model every aspect of the process in greater detail. In spite of the availability of conceptual models which could be run on medium and large computers, the simple rainfall-runoff relationships do have a

role to play in the estimation of water yields from small and medium catchments because of the relative ease with which they could be used on micro computers. A review of simple rainfall-runoff relationships has been undertaken covering empirical formulae, and graphical and statistical relationships. Some of the rainfall-runoff relationships used by the state and central water resources organisations for project planning and in research studies in India have also been reviewed.

The review has broadly indicated that except for a few, most of the rainfall-runoff relationships used only rainfall (current or previous time steps) for relating with runoff. To make the so called simple rainfall-runoff relationships more purposeful and reliable, it would be necessary to incorporate appropriate climatic and physiographic factors either directly or through their derivatives.

1.0 INTRODUCTION

For planning and execution of water resources development projects, the estimation of surface water yield is an important step. The total quantity of water that can be expected from a stream in a given time period such as a month, season or year is called the yield of the river. For estimating the dependable yield at any proposed location of a water resources development project, long period data of the yield is essential which is generally of a limited duration in a number of cases. In small catchment, usually little or no runoff data are available. Water yield is generally estimated from rainfall-runoff relationships.

Runoff is that part of the precipitation as well as any other flow contributions, which appears in surface streams of either perennial or intermittent form. This is the flow collected from a drainage basin or watershed and it appears at an outlet of the basin. Runoff is basically divided into three components depending on the path followed by the flowing water:

i) Surface runoff

ii) Sub-surface runoff (or interflow)

iii) Ground water runoff

Runoff resulting from rainfall over a catchment is dependent on various climatic factors and physiographic factors. Of the large number of factors affecting the formation of runoff, only the rainfall is measured directly. All the other indices required for forecasting can only be approximately estimated on the basis of meteorological and hydrological observational data.

Since direct measurements of runoff through river gauging are expensive, regional rainfall - runoff relations if developed over a region based on long period rainfall and runoff data could be readily used for the estimation of yields from ungauged basins in the region for a quick and rational assessment of the water resources of the region. To study the reliability and applicability of the different techniques for development of rainfall-runoff relations a review of the various rainfall - runoff empirical formulae and methods of developing such relations has been undertaken and reported here.

2.0 REVIEW

Runoff is an important component of the hydrological cycle. While it is made up of flow from all sources, rainfall is the single parameter which influences runoff directly as overland flow or indirectly as sub-surface flow and ground water. Chow (1964) had thematically indicated the various components of the runoff process which he had visualised as a cycle dependent on the nature of supply.

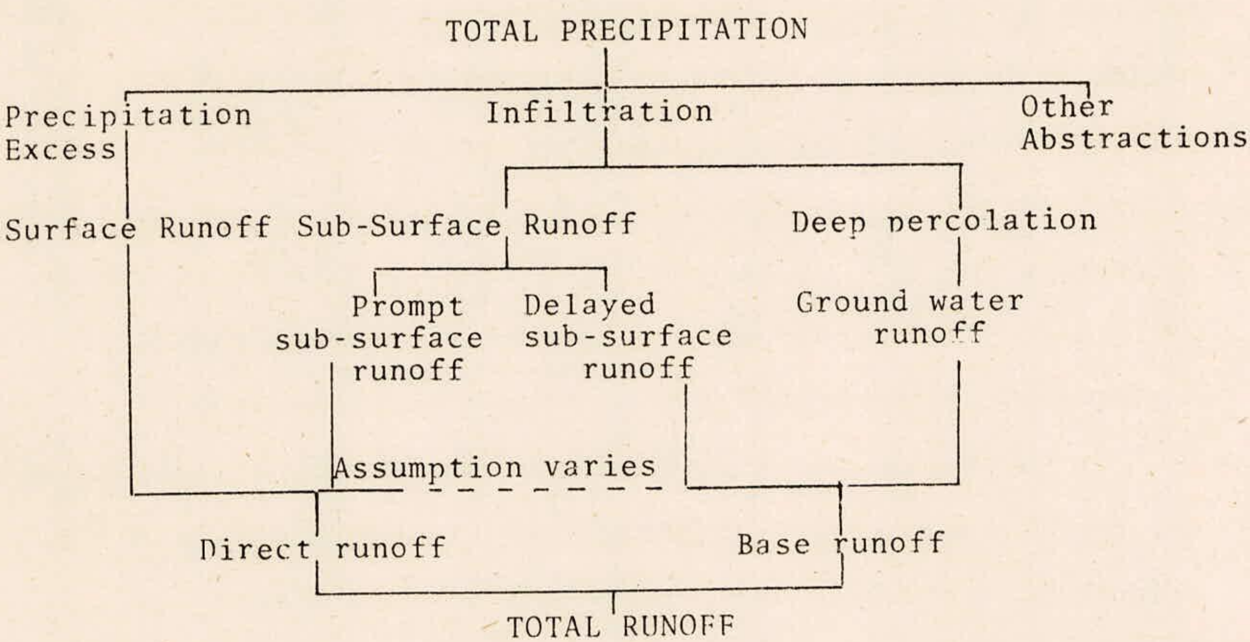

Figure 1 Thematic Diagram Showing Rainfall - Runoff Process (From Ven Te Chow, 1964)

Initially, when the rainfall takes place, the interception by vegetation is high. However, the available storage capacity decreases rather quickly so that interception rate decreases rapidly. More often interception is returned to atmosphere by the process of evaporation.

The rate at which depression storage is filled by incident precipitation decreases rapidly from a high initial value as the smaller depressions become filled up. Except in very intense storms, the greater portion of the soil moisture deficiency is satisfied before appreciable surface runoff takes place.

The rate of surface runoff starts at zero and increases slowly at first and then more rapidly, eventually approaching a relatively constant percentage of the rainfall rate. Effective rainfall may be considered as that rainfall which results when infiltration losses are subtracted from the incident rainfall. Direct runoff is the runoff which is actually measured at a certain point of reference of stream minus base flow. The effective rainfall may be considered as input to catchment system and direct runoff can be considered as output.

The total runoff appearing at the outlet of a basin or catchment consists of various components of runoff as shown in figure 1. Four principal components of runoff could be indentified.

Channel runoff : This occurs due to rain falling directly on a flowing stream or on the impervious surface of a stream flow measuring installation. It is generally a negligible quantity.

Surface runoff : This is the most important component of runoff especially in small catchments. It occurs when the rainfall rate is greater than the infiltration rate. Its magnitude during the storm varies and ends during or soon after the cessation of storm. Surface flow down deep channels is reduced by transmission losses which may be sometimes large enough to eliminate the surface flow entirely.

Sub-surface flow : When infiltrated rainfall meets an underground zone of low permeability, the water travels above the zone along the slope and appears over surface as a spring.

Base flow : The flow comes from an aquifer replenished by rainfall recharge, surface runoff seepage or bank storage of river channels (surface water ground water interaction). This type of flow appears rather delayedly and is important while considering longer duration flows.

Depending on the type of catchment geomorphology all or some of these flows might combine to form the total runoff. However, while dealing with small catchments it is customary to treat all the first three types of flow as direct runoff or direct surface runoff (DSRO) and deal with baseflow separately.

2.1 Factors Affecting Runoff

Runoff from drainage basin is influenced by two major groups of factors:

a) Climatic factors, and

b) Physiographic factors

(a) Climatic factors include mainly :

1. Precipitation - Form (rain, snow, frost, etc.) type, intensity, duration, time distribution, areal distribution, frequency of occurrence, direction of storm movement, antecedent precipitation and soil moisture.

2. Interpolation - Vegetation species, composition, age and density of stands, season of the year, size of storm

3. Evaporation - Temperature, wind, atmospheric pressure, soluble solids, nature and shape of evaporation surface.

4. Transpiration - Temperature, solar radiation, wind, humidity, soil moisture, kinds of vegetation

(b) Physiographic factors

1. Basin characteristics:

Geometric factors - Size, shape, slope orientation, elevation, streamflow, density

Physical factors - Land use and cover, surface infiltration condition, soil type, geological condtions such as the permeability and capacity of ground water formations, topographical conditions such as presence of lakes and swamps, artificial drainage

2. Channel characteristics

Carrying capacity - Size and shape of cross-section, slope, roughness, length, tributories

Storage capacity - Backwater effect

The formation of runoff involves a combination of the heterogeneous and irregular processes of precipitation, infiltration, the retention and loss of water in the catchment area and the concentration and discharge of waste precipitation water in watercourses.

The main factors in runoff are the quantity, intensity and duration of atmospheric precipitation and their distribution throughout the catchment area. In normal conditions, these factors determine the volume of runoff and have a significant effect on the form of the flood hydrograph.

No less important in rainfall-runoff process, are the absorptive characteristics of the river basin - the permeability and capacity of the upper soil layer and surface retention. Runoff further depends on the relief and microrelief of the catchment, swampiness, the number and dimensions of closed lakes or artificial ponds. The permeability of the soil depends on its mechanical composition, structure, its hydro-physical properties and the extent of antecedent wetting. These factors depend on the one hand on the characteristics of the basin itself (the nature and distribution of soils) and, on the other, on previous hydrometeorological conditions - the quantity of precipitation and evaporation.

The third basic factor in the formation of rainfall runoff is the sequence in which water flowing into the water courses in different parts of the catchment area passes to the outfall. The time distribution of the flood runoff (i.e., the form of the flood hydrograph) depends on the size and shape of the drainage basin, its relief, the density of the hydrographical network and the morphometric characteristics of the rivers and flood plains in the neighbourhood of the outfall. The temporal sequence of atmospheric precipitation also has a significant effect on the course of the flood.

The fourth factor playing an important part in the formation of rainfall runoff is the irregularity of the occurrence and absorption of precipitation in space and in time.

This factor presents the greatest difficulties in solving practical problems in the calculation of runoff from precipitation data.

The climatic and physiographic factors do not affect the small and large basins alike. In case of small catchments the overland flow is predominant when one considers a small time scale like daily runoff. Also, the response of small catchments is quick to high rainfall intensities and sensitive to land use changes. However, in large basins the channel storage is very much dominant with the result the other responses become relatively insignificant. Sometimes, two basins of nearly same size may have different runoff phenomenon as guided by their catchment behaviour.

Mustonen (1967) had studied the effect of climatological and basin characteristics on annual runoff in Finland. The climatological variables, especially seasonal precipitation and mean annual temperature were found to be much more important than basin characteristics such as soil type and vegetation.

2.2 Rainfall - Runoff Relationships

Rainfall-runoff relationships have generally been used for:

i) estimation of water yield from rainfall over the catchment,

ii) estimation of peak flood from rainfall intensity.

It is customary to use rainfall-runoff relationships for estimating runoff on monthly, seasonal and annual basis from rainfall of corresponding duration. These relationships are relatively simple techniques using some form of coefficient and other linear or non-linear relations. In case of daily runoff, the catchment condition is taken care of through the use of antecedent precipitation index (API) estimated by weighting precipitation over the previous 3 or 5 days.

The rainfall-runoff relationships generally used can be broadly classified as:

i) Empirical formulae

ii) Statistical techniques

iii) API method

iv) Curve numbers

v) Coaxial graphical techniques

The advantage and applicability of the method is dependent on the type of data available and the time duration for which the runoff is to be estimated.

2.3 Empirical Formulae

The first ever recorded quantitative experiment in rainfall-runoff relationships was reported (Linsley, 1967) to have been carried out by a French Scientist probably Pierre Perrault (1608-1680) by comparing rainfall and runoff from the Seine river basin in France. His work was subsequently confirmed by Edme Marriote (1620-1684) in a similar experiment.

Mead (1919) offered a variety of empirical relationships for computing monthly and annual volume of runoff. These were of the form:

$$R = KP - a \qquad \ldots (1)$$

Some formulae used temperature also as one of the factors (Justin, 1915):

$$R = 0.934\ S^{0.155}\ p^2/t \qquad \ldots (2)$$

where, t is the mean annual temperature in ^{o}F and S is the slope of the drainage area.

Langbein and others (1949) have also used mean annual temperature for arriving at a relationship between rainfall and runoff.

For urban runoff, Burkli - Ziegler (1880) gave a formula which was typical of many suggested during the late 19th century:

$$R = A\ C\ i\ \frac{S^n}{A} \qquad \ldots (3)$$

where, A is the drainage area, i is the rainfall intensity, C is constant, S is the slope, and n = 1/4.

2.4 Runoff Coefficients

For obtaining rough estimates of runoff from a given catchment rainfall especially on seasonal or annula basis it is convenient to use either a percentage or coefficient known as runoff coefficient.

Six Alexander Binnie was probably among the first to recommend certain percentages for use in India based on observations from rivers in Madhya Pradesh. Varshney (1979) listed the following runoff coefficients for different types of land surfaces:

Surface	Runoff coefficient
Urban	0.3 - 0.5
Forests	0.05 - 0.2
Commercial and Industrial areas	0.9
Parks, farms, pastures	0.05 - 0.3
Asphalt or concrete paved surfaces	0.85

Rodier (1967) has given runoff coefficient for use in the small catchments in Africa. They are:

Catchment area	Runoff coefficient
26-50 Km^2	0.95
51-100 km^2	0.90
101-150 Km^2	0.85
151-200 Km^2	0.80

2.5 Statistical Techniques

Using long term rainfall data a short term runoff data can be extended by statistical modelling. In this approach, using cuncurrent rainfall and runoff data, a statistical model is derived that is a regression equation is obtained by using the principle of least squares. Depending on the time unit selected for the analysis or performance testing of the project concerned, the runoff series are prepared on 10 daily, monthly, seasonal or annual basis. The general form of the relationship is:

$$y_n = \sum_{r=o}^{m} x_{n-r} h_r \qquad \ldots (4)$$

or

$$y_n = x_n h_o + x_{n-1} h_1 + x_{n-2} h_2 + \ldots x_{n-m} h_m \qquad \ldots (5)$$

where it is assumed that the effect of a variation in x has only effect for m time steps of duration on y. Due to the presence of errors in data sampling in other words imperfection in the linearity of the system, an error term e_n is added to give

$$y = x_n h_o + x_{n-1} h_1 + x_{n-2} h_2 + \ldots x_{n-m} h_m + e_n \ldots (6)$$

This equation expresses the dependence of y on x as a linear regression in which the successive terms of y constitute the values of the dependent variable and the corresponding value of x and the (n-1) previous values are the n independent variables.

The different types of regression relationships enerally used are

a) Bivariate linear relation of the form

$$R_i = a + b P_i \qquad \ldots (7)$$

b) Bivariate non-linear relation of the form

$$R_i = a P_i^b \qquad \ldots (8)$$

or $\log R_i = \log a + b \log P_i \qquad \ldots 8(a)$

c) Multivariate relation of the form

$$R_i = a + b \left[cP_i + (1-c) P_i \right] \qquad \ldots (9)$$

d) Multivariate linear relation of the form

$$R_i = a + b\, R_{i-1} + c\, P_i \qquad \ldots (10)$$

Equation 8(a) is of the same form as equation 7.

The WMO guide to Hydrological practices (1981) has recommended use of regression analysis methods for establishing quantitative relations between runoff characteristics and a number of hydrological, climatological and physiographic factors. A simple plot of annual (or seasonal) rainfall versus annual (or seasonal) runoff would often indicate some correlation, generally of the linear type. Where ground water is an appreciable part of the total flow, introduction of rainfall during the previous season might improve the relation.

2.6 Antecedent Precipitation Index (API) Method

The initial soil moisture condition or antecedent moisture condition is an important parameter in determining the rainfall-runoff relations. However, because of the difficulties involved in determining this factor directly, for practical purposes it is usually expressed in terms of other measurable quantities such as rainfall. The antecedent precipitation could be used as an index because it affects soil moisture, Butler (1957) had shown that an antecedent precipitation index (API) could be expressed as:

$$API = a\, P_o + b\, P_1 + c\, P_2 \qquad \ldots (11)$$

where, P_o, P_1 and P_2 are the annual rainfalls of current year, previous year and the second previous year respectively.

For estimation of daily runoff, Kohler and Linsley (1951) h d proposed a daily API:

$$Pa = b_1 P_1 + b_2 P_2 + \ .. \ + b_t P_t \qquad ... \quad (12)$$

where. P_t precipitation of t days prior to the storm event and b_t was assumed to decrease exponentially with t.

Thus:

$$P_{at} = P_{ao} K^t \qquad ... \quad (13)$$

where, P_{ao} is the initial value of API and P_{at} is the reduced value t days later.

Mockus (1949) proposed that surface runoff could be estimated from the following information:

1. Soils : Types, areal extents, and locations
2. Land use: Kinds, areal extents and locations
3. Antecedent rainfall
4. Duration of a storm and associated rainfall amount
5. Average annual temperature and date of storm

Mockus (1949) combined these parameters into an index value, b which was solved from the equation:

$$b = \frac{0.0374 \ (10)^{0.229 \ M_C} \ 1.061}{T^{1.990} \ D^{1.333} \ (10)^{2.271 \ (S/D)}} \qquad ... \quad (14)$$

where,

M = 5 day antecedent rainfall in inches,

C = Cover practice index

T = Seasonal index, which is a function of date and temperature (^oF)

D = Duration of storm, hours

S = Soils index, inches per hour

Resulting b values were used as the second independent variable (P being the initial independent variable) in a graph of P vs R in which,

$$R = P\left[1 - (10)^{-bp}\right] \qquad \ldots (15)$$

where,

R = direct runoff in inches

P = storm rainfall, inches

2.7 SCS Curve Number Technique

The Soil Conservation Service (SCS) runoff equation, which came into common use in the mid 1950's in the U.S.A. was developed for estimating direct runoff from storm rainfall after more than 20 years of studies of rainfall-runoff relationships from small rural watershed areas in U.S.A. The procedure, which is frequently referred to as the curve number technique, is basically empirical and has proven to be very useful for estimating the amount of direct runoff under varying land use and soil types. The equation was initially used by the SCS for project planning of small watersheds. At present, it is the procedure most frequently used within SCS to estimate direct runoff from ungauged areas (Rallison and Miller, 1982).

2.8 Graphical Technique

Sherman (1949) was one of the first to propose plotting direct runoff versus storm rainfall. However, to account for the soil wetness the API is also taken care of by using a graphical relation of the form shown in figure 2. Another possible method is to construct a coaxial graph as in figure 3 to bring out the functional relationship between rainfall depth, its duration, the API and the time of the year or season. The time of the year or season takes into account to a certain extent the evaporation differences and the state of vegetative cover.

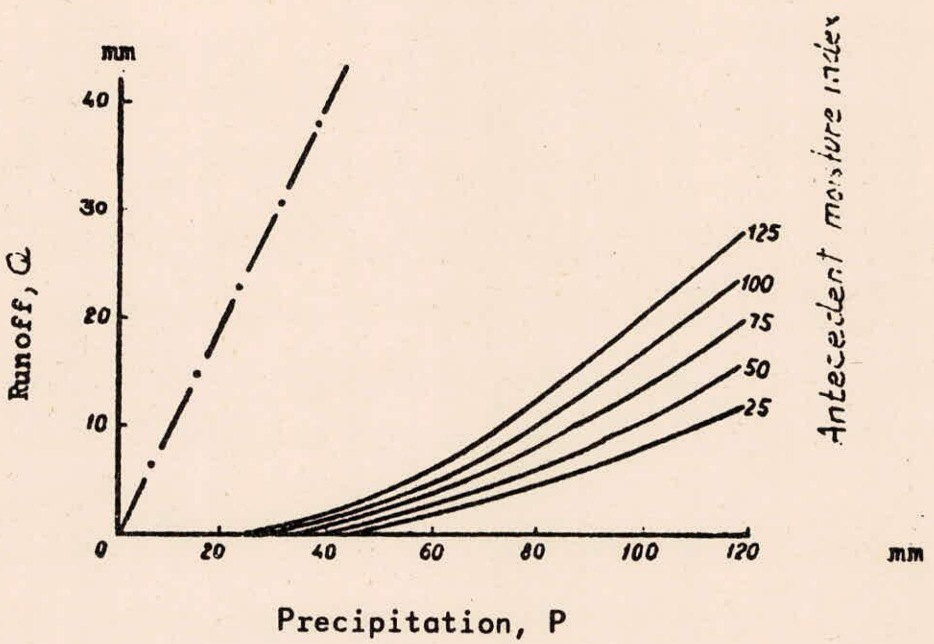

Figure 2 General Form of Relationship Between Flood Runoff, Precipitation and Basin API

Kohler and Linsley (1951) had demonstrated the usefulness of the coaxial graphical technique to incorporate the multivariate relation of rainfall to runoff. Linsley et al (1949) described the procedure for constructing such coaxial graphs. The graphs relate storm rainfall, antecedent basin conditions, storm duration and the resulting storm runoff. In the rainfall runoff relation, the antecedent basin conditions

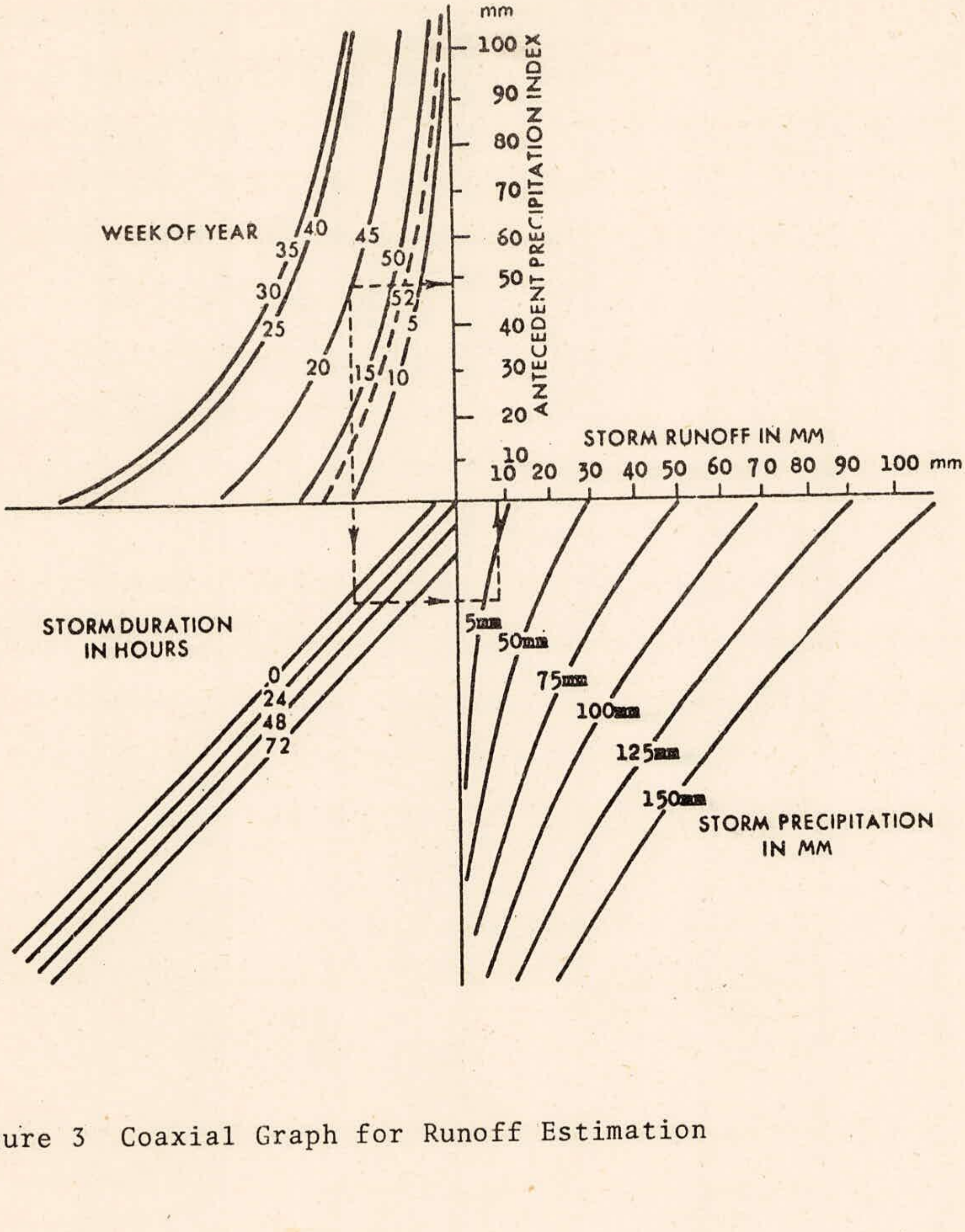

Figure 3 Coaxial Graph for Runoff Estimation

are represented by the simulation of precipitation amounts occuring prior to the storm weighted according to the time of occurrence.

2.9 Rainfall-Runoff Relationships Used in India

Several empirical formulae and tables ahve been developed for estimation of runoff from Indian rivers for over a century now. In the recent years, regression techniques have also come to be used most widely.

2.9.1 Binnie's percentages

From 1869 to 1872 Sir Alexander Binnie made some observations on a single reservoir (Ambajari) in the then Central India and prepared a table giving the percentage of rainfall which appeared as runoff. These are in use for projects in Madhya Pradesh region:

Annual Rainfall		Runoff
inches	mm	%
20	500	15
24	600	21
28	700	25
32	800	29
36	900	34
40	1000	38
44	1100	40

2.9.2 Barlow's tables

T.G. Barlow carried out studies of catchments mostly under 130 sq.km. in U.P. and gave the following values of K (in percentage) for various types of catchments.

Table 1 : Barlow's Percentage Runoff Coefficients(K)

Class	Description of the Catchment	Percent runoff
A	Flat, cultivated and black cotton soils	10
B	Flat, partly cultivated-various soils	15
C	Average	20
D	Hills and plains with little cultivation	35
E	Very hilly and steep, with hardly any cultivation	45

These percentages are for the average type of monsoon and are to be modified by the application of the following coefficients according to the nature of the season.

Table 2 : Barlow's Runoff Coefficients for Different Nature of Season

	Nature of season	Class of Catchments				
		A	B	C	D	E
1.	Light rain, no heavy downpour	0.70	0.80	0.80	0.80	0.80
2.	Average or varying rainfall, no continuous downpour	1.00	1.00	1.00	1.00	1.00
3.	Continuous downpour	1.50	1.50	1.60	1.70	1.80

He divided special tropical rainfall into the following four classes:

i) Negligible falls: All falls under 12 mm a day unless continuous for several days; also falls 12 to 24 mm a day not followed or preceded by any rain.

ii) Light falls : All falls upto 25 mm a day followed by similar or heavier falls. Steady pours of 25 to 40 mm a day, when there is no rain of similar or greater amount before or after that.

iii) Medium falls: Falls from 25 to 40 mm a day when preceded or followed by any but light falls

iv) Heavy falls:

a) All falls over 75 mm a day or continuous fall at 50 mm a day

b) All falls of an intensity of 50 mm or more per hour.

He gave the run-off percentages as shown in Table 3.

Table 3 : Barlow's Run-off Percentages

Nature of rainfall		Percentage of flow on catchments of different types A	B	C	D	E
1.	Negligible fall	-	-	-	-	-
2.	Light fall	1	3	5	10	15
3.	Medium fall	10	15	20	25	33
4.	Heavy fall	20	33	40	55	70

2.9.3 Strange's tables

On the basis of data from Maharashtra, W.L. Strange has formulated two tables (table 4 and 5) giving runoff as a percentage of:

a) total monsoon rainfall, and

b) daily rainfall

For the purpose of monsoon runoff, the catchment has been classified as good, bad and average though the basis of such a classification is not known.

In the case of the daily runoff, the catchment condition was classified as dry, damp and wet. Though it was not specified whether the tables recommended were for use of good, bad or average catchments, on the presumption that these were for average catchments, Varshney (1979) had recommended the addition or deduction of yield upto 25% depending on whether the catchment is good or bad respectively.

The curves based on the Strange's tables are being adopted for project formulation in Maharashtra.

2.9.4 Inglis-desouza formulae

Sir CC Inglis and De Souza on the basis of some catchments in the ghats and plains of the then Bombay State had recommended the following empirical formulae for use in the ghats and plains regions.

For ghat area $R = 0.85 P - 12$ ... (16)

For plain area $R = \frac{P - 7}{100} \times P$ ... (17)

TABLE 4 Strange's Tables of Runoff Coefficient K_s in Percent

Total monsoon rainfall (cm)	Runoff coefficient K_s percent		
	Good catchment	Average catchment	Bad catchment
25	4.3	3.2	2.1
50	15.0	11.3	7.5
75	26.3	19.7	13.1
100	37.5	28.0	18.7
125	47.6	35.7	23.8
150	58.9	44.1	29.4

TABLE 5 Daily Runoff According to Strange

Daily rain-fall in mm	Runoff percentage and yield when the original stage of ground is					
	Dry		Damp		Wet	
	Percent-tage	Yield in mm	Percen-tage	Yield in mm	Percen-tage	Yield in mm
5			4	0.2	7	0.35
10	1	0.10	5	0.5	10	1.0
20	2	0.40	9	1.8	15	3.0
25	3	0.75	11	2.75	18	4.5
30	4	1.20	13	3.9	20	6.0
40	7	2.80	18	7.2	28	11.2
50	10	5.00	22	11.0	34	17.0
60	14	8.46	28	16.8	41	24.6
70	18	12.61	33	23.1	48	33.6
75	20	15.0	37	27.75	52	41.25
80	22	17.6	39	31.2	55	44.0
90	25	22.5	44	39.6	62	55.8
100	30	30.0	50	50.0	70	70.0

where, R and P are annual runoff and annual rainfall respectively in inches.

Equations (16) and (17) when written for R and P in cms are expressed as:

$$R = 0.85\, P - 30.5 \quad \ldots (18)$$

and

$$R = \left(\frac{P - 17.8}{254}\right) P \quad \ldots (19)$$

2.9.5 Comparative study

Curves corresponding to Binnie's table, Strange's tables and Inglis formulae were prepared by Bhalerao et al (1977) and are shown in figure 4. From a comparative study of these curves, they concluded that :

i) The runoff as per Strange's curves from the good, average and bad catchments for the same rainfall are in the ratio 2.0 : 1.5 : 1.0.

ii) For monsoon rainfall beyond 121 cm, the incremental runoff is more than 1 cm, for every increase of 1 cm in the rainfall according to Strange's curve for a good catchment. In the case of an average catchment this condition is obtained for monsoon rainfall beyond 159 cm. A similar condition was obtained in the case of Ingli's formulae for plain catchments for monsoon rainfall values higher than 136 cm. Such inconsistency is, however, not noticed in Binnie's percentages or Strange's bad catchment

iii) Upto a rainfall of 115 cm Binnie's curve and Strange's curve for good catchment are close to each other. Above 115 cm, the runoff given by Binnie's

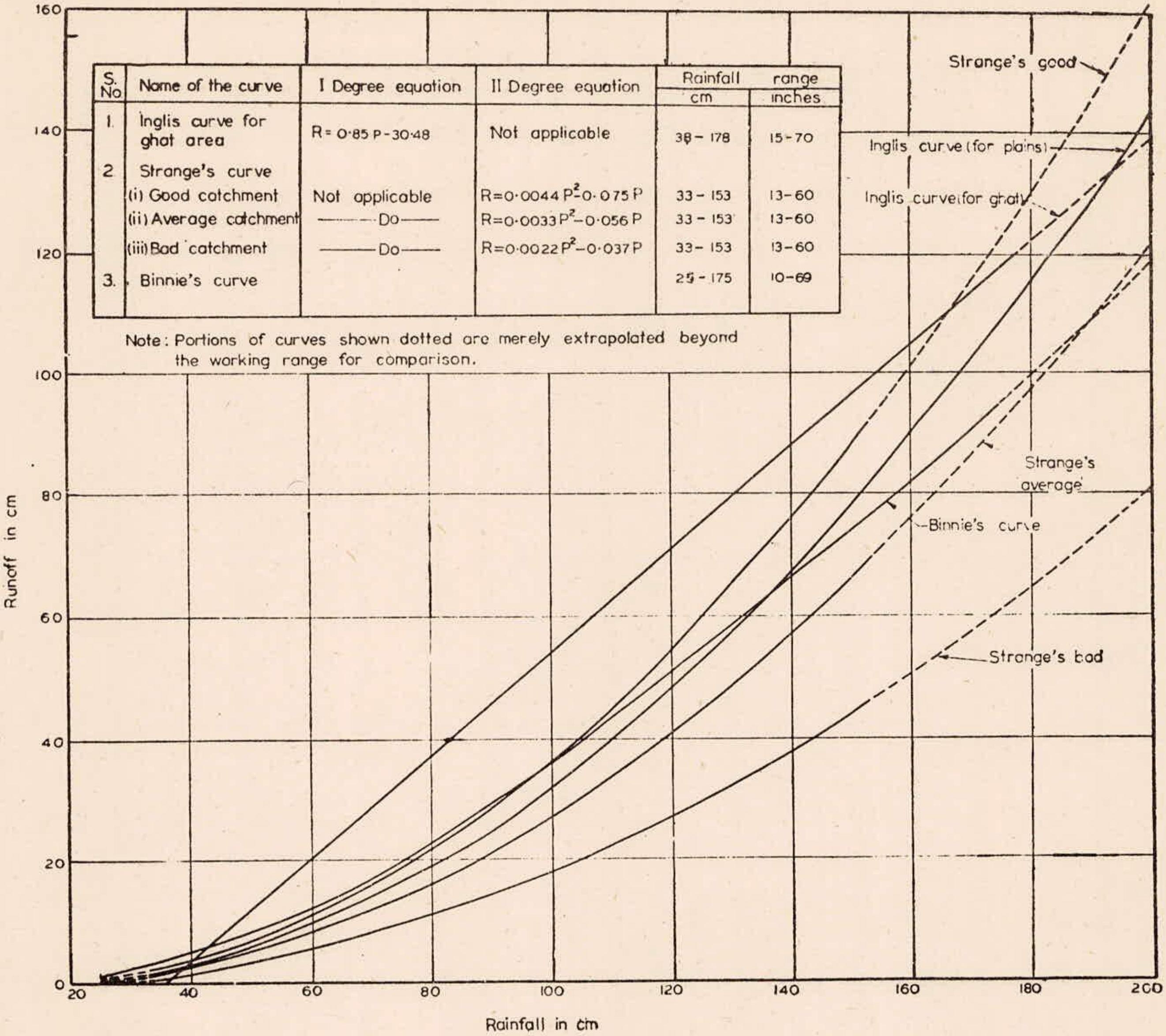

Figure 4 Empirical Rainfall-Runoff Curves (from Bhalerao et al, 1977)

curve is less.

iv) Ingli's formula for plain catchment gives a runoff value lying between that given by Strange's curve for a good and an average catchment and that for Ghat catchment gives a runoff upto 17 cm higher than that given by Strange's curve for a good catchment.

Also, there is inconsistency between the formulae for ghats and plains recommended by Inglis and De Souza. It is generally expected that ghat areas should give more runoff than non-ghat areas for the same rainfall, other conditions remaining same. However, from the formulae it is seen that the non-ghat formula gives more runoff for rainfall value below 400 mm (16") and above 1900 mm (76") of rainfall. Also, the non-ghat formula starts giving runoff only after 175 mm of rainfall is received and the ghat formula after 350 mm of rainfall.

Bhalerao et al (1977) had attempted to derive mathematical formulae for Binnie's percentages and Strange's tables. The equations corresponding to Binnie's percentages are given below:

Range of Rainfall (cm)	Relation between K and P	Relation between R and P
25-102	$K = 0.394\ P - 3$	$R = \frac{P}{100}(0.394\ P-3)$
102-112	$K = 0.325\ P + 4$	$R = \frac{P}{100}(0.325\ P + 4)$
112-122	$K = 0.276\ P + 9.4$	$R = \frac{P}{100}(0.276P + 9.4)$

122-147 $K = 0.232\ P + 14.78$ $R = \frac{P}{100}(0.232\ P + 14.78)$

147-175 $K = 0.197\ P + 20$ $R = \frac{P}{100}(0.197\ P + 20)$

where P is rainfall in cm, R is runoff in cm, and K is the percentage as given by Binnie.

Likewise, the runoff from good, average and bad catchments in case of Strange's tables are expressed as:

$$\text{Good} \quad .. \quad R = \frac{P}{100}(0.4436 - 7.48) \qquad ...\ (20)$$

$$\text{Average} \quad R = \frac{P}{100}(0.3327\ P - 5.55) \qquad ...\ (21)$$

$$\text{Bad} \quad .. \quad R = \frac{P}{100}(0.2218\ P - 3.7) \qquad ...\ (22)$$

Thus the Binnies percentages correspond to a set of five segments of different parabolas while the Strange's table are single parabolas for ranges of rainfall between 33 to 152 cm.

2.9.6 Khosla's formula

Based on the rational concept of considering mean annual runoff of any catchment as a residual of annual rainfall after accounting for losses due to evapotranspiration, Khosla (1949) had postulated that temperature could be regarded as a single effective comprehensive variable to account for all the losses from rainfall to yield runoff over any catchment. The procedure outlined for evaluating the anticipated annual runoffs required the anticipated runoffs for several component periods of 10 days, one month or season.

$$R_m = P_m - X\ (T_m - 32) \text{ for } T > 40^{\circ}F \qquad ...\ (23)$$

where, R and P are in inches,

T in ^{o}F and m referred to the sub-period.

X is a constant chosen approximately for each catchment.

The annual runoff is estimated by integrating the sub-period estimates:

$$R_A = \Sigma R_m \qquad \ldots (24)$$

Because of the time lag differences, the formula was found to yield good estimates of annual runoff.

The loss is related to the mean monthly temperature T in ^{o}F as follows:

$T^{o}F$	0	10	20	30	40	> 40
Loss in inches	0.40	0.50	0.60	0.70	0.84	(T-32)/9.5

In furtherance of these formulae, Panchang (1954) of Central Water and Power Research Station, Pune suggested that the losses by evaporation and transpiration depend on:

i) the actual amount of rainfall, and

ii) the temperature

The evaporation losses are known to increase at faster rate with increasing temperatures. Thus the equation (24) is written as:

$$R_A = \Sigma R_m = \Sigma P_m e^{\frac{-(T_m-32)}{\alpha}} \qquad \ldots (25)$$

where, α is the constant for the catchment.

Sehgal and Gulati (1967) had modified Khosla's formula by assuming a monthly average detention rate of 50% while the remaining 50 percent was considered to be available for runoff and evapotranspiration. The modified formula was tested in case of seven catchments namely Miami, Kosi, Mahanadi, Ashti, Dhukwan, Damodar and Barak. The study has shown that the estimates of annual, seasonal and monthly runoff determined by the modified formula were more accurate than those given by the original formula.

Raja Rao and Pentaih (1971) had examined the effectiveness of Khosla's original and modified formula using the data of four cat-hments in Andhra Pradesh. They concluded that estimates of neither Khosla's original formula nor the modified formula of Panchang were in agreement with the observed values of runoff.

2.0.7 Regression equations used for project planning

While estimating the dependable yield for project planning, the most widely used rainfall - runoff relationships were bi-variate and multi-variate linear regression equations using either only current month's rainfall as independent variables. Some of the regression equations recommended by the Central Water Commission (1976) are given at equations 7 to 10. Krishnaswamy (1976) had proposed two regression models, a linear model of the form $P = PE + L$ ... (26)

and a non-linear model of the form $P_{qt} = k\ PE_t$ ... (27)

Estimates of annual yield at Navagam (CA : 87516 km^2) on river Narmada were obtained by Majumdar (1965) from the rainfall - runoff relation developed for Punasa (CA : 61642 km^2) upstream of Navagam. The relation is

$$R = -13.578 + 0.6344 P \quad \ldots (28)$$

where both R and P are in inches

Bhalerao et al (1977) had used first degree and second degree regression equations between rainfall and runoff for study of Ghorajari tank flows in the Vidarbha region of Maharashtra. The equations obtained were

$$\text{1st degree} : R = -37.2872 + 0.8098 P \quad \ldots (29)$$

$$\text{2nd degree} : R = -19.9974 + 0.5256 P + 0.00108 P^2 \quad \ldots (30)$$

Subba Rao (1979) had established 1st, 2nd and 3rd degree polynomial regression relationships for the estimation of runoff from an experimental watershed near Dehradun from monthly rainfall during the monsoon season (June-Oct.).

For June

$$Y = -18.4949 + 0.1131X \ (r = 0.838)$$

$$Y = 5.707 - 0.08617X + 2.438 \times 10^{-4} X^2 \ (r = 0.915)$$

$$Y = 3.6377 - 5.0719 \times 10^{-2} X + 1.1953 \times 10^{-4} X^2 + 1.072 \times 10^{-7} X^3 \ (r = 0.9155) \quad \ldots (31)$$

For July

$$Y = -101.95 + 0.3462X \ (r = 0.549)$$

$$Y = 575.09 - 1.373 \times 1.048 \times 10^{-3} X^2 \ (r = 0.6198)$$

$$Y = 1294.0 - 48.411 X + 5.860 \times 10^{-2} X^2$$
$$-2.27 \times 10^{-5} X^3 \text{ (r = indeterminate)} \quad \ldots (32)$$

For August

$$Y = -214.23 + 0.8664 X \text{ (r = 0.965)}$$
$$Y = -612.86 + 1.6029X - 2.8786 \times 10^{-4} X^2 \text{ (r = 0.9637)}$$
$$Y = -40.20 - 0.2107X + 1.442 \times 10^{-3} X^2$$
$$-4.896 \times 10^{-7} X^3 \text{ (r = 0.975)} \quad \ldots (33)$$

For September

$$Y = -47.74 + 0.7965 X \text{ (r = 0.9527)}$$
$$Y = -148.559 + 1.292 X - 4.345 \times 10^{-4} X^2 \text{ (r= 0.9637)}$$
$$Y = -143.64 + 1.249 X - 3.3491 \times 10^{-4} X^2$$
$$-6.125 \times 10^{-8} X^3 \text{ (r= 0.9638)} \quad \ldots (34)$$

For October

$$Y = 6.6672 + 0.40247 X \text{ (r = 0.7893)}$$
$$Y = 8.194 - 0.6963 X + 8.950 \times 10^{-3} X^2 \text{ (r = 0.9444)}$$
$$Y = -0.8221 + 0.45541 X - 0.00181 X^2$$
$$+1.515 \times 10^{-4} X^3 \text{ (r= 0.9908)} \quad \ldots (35)$$

Similar correlation equations both linear and second order polynomial between the cumulative monsoon season rainfall and cumulative monsoon season runoff were established for the watershed under study. The monthly cumulative values 1965 to 1977 (except 1975) were taken for this purpose. As the cumulative values indirectly account for antecedent precipitation condition they show high correlation.

The linear correlation equation was:

$$Y = -262.27 + 0.5425 X \text{ (r= 0.8094)} \quad \ldots (36)$$

and the second order polynomial equation was:

$$Y = -35.1731X + 1.4805 \times 10^{-4}X^2 \text{ (Ry = 0.9914)} \quad ... (37)$$

where, Y and X are cumulative runoff and rainfall respectively upto the end of a month during the monsoon period.

For the estimation of water availability at three sites in the Mahanadi basin, National Institute of Hydrology (1986) had used different types of rainfall-runoff relationships such as:

$$Q_t = KP_t^n \quad ... (38)$$

$$Q_t = K(P_t - P_o)^n \quad ... (39)$$

and $$Q_t = a + b P_t + c P_{t-1} \quad ... (40)$$

where, P_t is the rinfall in mm in the t^{th} month

and P_o is the initial loss.

Relationships (38) and (39) were tried keeping in view the non-linear relationship indicated by graphical plots between rainfall and runoff. Relationship of the form given in equation (40) was tried to account for the effect of previous month's rainfall also on the runoff. It was found that relationship (40) was able to explain comparatively more variance of runoff data and gave better correlation.

For annual rainfall-runoff relation of the type of equation (39) has been adopted. The non-monsoon flows (Nov. - May) were derived as:

$$Q_{(Nov. - May)} = K\, Q_{Annual} \quad ... (41)$$

The value of constant K was obtained as a ratio of average non-monsoon flow to average flow for a site.

The monthly and annual relationships for the different sites in the Mahanadi basin are given below:

Site : Hirakud (Mahanadi)

June

$$Q_{June} = -12.3382 + 0.105078\ P_{June} + 0.25704\ P_{May}$$

Coorelation Coefficient is 0.812

July

$$Q_{July} = -108.8813 + 0.40005639\ P_{July} + 0.25561219\ P_{June}$$

Correlation Coefficient is 0.8506

August

$$Q_{August} = -89.062709 + 0.52422789\ P_{August} + 0.14433192\ P_{July}$$

Correlation Coefficient is 0.7396

September

$$Q_{September} = -108.8022 + 0.53181646\ P_{September} + 0.2384006\ P_{August}$$

Correlation Coefficient is 0.8529

October

$$Q_{October} = -15.642107 + 0.41316135\ P_{October} + 0.11343826\ P_{September}$$

Correlation Coefficient is 0.939

Annual

$$Q_{Annual} = 0.044\ (P-500)^{1.368} \qquad \ldots (42)$$

Correlation Coefficient is 0.939

Site : Salebhata (Ong)

<u>June</u>

$$Q_{June} = -3.9995 + 0.04225\ P_{June} + 0.08017\ P_{May}$$

Correlation Coefficient is 0.9054

<u>July</u>

$$Q_{July} = -114.28 + 0.2758\ P_{July} + 0.5388\ P_{June}$$

Correlation Coefficient is 0.9170

<u>August</u>

$$Q_{August} = -125.987 + 0.896\ P_{August} + 0.1036\ P_{July}$$

Correlation Coefficient is 0.9150

<u>September</u>

$$Q_{September} = -83.481 + 0.8847\ P_{September} + 0.1188\ P_{Aug.}$$

Correlation Coefficient is 0.7826

<u>October</u>

$$Q_{October} = -15.210 + 0.597\ P_{Oct.} + 0.07528\ P_{Sept.}$$

Correlation Coefficient is 0.7826

<u>Annual</u>

$$Q = 0.9013\ (P - 430.0)^{0.924}$$

Correlation Coefficient is 0.704 ... (43)

Site : Kantamal (Tel)

<u>June</u>

$$Q_{June} = -20.7949 + 0.192727\ P_{June} + 0.0425\ P_{May}$$

Correlation Coefficient is 0.878

<u>July</u>

$$Q_{July} = -62.395 + 0.7078\ P_{July} + 0.07143\ P_{June}$$

Correlation Coefficient is 0.725

August

$$Q_{August} = -145.80 + 0.7078\, P_{Aug.} + 0.2286\, P_{July}$$

Correlation Coefficient is 0.8477

September

$$Q_{September} = -93.98 + 0.87\, P_{Sept.} + 0.12\, P_{Aug.}$$

Correlation Coefficient is 0.7863

October

$$Q_{October} = -4.2729 + 0.62619\, P_{Oct.} + 0.04219\, P_{Sept.}$$

Correlation Coefficient is 0.692

Annual

$$Q_{Annual} = 3.993\,(P - 590)^{0.75}$$

Correlation Coefficient is 0.867 ... (44)

2.9.7.1 monthly rainfall runoff relationships

Some of the monthly rainfall runoff relationships developed for use in the project hydrology are given here

Site : Ramganga upto dam site   Source: Patri (1978)

District: Bijnor   State : Uttar Pradesh

June $Q_{Jun} = -14.97182 + 0.440323\, R_{Jun}$

July $Q_{Jul} = -2.092773\, R_{Jul} + 0.0399106\, R_{Jun} + 1240.616$

August $Q_{Aug} = -1.433794\, R_{Aug} - 1.414085\, R_{July} + 1852.707$

September $Q_{Sept} = 3.7824466\, R_{Sept} - 1.252370\, R_{Aug} + 349.8354$

October $Q_{Oct} = 1.241558\, R_{Oct} - 0.0860485\, R_{Sept} + 158.3752$

The regression for the non-monsoon runoff was derived on the basis of rainfall in October and the non-monsoon season.

$$Q_{Nov-May} = -0.1728778\, P_{(Nov-May)} + 1.724675\, R_{Oct} + 402.4603 \quad \ldots (45)$$

Site : Yeleru Dam Source : A.P. Irrigation Dept (1981)

District : East Godavari State : Andhra Pradesh

Month	Bi-variate $R = aP + b$	Multi-variate $R = ap_o + bp + C$
June	a = .1276 b = -0.0509	a = .009898 b = .128716 c = -0.097268
July	a = .192 b = -0.848	a = .16967 b = .099533 c = -0.679969
August	a = .1892 b = .6523	a = .0989 b = .2307 c = -0.64188
September	a = .133 b = 1.0176	a = .329866 b = .0638 c = -0.64188
September	a = .133 b = 1.0176	a = .329866 b = .0638 c = -0.3856
October	a = .37328 b = -0.4318	a = -0.04229 b = 0.40675 c = -0.36177
November	a = -0.01753 b = 8.375777	a = 0.0655 b = 0.0536 c = 0.11318

P_o = Rain of previous month in inches
P = Rain in current month in inches
R = Runoff in inches

... (46)

Site : Bhimkund Source : Orissa Irrig & Power Dept. (1981)

State : Orissa

June $R = -14.5655 + .1838\, P$

July $R = 0.0530\, P^{1.27}$

August $R = 6.2151 + 0.4552P$

September $R = 16.7013 + 1.2840\ P - 0\ 4156\ P_o$

October $R = -33.8468 + .1802\ P + .3551\ P_o$

November $R = 0.5852\ P^{0.8371}$

December $R = 1.6833 + 0.10992\ P$ ... (47)

P = Current month's rainfall (mm)

P_o = Previous month's rainfall (mm)

R = Runoff in mm.

Site : Gardi (Lower Sukhel) Source : Orrissa Irrig. and Power Dept. (1984)

Dist.: State : Orissa

August $R = 90.348 + .5629\ P$

and $R = 736.75\ P^{.2794}$

September $R = -24.531 + .6621\ P$

October $R = 5.64 + 0.828\ P$ ... (48)

Where P and R in mm.

Regional Relationship for Challakudy Basin

based on: Source : Kerala Irrig.Dept.

Sites : Parambikulam (190 $mi.^2$)

Karappara (15 $mi.^2$)

Kuriakutty (49 $mi.^2$)

Peringal Kuttu (390 $mi.^2$)

June $\text{Log } R = 1.9 \text{ Log } P - 1.88$

July $R = -13.77 + 0.764\ P + 0.399\ R_o$

August $R = -8.67 + 0.886\ P + 0.24\ P_o$

September $R = -1.43 + 0.4\ P + 0.197\ P_o$

October $R = -1.037 + 0.473\ P + 0.18\ P_o$

November $R = -1.65 + 0.43\ P + 0.36\ P_o$ ... (49)

R_o and P_o are runoff and rainfall in previous month

2.9.7.2 monsoon rainfall-runoff relationships

Site: Sukhta Project in Narmada Basin — Source: M P Irrig. Dept.

District: Nimar — State : Madhya Pradesh

$$R = -4.7283 + 0.5040\ P \quad \text{... (50)}$$

Where R and P are in inches

Site : Jobat Project in Narmada basin — Source: M.P.Irrig.Dept.

District: Jhabua — State : Madhya Pradesh

i) Reach between Mortakka and Garudeshwar

$$R = -220.6 + 0.581\ P \quad \text{... (51)}$$

ii) Kundi at Kogaon

$$R = 48.58 + 0.227\ P \quad \text{... (52)}$$

R and P in mm.

Site: Jagdalpur (Polavaram Project) — Source: A P Irrig. and Power Dept.

District: Bastar — State: Madhya Pradesh

$$R = -0.7924 + 0.4049\ P$$

Where R and P are in inches

Sites: Bhamli and Jhonkee in Gopal Hydel Scheme — Source: M P Elect. Board

Dist.: Sidhi — State: Madhya Pradesh

Bhamli $R = 0.1798\ P^{1.2074}$ ... (53)

Jhonkee $R = 0.3007\ P^{1.06}$ ... (54)

R and P are in inches

2.9.8 Use of curve numbers

The relation between rainfall, runoff and retention at any point can be expressed as:

$$Qt = f(P_t, S, Ia) \quad \ldots (55)$$

Where, Qt is the depth of runoff over the catchment during selected time period 't',

P_t is the depth of rainfall over the catchment during time period 't',

S is the potential maximum retention of water by the soil in equivalent depth over the catchment, and

Ia is the initial abstraction during the period between the beginning of rainfall P_t and runoff Qt in equivalent depth over the catchment

The Soil Conservation Service, USA has given the curve number runoff equation as:

$$Q = \left(\frac{P - 0.2S}{P + 0.8S}\right)^2 \quad \text{for } P > 0.25 \quad \ldots (56)$$

in which,

Q = total event runoff

P = total event rainfall

S = potential maximum retention

The initial abstraction Ia has been considered as equal to 0.2S.

The parameter S is related to curve number CN

by:

$$CN = \frac{1000}{10+S} \quad \ldots (57)$$

for S in inches and

$$CN = \frac{1000}{10 + S/25.4} \quad \ldots (58)$$

for S in mm.

Such equations have also been developed in India (Ministry of Agriculture, 1972).

1. $$Q = \frac{(P - 0.3S)^2}{P + 0.7S} \qquad \ldots (59)$$

2. $$Q = \frac{(P - 0.1S)^2}{P + 0.9S} \qquad \ldots (60)$$

where,

Q is the actual runoff

S is the potential maximum retention

P is the rainfall

To show the rainfall-runoff relationship graphically, S values are transformed into curve numbers (CN) by the following equation:

$$CN = \frac{25400}{254 + S} \text{(Metric system)} \qquad \ldots (61)$$

Equation (59) is applicable to all soil regions of India except the black soil areas.

Equation (60) applies to the black soil regions.

This method of estimating direct runoff from storm rainfall is based on methods developed in the last three decades. Because most small catchment work is with ungauged watersheds (not gauged for runoff) the method was made to be usable with rainfall and catchment data that are ordinarily available or easily obtainable for such catchments in India. A typical SCS curve recommended for India is shown in Fig. 5.

2.9.9 Relationships using physiographic factors

Many of the physiographic characters of the catchment have been related with rainfall and runoff by Das et al (1971). The relationship developed by them is:

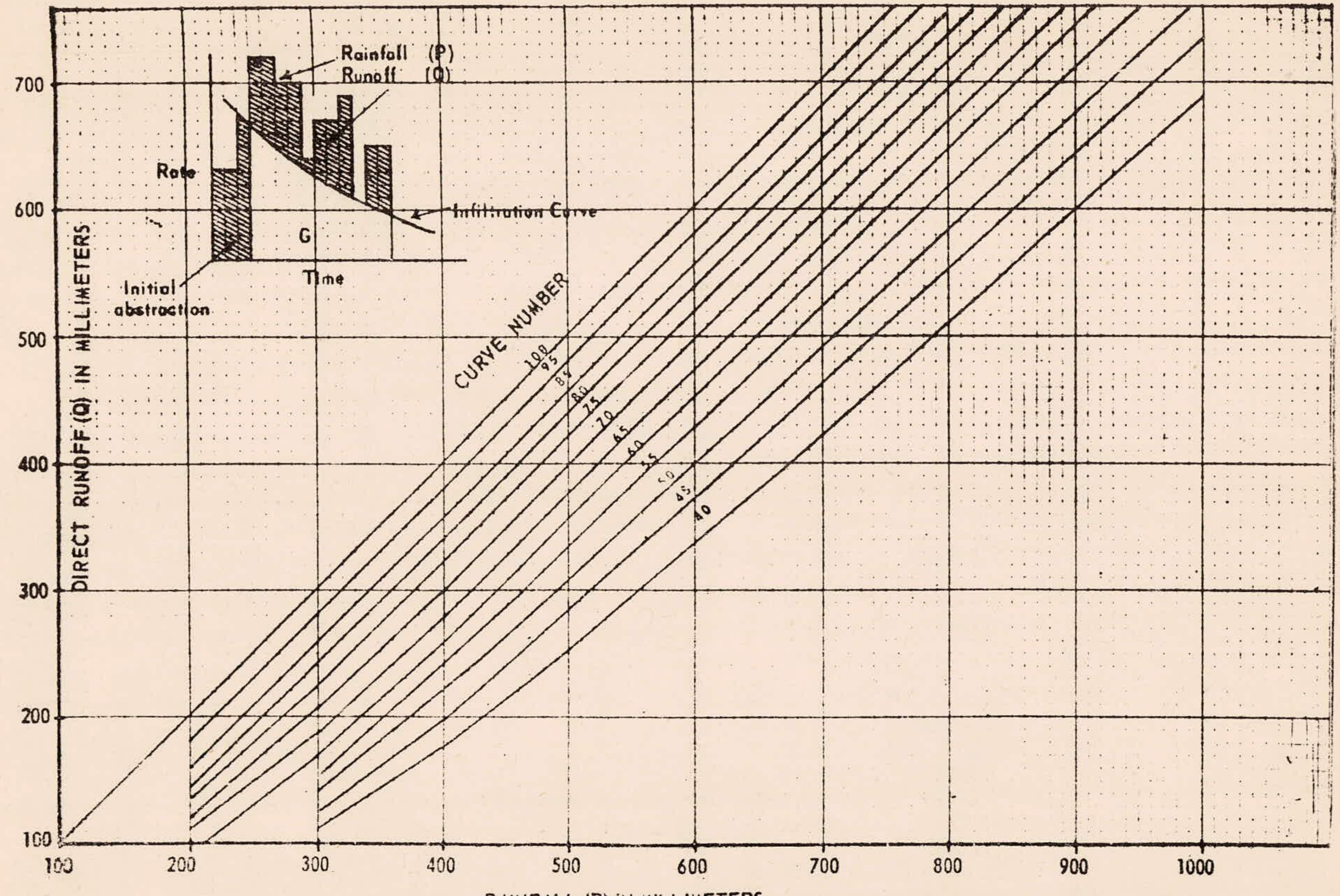

Figure 5 SCS curve for Black Soil Regions of India
(Ministry of Agriculture, Govt. of India, 1972)

$$Q = \frac{P^{1.44}\ A^{0.63}\ RT^{0.66}}{15.19\ F_F^{2.05}\ L_S^{2.05}\ T_m^{1.34}} \quad \ldots (62)$$

where,

Q = Annual runoff, cms

P = Annual rainfall, cms.

A = Watershed area, sq. km.

R_T = Total relief

F_F = Form factor,

L_S = Length of mainstream

T_m = Mean annual temperature

However, total relief, length of mainstream and form factor have been related with area and relationship are:

R_T = $169.6\ A^{0.372}$

L_S = $0.96\ A^{0.625}$

F_F = $1.081\ A^{-0.257}$

Substituting these equations in the equation (62), we get:

$$Q = \frac{1.911\ (P)^{1.44}}{(T_m)^{1.34}\ (A)^{0.0613}} \quad \ldots (63)$$

Thus, the computation involves only three variables instead of six.

2.9.10 Graphical techniques

Central Water Commission (1980) described a number of graphical techniques used for forecasting runoff or flood flow at a downstream point using information of stage or stage, rainfall and API in the upstream catchment.

Once the average amount of rainfall over the catchment area is known, the effective rainfall which would contribute to the direct runoff is estimated from graphical rainfall-runoff relationships of the form shown in Figure 6(a) and 6(b). These relationships are developed using past rainfall-runoff records. Sometimes additional parameters such as API or baseflow are also considered to improve the accuracy of runoff estimates.

Coaxial graphs or correlation diagrams have been developed by Central Water Commission for a number of orecasting sites in different river basins of India. Figure 7 shows a typical coaxial graph for forecasting at Dowlaiswaram in Godavari basin.

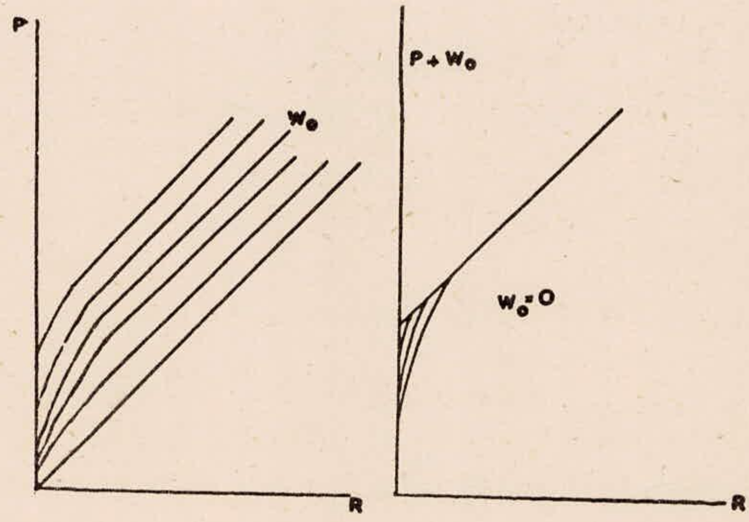

Figure 6(a) Typical Rainfall-Runoff Relationship Used in India

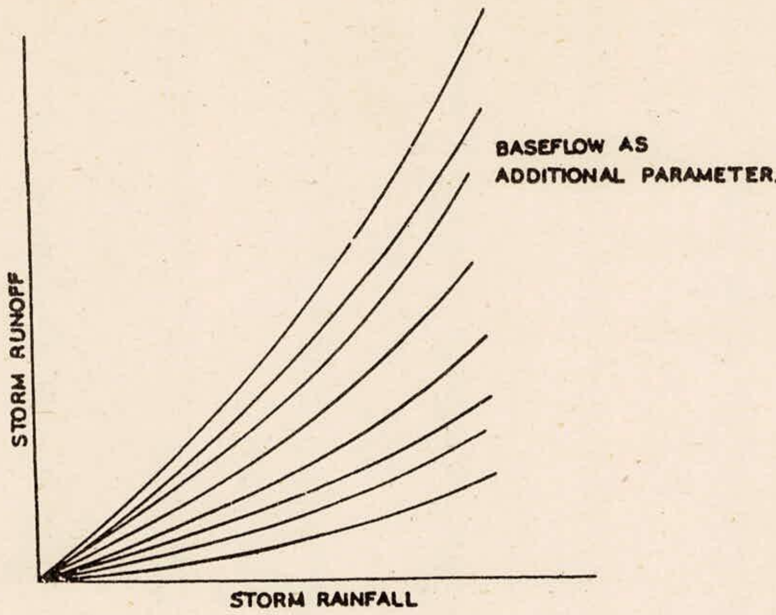

Figure 6(b) Typical Rainfal-Runoff Relationship Used in India
WITH BASE FLOW ADDITIONAL PARAMETER.

Using daily rainfall and runoff data of Kallada river at Punalur in Kerala (CA:867 km^2) for the period 1952 to 1957, Narayana Pillai (1964) had developed coaxial graphical correlations between monthly rainfall and monthly runoff for the months April to December Figure 8. The variables considered were previous month's rainfall, current month's calendar number (1, 2, ..., 12) current month's rainfall and the monthly direct runoff obtained after subtracting base flow.

The coaxial graph has been used for estimating the flow from April to December at Pamba river at Erapuzha

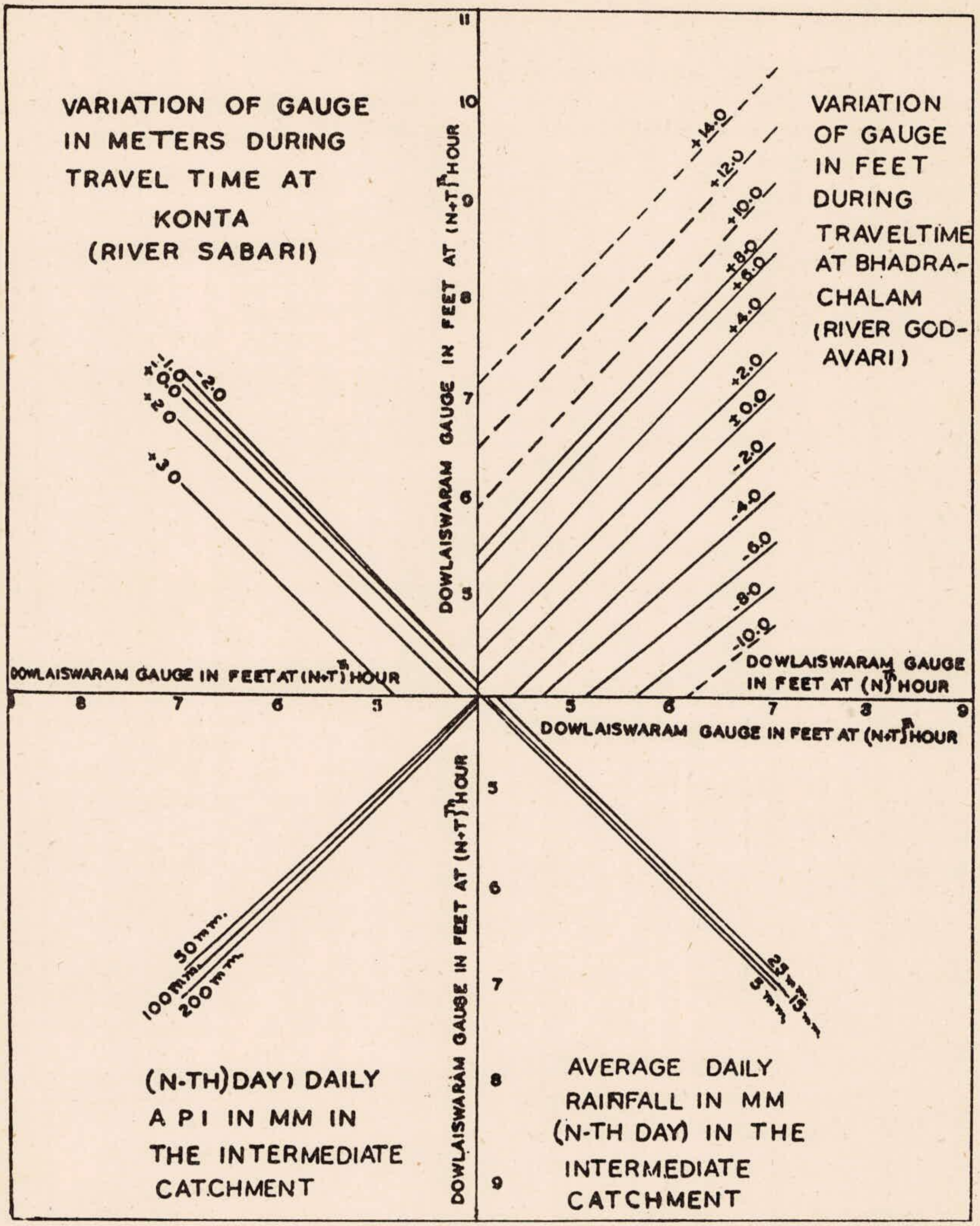

Figure 7 Typical Coaxial Graph Used for Flood Estimation in Godavari Basin (Central Water Commission,1980)

(CA : 655 km^2) and Achenkoil and Pandalam (CA : 327 km^2). The total monthly or annual runoff was obtained by adding 305 mm (12 inches) as base flow.

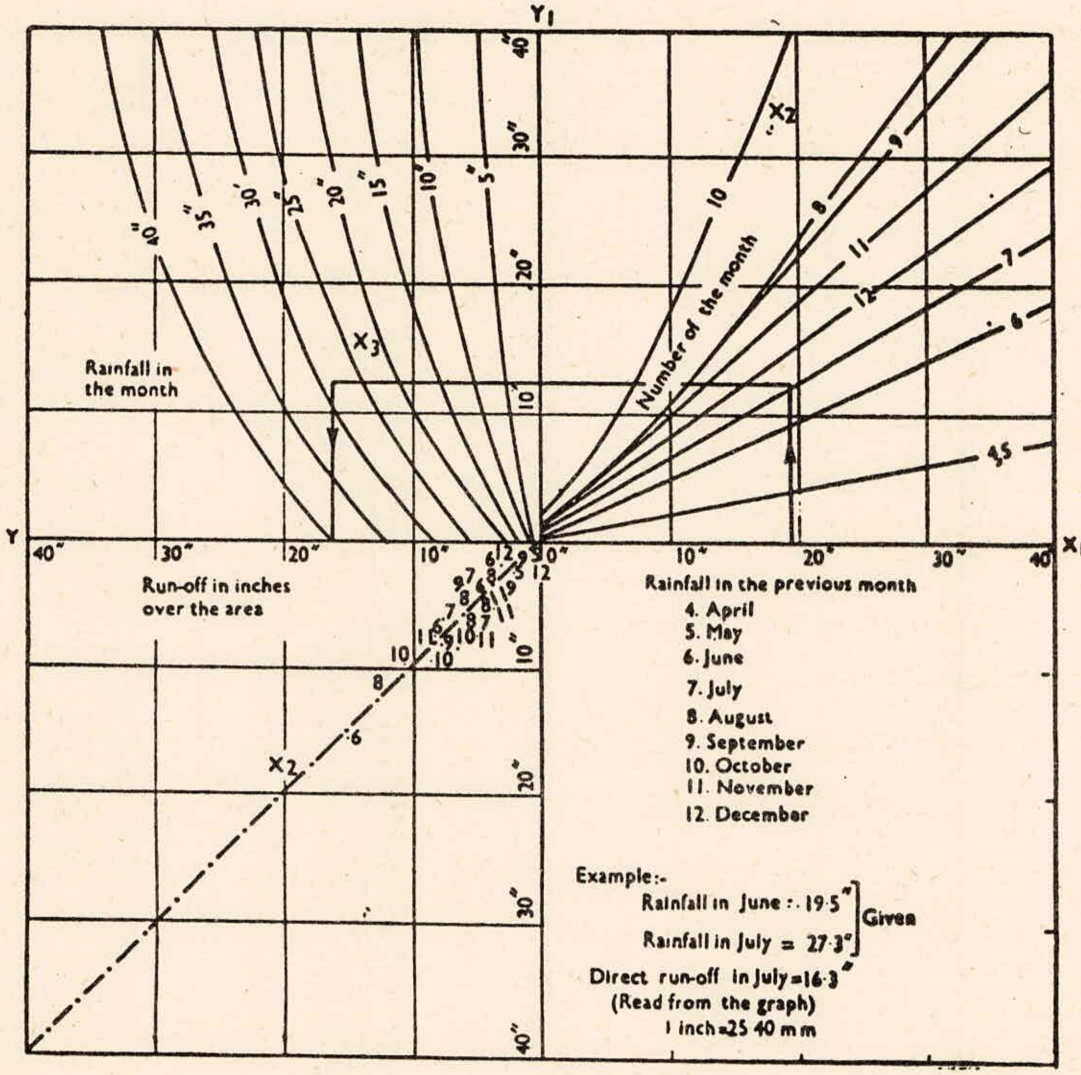

Figure 8 Coaxial Correlation for Kallada River in Kerala (Narayana Pillai, 1964)

3.0 REMARKS

Rainfall is the single important parameter which nfluences runoff directly as overland flow or indirectly as sub-surface and ground water. In the absence of direct measurements of runoff, regional rainfall-runoff relationships. developed over a region based on long period rainfall and runoff data should be used for estimation of yields from ungauged catchments in the region.

Inspite of the availability of conceptual models which could be run on medium and large computers, the simple rainfall runoff relations do have a role to play in the estimation of water yields from small and medium catchments because of the relative ease with which they could be used on micro computers. The review of such simple rainfall-runoff relationships used in general and those used particularly in India has indicated that:

(i) For daily runoff estimation not only the current day's rainfall but also the rainfall of previous days in the form of antecedent precipitation index is to be considered to account for carry over flow from previous rainfall.

(ii) In case of durations of month, season or year, regression analysis, either bi-variate linear or non-linear and multivariate linear relationships are more widely used. To account for delayed contribution as base flow, the previous month's or previous monsoon season's rainfall is used as an independent variable in the multivariate analysis.

With the availability of micro-computers at more number of locations, the Strange's and Barlow's tables have been found to be not in much use.

A practice which has come to be noticed in some of the project reports is the use of rainfall-runoff relationships developed for a neighbouring catchment or an upstream site to estimate the runoff at the project site. For reasons explained under section 2.1, mere meteorological homogenity could not be considered as the criteria. The catchment characteristics like shape, size and slope; and other land use characteristics also need to be considered while adopting such relationships.

Likewise, relationships developed on the basis of data over a particular period of time need to be updated with the availability of more data to account for changes in land use and other catchment characteristics.

While developing rainfall-runoff relationships for small catchments or shorter durations, information on catchment characteristics also could be accounted for directly by including relevant catchment parameters in the multivariate regression relationships.

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