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REGIONAL UNIT HYDROGRAPH

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ABSTRACT

The estimation of runoff from the watershed is needed for comprehensive water resources planning, flood flow forecast, adequate design of hydraulic structures etc. The climatic and physical characteristics of the watershed are the main factors affecting runoff. The climatic factors include nature of precipitation, evapotranspiration and interception, rainfall intensity, duration of rainfall, areal and temporal distribution of rainfall and direction of storm movement. The primary physical characteristics of the watershed which influence runoff are its area,length,shape,elevation,slope,orientation, soil type, drainage or channel system,water storage capability and vegetal cover etc.

Unit hydrograph is one of the most popular simple technique for the computation of runoff from the watershed. It is characteristics for a given watershed and it represents the integrated effect of various physical features on the routing of the rainfall input through the catchment system. The unit hydrograph for gauged catchments can be derived by analysing the available rainfall-runoff data. However, for many small catchments the stream flow data are limited and for ungauged catchments it is not at all available. Therefore, the unit hydrograph for such catchments can only be derived using their physical and storm characteristics. This necessitates the development of suitable regional relationship for unit hydrograph derivation. The procedure used for this purpose

involves the derivation of the parameters that describe the unit hydrograph for gauged catchments and then the development of the regional relationships between the unit hydrograph parameters with pertinent physiographic and storm characteristics of the catchments. The catchments considered for such regional study have to be similar in hydrological and meteorological characteristics.

In this report, the basic steps involved for developing such regional unit hydrograph relationships are described in detail. Various regional unit hydrograph studies conducted in India as well as abroad have also been reviewed. In general, multiple linear regression analysis have been used by many investigators for developing the regional unit hydrograph relationships. Conceptual models have also been used by many investigators abroad for developing the regional unit hydrograph relationships. However, in India very little work has been done for developing such relationships using the conceptual models. Some investigators have studied the effects of forest, agricultural practices and urbanisation on the shape of the unit hydrograph. There is need for similar studies for Indian basins.

1.0 INTRODUCTION

The estimates of design flood are required for comprehensive planning and economic design of the water resources structures. The unit hydrograph technique is one of the powerful techniques among others for the estimation of design flood. Whenever sufficient and reliable records on streamflow and rainfall are available, the unit hydrograph for those catchments can be derived analysing the rainfall-runoff data. However, most of the small catchments are generally not gauged. Therefore, the unit hydrograph characteristics for such catchments has to be estimated by using data on climatological, physiographic and other factors of these catchments.

The purpose of the regional unit hydrograph study is to estimate values of unit hydrograph parameters for basins for which no gauged hydrograph data are available. The procedure used for this purpose involves the derivation of unit hydrograph parameters for gauged catchments of the region and then to develop the relationship between the unit hydrograph parameters and physiographic and climatic characteristics of those catchments using multiple regression analysis. The catchments for which data is used in a regional study have to be similar in hydrological and meteorological characteristics. However, it is usually difficult to locate catchments,strictly satisfying these requirements. Some adjustments are,therefore, required while transferring the unit hydrograph parameters from gauged catchments to ungauged catchments through regional relationships.

The idea of relating physical characteristics of the catchments falling in a hydrometeorologically homogeneous region with the unit hydrograph parameters was used by Snyder (1938) in his work on Applachian Highlands, wherein he related the time lag of the unit hydrograph(t_p) with the product of length of the main stream(L) and length of the stream from a point on the stream nearest the centroid of the catchment to the outlet(L_c). Later, it was found by Linsley(1975) that the better results could be obtained by relating $\left(\frac{LL_c}{\sqrt{S}}\right)$ with basin lag t_p, where S is average slope of the main stream. Nash(1960) related the first and second moments of instantaneous unit hydrograph with various physical characteristics of the catchments. HEC(1982) developed the regional unit hydrograph relationships relating the unit hydrograph parameters of Clark Model and Snyder method with pertinent physical characteristics of the catchments.

The small catchments directorate of Central Water Commission has carried out the regional unit hydrograph study for some Indian basins. Specific regions have been identified by dividing whole of India in to 26 hydrometeorologically homogeneous subzones(as homogeneous as practicable). All the major storms are analysed for each of gauged catchments to derive reasonable representative unit hydrographs. The unit hydrograph parameters are then related with physical characteristics of the catchments in the subzone in order to develop the regional unit hydrograph relationships for the particular subzone.

In this report, the basic steps involved for developing the regional unit hydrograph relationships are described and discussed. Various regional unit hydrograph studies conducted in India as well as abroad are also reviewed.

2.0 REVIEW

2.1 Unit Hydrograph(UH) and Instantaneous Unit Hydrograph(IUH):

2.1.1 Unit hydrograph theory, assumptions and limitations

The concept of unit hydrograph was first introduced by Sherman in 1932. It represents the relation between effective rainfall and storm runoff as shown in Figure 1.

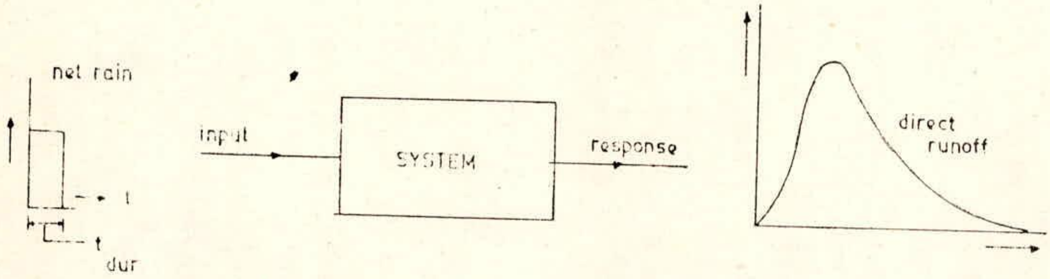

FIGURE 1- Relation between input as a net rain and direct runoff as a response

The unit hydrograph of duration T is defined as the storm runoff due to unit volume (one inch/mm/cm) of excess rainfall generated uniformly in space and time over the catchment in time T. Generally they are three basic factors which determine the shape of an observed hydrograph from a small watershed namely: i) storm characteristics,(ii) physiographic characteristics and (iii) physical condition of the watershed. It is hypothesized that the unit hydrograph for a typical watershed considers all three basic factors. The following basic assumptions and limitations constitute the unit hydrograph theory (Chow,1964).

i) The effective rainfall is uniformly distributed within its duration:-

This assumption requires that the selected storm should be of short duration and most intense. Such storms would most likely produce uniform effective rainfall giving a well defined single peaked hydrograph of short time base.

ii) The effective rainfall is uniformly distributed over the watershed:-

This assumption requires that the watershed considered should be small in size. The unit hydrograph theory becomes inapplicable for the larger watersheds (generally more than 5000 sq.km.). However, by subdividing the watershed and assuming the uniform rainfall over those sub-watersheds, different unit hydrographs can be derived for each sub-watershed.

iii) The base or time duration of the hydrograph of direct runoff due to an effective rainfall of specific duration is constant:

Due to the subjectivity involved in the method of base flow separation, the base lengths or time duration of the hydrographs of direct runoff due to different burst of excess rainfall blocks are different. Theoretically speaking the recession curve of a hydrograph decreases exponentially with time and should have an infinite time base. However, a finite base length is essential for practical convenience. Fig.2 shows the hydrograph of a typical catchment generated by rainstorms of the same duration having the same base width regardless of the net rainfall intensity.

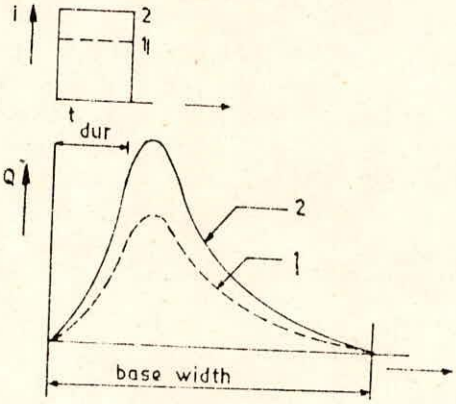

Figure 2 - Base width of unit hydrograph

iv) The ordinates of direct runoff hydrographs of a common base time are directly proportional to the total amount of direct runoff represented by each hydrograph:

This assumption gives the principle of linearity(super position or proportionality). Although the hydraulic relations between discharge and depth or head are of a non-linear nature, the assumed linearity between depth of direct runoff and stream discharge is a fairly acceptable approximation in a large majority of river basins. This is due to the simultaneous occurrence, in most basins, of effects of natural reservoirs and over bank storage effects. A significant departure from linearity can only be expected when one of the two is predominant. Non-linearity also exists when neither of the two is significantly affecting the flow process e.g. in very small watersheds or in plots.

The conventional unit hydrograph based on the assumption of linearity is specifically known as linear unit hydrograph theory. Suppose the input X_1 reproduce the response $\psi(X_1)$. If the system response follows the principle of proportionality, then the input AX_1 will produce the response $A\psi(X_1)$, where A is a constant. Figure 3 shows the hydrograph due to the depths of net rainfalls i_1 and i_2 of the same duration.

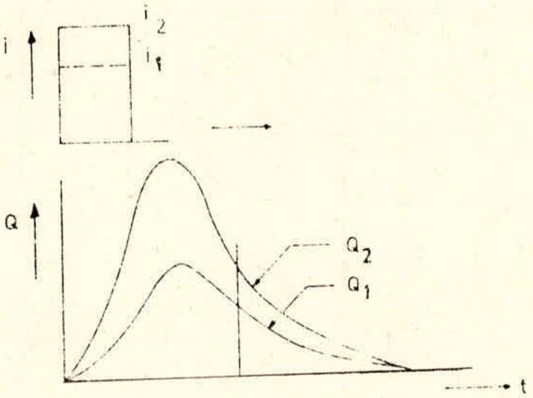

Figure 3 - Principle of proportionality

Now, supposing that X_1 and X_2 are the two inputs to the system and ψ is the operator acting on the input to produce the responses $\psi(X_1)$ and $\psi(X_2)$, then the principle of super-position tells us that the response $\psi(X_1 + X_2)$ due to the input $(X_1 + X_2)$ will be equal to the sum of the individual responses. Fig.4 shows the example for principle of superposition where A is a given hydrograph for depth of net rainfall of 5 cm and a duration Δt. The hydrograph for a rain consisting of two successive periods, each with the same duration Δt as the given one but with depths of net rainfall of 6 and 3 cm respectively, can be found by adding the ordinates of the hydrographs B and C. Here B and C are the hydrographs due to the net rainfall of 6 and 3 cms respectively.

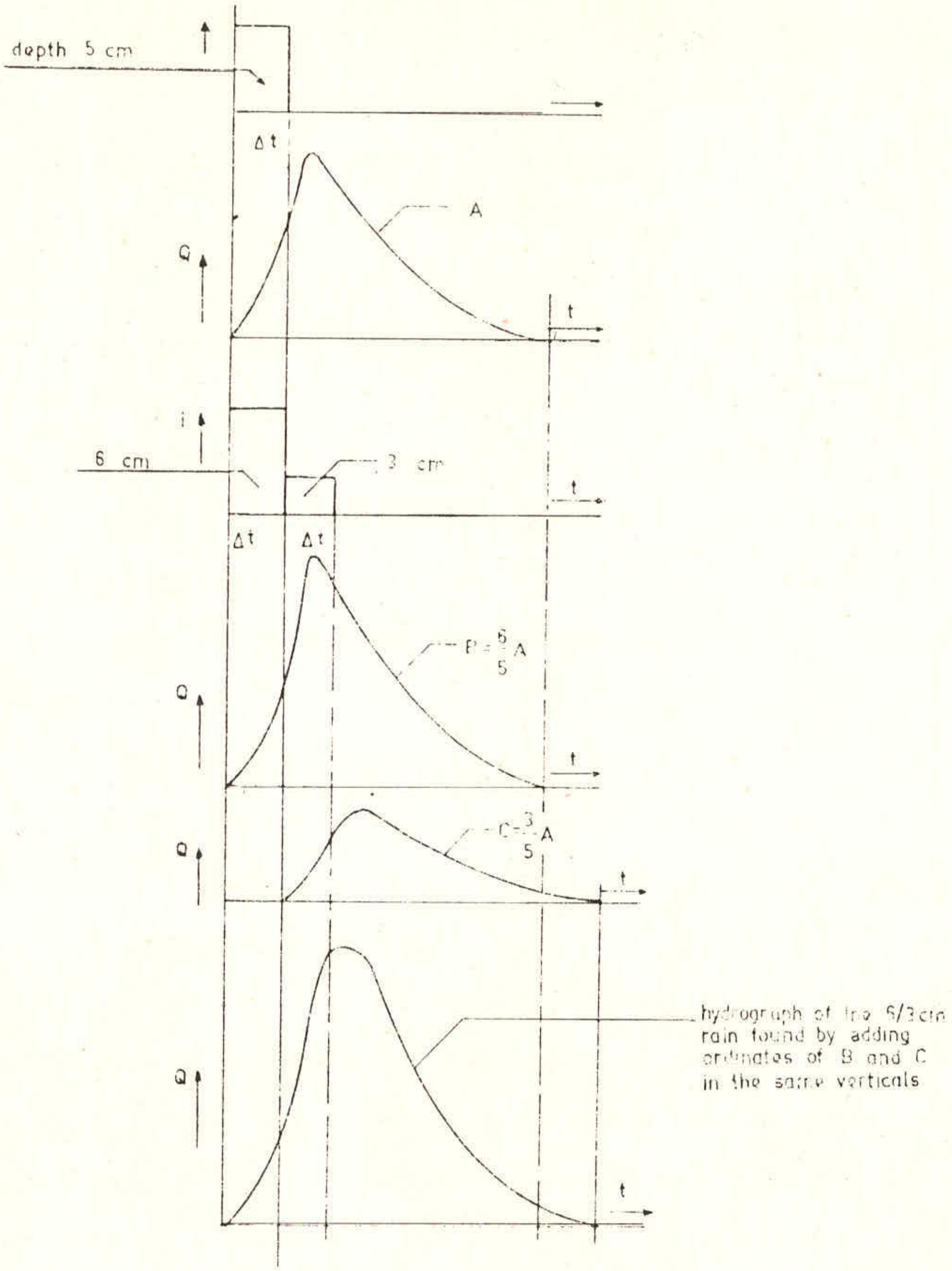

Figure 4- Principle of superposition

The system which obeys the principles of superposition and proportionality is known as the linear system. Here the watershed is assumed to be a linear system.

(v) For a given watershed, the hydrograph due to a given pattern of effective rainfall in a unit duration reflects all the confined physical characteristics of the watershed :-

This assumption gives the concept of time invariance. However, in practical life the physical characteristics of the watershed do change with time due to man-made adjustments and land use effects. Therefore, this principle is valid only when time and conditions of the watershed are specified.

Based on the above assumptions it can be realized that the unit hydrograph derived from an isolated, intense, short duration storm of nearly uniform distribution in space and time is the most desirable. However, such storms are rarely available in practice. Therefore, the complex storms are to be used for deriving the unit hydrograph. Secondly, the unit hydrograph derived from different storms of the same watershed may vary due to different effective storm pattern and the physical condition of the watershed prior to each storm.

2.1.2 Application of Unit hydrograph :-

The principle of the unit hydrograph can be applied for :

(i) Estimating the design flood,

(ii) Supplementing the missing flood records, and

(iii) Short-term forecasting based on recorded rainfalls.

2.1.3 Instantaneous Unit Hydrograph (IUH) :

Chow (1964) stated that the instantaneous unit hydrograph is the unit hydrograph of infinitesimally small duration.

2.1.4 Relationship between UH and IUH :-

Various methods are available to derive the unit hydrograph analysing the available rainfall-runoff records. However, the methods based on systems approach (conceptual models) first derive the instantaneous unit hydrograph as the function of certain number of parameters. Then the following relationship between the instantaneous unit hydrograph and unit hydrograph is to be utilised to compute the unit hydrograph of duration T, (Chow, 1964) :

$$U,(T\ t) = \int_0^t U(0,t)\,dt - \int_0^{(t-T)} U(0,t)\,dt \qquad \ldots(1)$$

where $U(T,t)$ represents the t th ordinate of T-hour unit hydrograph,

$U(0,t)$ represents the t-th ordinate of IUH.

2.2 Basic steps involved in Developing the regional unit Hydrograph :

The following steps should be followed in executing a regional study to develop regional unit hydrograph relationships for a basin :

(i) Choice of the catchments :- In regional study, care should be taken to select those catchments which are indeed similar in hydrometeorological characteristics. The catchments considered for developing the regional unit hydrograph should be able to represent the regional behaviour as close as possible. Further, one should always try to include maximum no. of gauged catchments in the regional study. However, minimum eight to ten catchments are required for the regional study.

(ii) Split sample test for the region :-

In order to test the performance of the developed regional relationships, the data of at least two to three gauged catchments should be kept independent. It means, those catchments should be treated as ungauged catchments and they should not be considered while developing the regional relationships.

(iii) Rainfall-runoff data :-

Rainfall-runoff data of different catchments for each of the major past flood events should be considered for analysis. If the catchment underwent to some major changes due to man's influence or landuse changes, then the rainfall-runoff data of only recent past flood events should be considered for analysis.

(iv) Computation of excess rainfall :-

A suitable technique should be adopted to separate the loss from total rainfall in order to get the excess rainfall hyetograph.

(v) Base flow Separation :-

The base flow should be separated from the streamflow hydrograph using a consistent base flow separation technique, in order to get the direct surface runoff hydrograph.

(vi) Derivation of Unit hydrograph :-

The unit hydrographs should be derived by analysing the excess rainfall-direct surface runoff data for each event of different catchments using a suitable unit hydrograph derivation technique.

(vii) Derivation of representative unit hydrograph :-

The representation unit hydrograph for each catchment may be derived by averaging the unit hydrographs obtained from different events of the catchment using standard averaging procedure. However, if considerable variations are observed in unit hydrographs derived from different events of a catchment, then the unit hydrograph parameters of each event should be considered, along with the catchment and storm characteristics, in the regional study.

(viii) Split sample test for the storms :-

The performance of the representative unit hydrograph of a catchment should be tested by reproducing the two or three independent storms which are not to be used for deriving the representative unit hydrograph.

(ix) Development of regional unit hydrograph relationships :-

Step-wise Multiple linear regression analysis can be performed, taking the unit hydrograph parameters of different catchment as dependent variables and the catchment and/or climatic characteristics as independent variables, to develop the optimal regional unit hydrograph relationships.

(x) Representative Unit hydrograph for ungauged catchments :-

The regional relationships developed at step (ix) are used for split sample test for the region as described in step (ii). Further the representative unit hydrograph for the ungauged catchments of the hydrometeorologically homogeneous region can be derived using measurable catchment and/or climatic characteristics in the generalized relationships developed in step (ix).

Singh (1984) conducted a regional unit hydrograph study for Godavari basin subzone 3f following the above steps. However, due to data problem only six catchments were considered in the study.

2.3 Description of Regionalization parameters :-

2.3.1 Physical and climatic parameters of the basin :-

Various physical and climatic parameters which are considered to be most important in affecting the basin hydrologic response are already described in report "Use of catchment characteristics for unit hydrograph Derivation (RN-15)". However, definitions of some of the physical parameters of the basin which are most commonly being used by many investigators are listed as follows :

(i) Catchment area (ca)

(ii) Slope (s) Equivalent stream Slope of the longest water-course.

(iii) Length of the longest water course (L) :-

This is the length along the watercourse from the outflow point of the designated sub-basin to the upper limit to the watershed boundary as shown in figure 5.

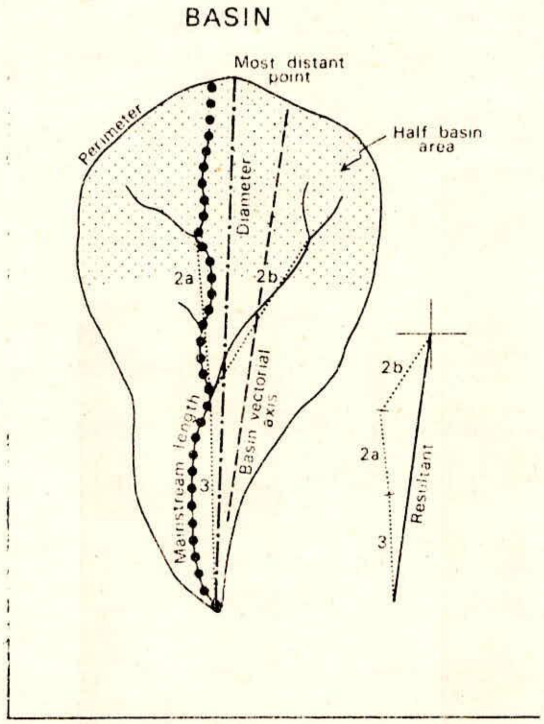

Figure 5 - Main stream length for a typical watershed

(iv) L_c - This is the water course length from the outflow point to a point on the stream nearest to the centroid of the basin.

(v) IMP - This is an index of impervious cover in per cent of total land area.

2.3.2. Parameters of Unit Hydrograph or its model :-

(a) Unit Hydrograph parameters :-

The following parameters are considered by many investigators for describing the shape of the representative unit hydrograph :

(i) t_p = Time from the centre of unit rainfall duration to the peak of the unit hydrograph in hours.

(ii) Q_p = Peak discharge of unit hydrograph in cubic meters per second.

(iii) t_r = Unit rainfall duration adopted in a specific study.

(iv) T_B = Base width of unit hydrograph in hours.

(v) W_{50} = Width of unit hydrograph measured at discharge ordinate equal to 50% of Q_p in hours.

(vi) W_{75} = Width of unit hydrograph measured at discharge ordinate equal to 75% of Q_p in hours.

(vii) W_{R50} = Width of the rising side of unit hydrograph measured in hours at discharge ordinate equal to 50% of Q_p in hours.

(viii) W_{R75} = Width of the rising side of unit hydrograph measured in hours at discharge ordinate equal to 75% of Q_p.

A typical unit hydrograph describing the above parameters are shown in fig.6.

(b) Parameters for conceptual Models of IUH

(i) O'Kelly's Model :-

O'Kelly (1955) suggested that the instantaneous unit hydrograph could be obtained by routing an isosceles triangular inflow of the unit volume and of base length T hours through a single linear reservoir having the storage co-efficient K hours. Therefore, T and K are the two parameters which describe the shape of the instantaneous unit hydrograph based on O'Kelly's approach. Fig.7 shows the IUH by routing an isosceles triangle through a linear reservoir (O'Kelly's model).

(ii) Clark's Model :-

Clark (1945) suggested a procedure to derive instantaneous unit hydrograph by routing the time area diagram of the catchment having base length equal to time of concentration of the catchment through a single linear reservoir. Therefore, the method requires knowledge of two quantities, T_c and K in addition to the time area diagram of the catchment. Here, T_c and K are time of concentration and storage co-efficient in hours respectively. The time area curve can be derived using the topographical characteristics of the catchment. Thus, the two parameters T_C and K are required to estimate the instantaneous unit hydrograph by this approach. Fig.8 describes the procedure for Clark Model.

(iii) Nash Model :-

Nash (1957) derived the IUH by routing the unit impulse input through n linear reservoirs of equal

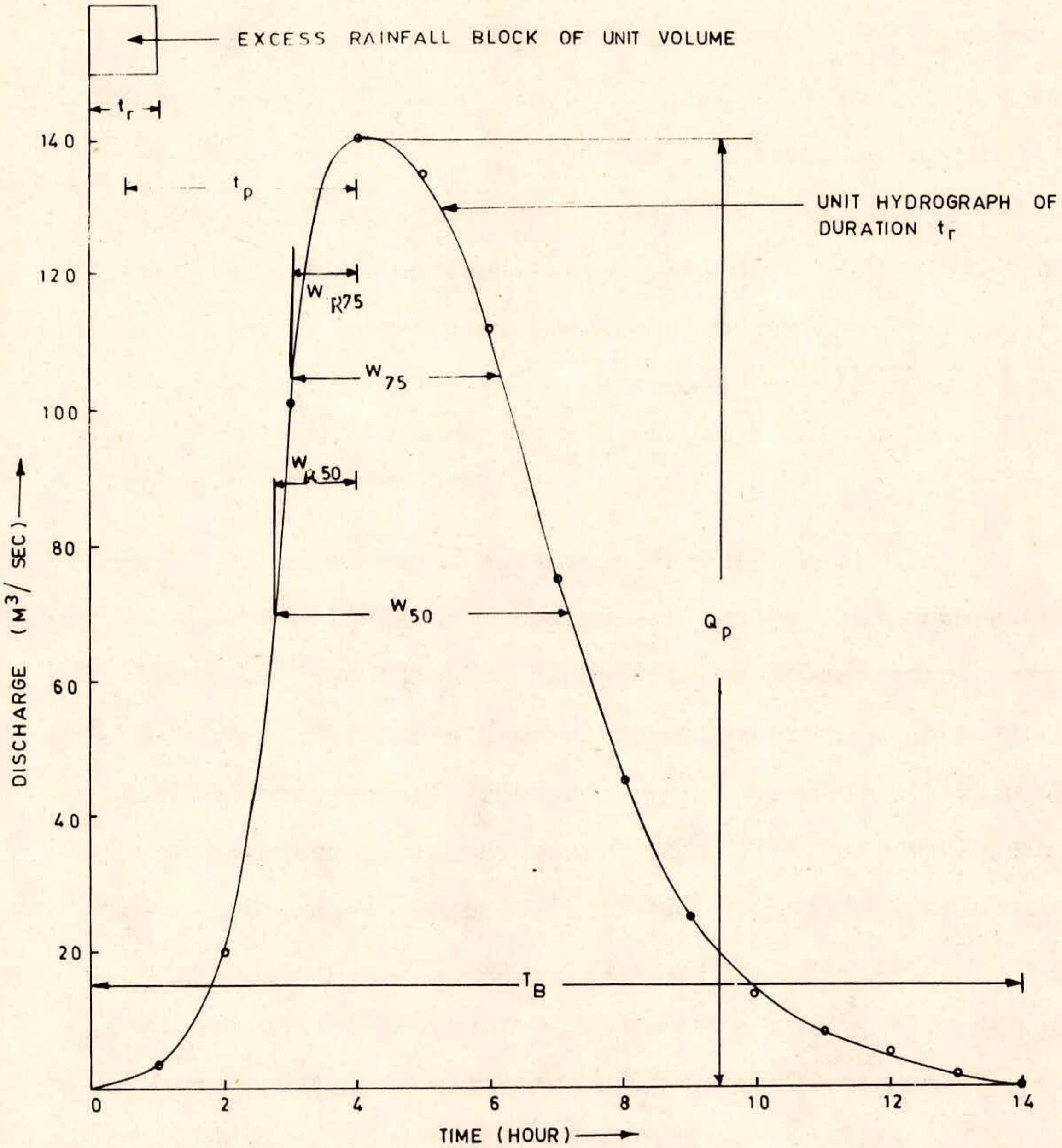

FIG. 6 - A TYPICAL UNIT HYDROGRAPH.

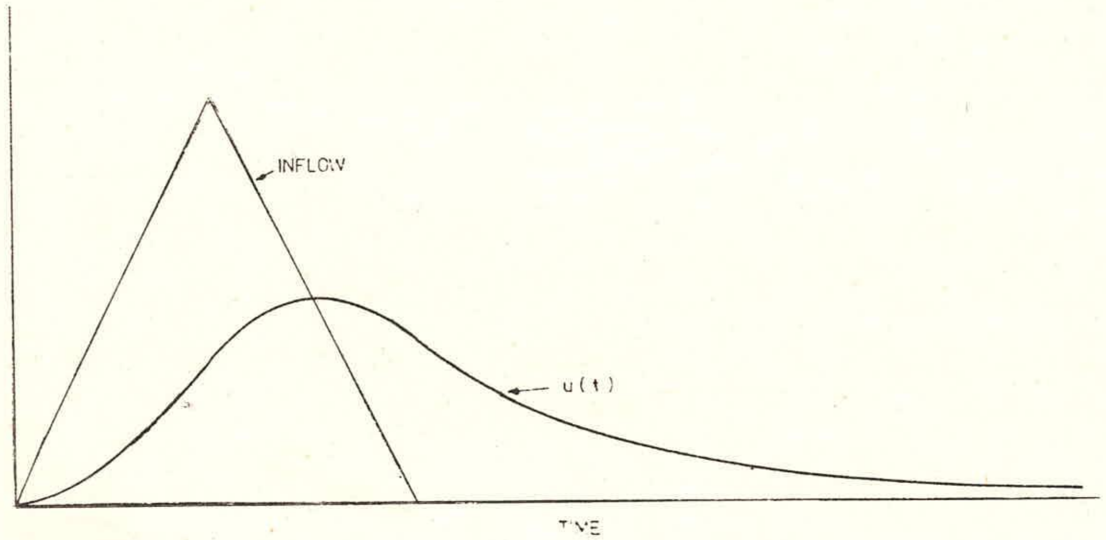

Figure 7 - O'Kelly's Model

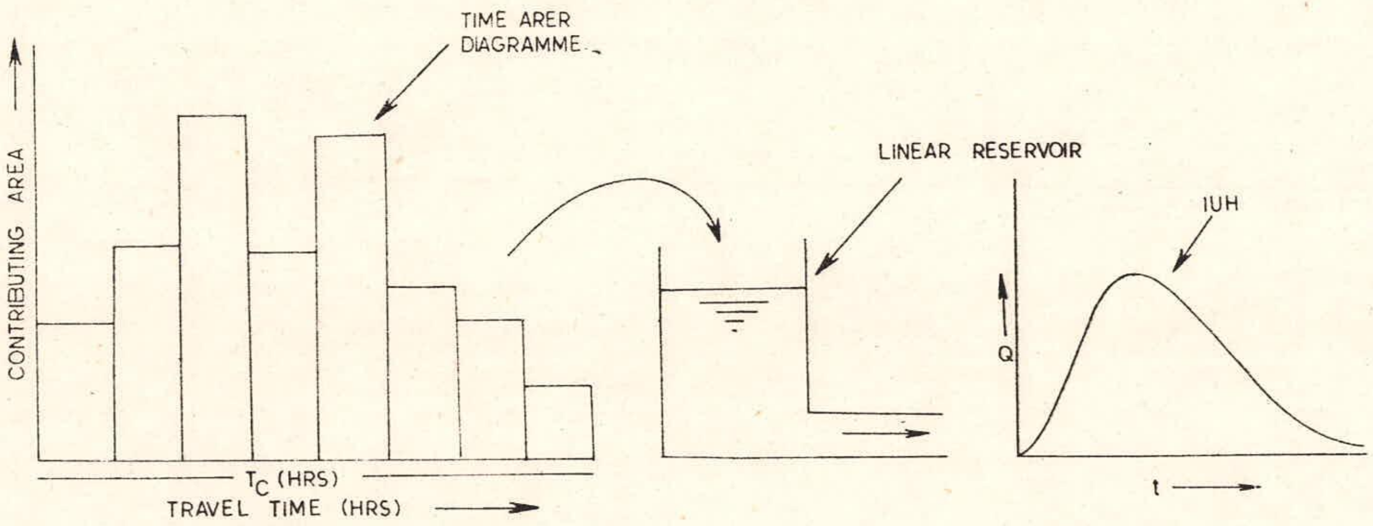

Figure 8- Clark Model

storage co-efficient K. Therefore, the two parameters n and K define the complete shape of IUH. The diagrammatic representation of Nash Model is shown in Fig.9.

In addition to the above commonly used conceptual models, various other models have been proposed by many investigators ((Dooge 1959), Sato and Mikkawa (1956), Zoch Model (1934, 36, 37), Singh (1964), Diskin (1972), Laurenson (1964)) for the derivation of IUH.

2.4 Basic Techniques for the Derivation of Regional Unit Hydrograph :-

The basic techniques available for regional analysis are correlation techniques which include the following :

(i) Graphical correlation

(ii) Simple linear regression, and

(iii) Multiple linear regression.

2.4.1 Graphical Correlation :-

In graphical correlation technique the unit hydrograph parameters are plotted as a function of the physical characteristics of the catchments. Usually logarithmic graph paper is used, and a best fit line is drawn by eye. Other information, such as knowledge of the approximate slope of the curve or limits on some of the parameters can often be used to aid in positioning the curves. As an example a typical plot between t_p and LL_c is shown in fig.10.

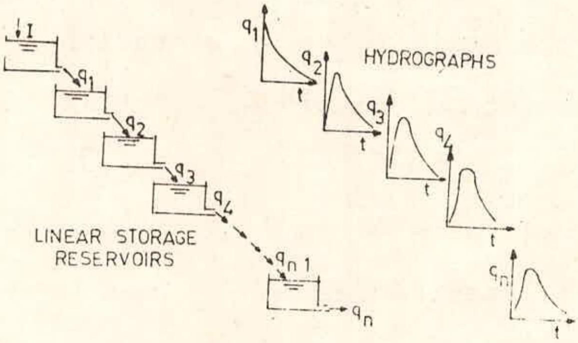

Figure 9 - Nash Model

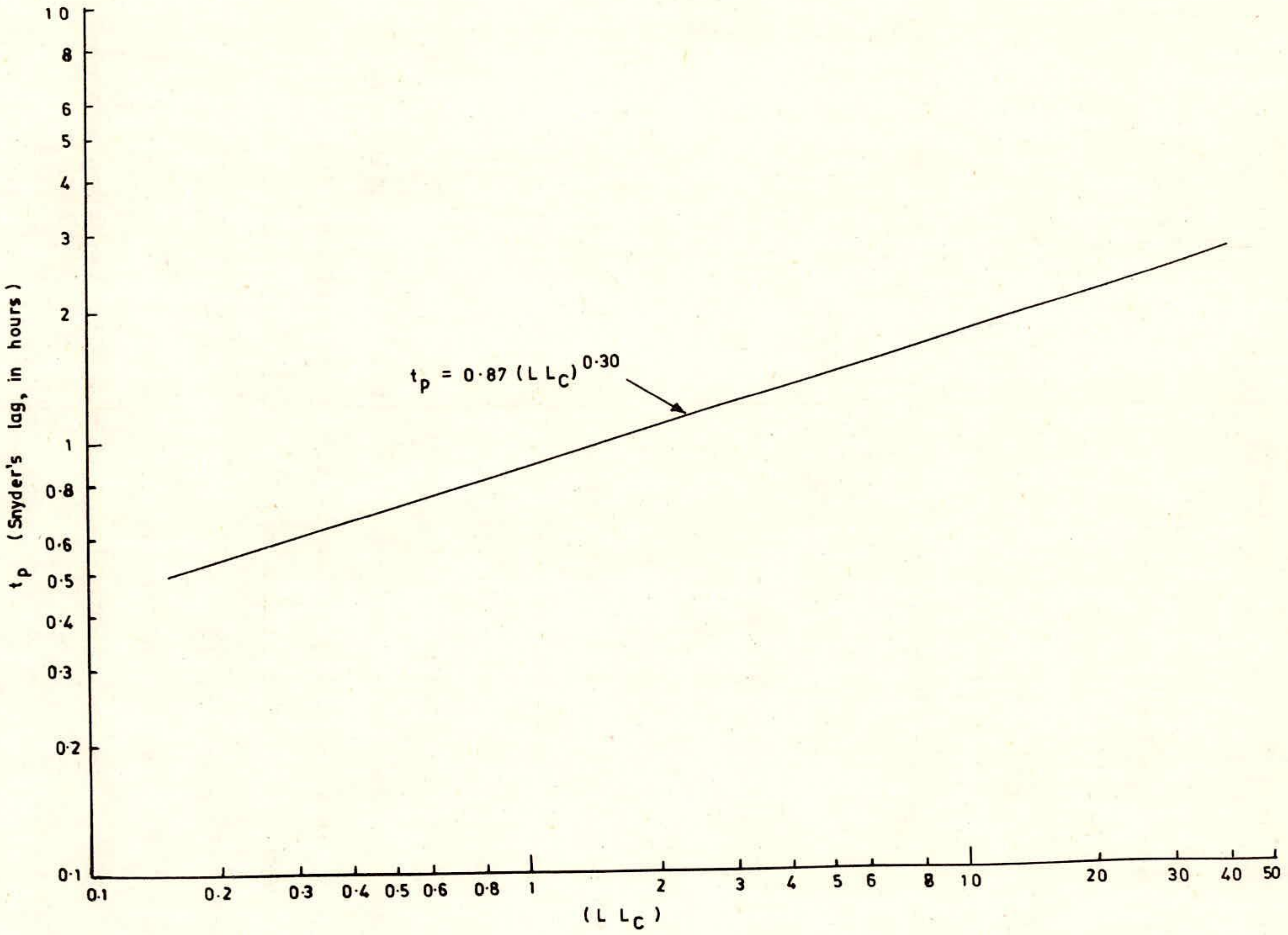

FIG. 10 RELATIONSHIP BETWEEN t_p AND $L\,L_C$

2.4.2 Simple linear regression :-

In simple linear regression, it is assumed that the parameters (or their logarithms) are related to each other by the equation for a straight line. The regression equation is :-

$$Y = a + bX \qquad \ldots(2)$$

where Y = the dependent variables, or its logarith. In this case the unit hydrograph parameters of different catchments are considered as dependent variable.

a = regression constant

b = regression co-efficient, and

X = the independent variable, or its logarithm. In this case the physical characteristics of the catchments are considered to be the independent variable

Many programs are available for determining values of a and b that give a least squares best fit to a given set of data. These include programs for hand held or desk top calculators. If the data sets are not large, then hand calculations can also be made.

2.4.3 Multiple linear regression :-

In general, watershed response is dependent on several watershed parameters (Gray (1970)). An equation of the following form can be used to provide a mathematical expression that involves several independent variables :

$$Y = a + b_1X_1 + b_2X_2 + \ldots\ldots b_nX_n \qquad \ldots(3)$$

where Y = the dependent variable (or its logarithm)

a = regression constant

$b_1, b_2 \ldots$ = regression co-efficients, and

$X_1, X_2 \ldots$ = independent variables, or their logarithms

This type of anlaysis is generally known as the multiple linear regression. When several watershed parameters are being considered, some of the proposed parameters may have little effect on the dependent variable. These parameters, of course, should be dropped from consideration, and the final expression should include only those parameters which significantly affect the result. Thus the objective of a multiple linear regression is to select an optimal equation combining independent variables and co-efficients from which a response may be estimated. The optimal equation may be either :

(i) the one which best describes the actual relationships between the independent and dependent variables (the physical approach), or

(ii) the one which most accurately estimates the dependent variable from the independent ones (the statistical approach), if the true physical relationships are known.

The primary structural difference between these two approaches is that the statistical model tolerates correlation between the independent variables, whereas the physical approach does not.

Since the physical characteristics of the catchment are correlated and the true physical relationships are not known, therefore, one has to go for physical approach rather than the statistical approach. Thus the optimal regression equation may be obtained by successive elimination of the independent variables which are statistically least significance in the equation.

Transformation approaches have also been used to transform the correlated variables into new independent components which are in some way related to the characteristics of the actual physical situation. The principal component transformation and factor analysis (Wallis, 1965, Diaz et al, 1968; Haan 1977) are such transformations. These methodologies have two major drawbacks with respect to an application for multiple linear regression:

i) The statistical predictive accuracy of the resulting regression equation is often less than that of the equation derived using normal regression techniques (Wallis 1965; Haan 1977).

ii) In most hydrologic applications, a clear and distinct physical interpretation of the transformed variables has not been possible (Diaz et al, 1968, Haan 1977).

Therefore, it is appropriate to first determine whether the fundamental methodology of regression analysis is a sufficiently accurate means of performing the regional unit hydrograph studies. If not, then there is no point in carrying out additional variable transformations in an attempt to preserve actual cause and effect relationships between parameters, since this generally results in a reduction of the predictive accuracy of the regression relations.

2.4.3.1 Criteria for accepting results of regression analysis.

The results of the regression analysis are evaluated by looking at the statistics describing the goodness of fit of the regression equation to the data. The following statistical parameters are generally used as criteria for accepting the results of regression analysis.

i) Multiple orrelation coefficient (R): It provides a measure of the percent of variance in the dependent variable explained by the independent variables. The magnitude of these coefficients varies between 0 to 1. The closer the value is to unity the greater the relaibility of the estimate.

ii) Standard error of estimate (Se) : It is the standard deviation of the differences between the observed dependent values & the values computed from the regression equation in the units of dependent variable. Therefore, it must be compared with the mean and standard deviation of that variable.

iii) t-Test: The significance tests for the independent variables involved in regression equation are performed at the 95% confidence level using the t-statistic (Haan 1977).

iv) F-test: The significance of overall regression equation at the 95% confidence level is tested using the F-statistic (Haan 1977).

2.5 Regional Unit Hydrograph Studies Conducted Abroad:

i) Bernard's approach: Bernard (1935) accomplished the transformation of rainfall to streamflow through the medium of a 'distribution-graph', which was also found to be a function of watershed characteristics. The distribution graph is only a differently dimensioned unit hydrograph with the time scale expressed in days from the beginning of the storm and the flow scale in effective percentage of area contributing or percentage of the total runoff contributed each day. Bernard graphically correlated the effective percentage, the day from the beginning of the storm, and watershed characteristic U, defined as

$$U = \left(\frac{60\ P}{L} \right)^{4eg} F^{8eg} \frac{5^{1.5eg}}{1000^{2eg}} \qquad \ldots(4)$$

where,

P is constant, depending on the shape of the area of watershed and its manner of concentration.

L is the length in feet which water has to traverse in running from the most remote portion of the watershed to the outlet.

F is a constant depending on the shape and condition of the main flow channel.

e is a positive fractional exponent of t in the rainfall intensity formula.

$$i = \frac{aT^n}{t^e} \qquad \ldots(5)$$

t is the duration of rain and T is the recurrence interval.

g is $\frac{1}{4-e}$

The approach may be considered the first correlation of basin characteristics with parameters with parameters of the unit hydrograph.

ii) Mc Carthy Approach:

Mc Carthy (1938) (stated by Dickinson and Holland 1967) correlated the unit hydrograph and topographic parameters and the results were summarized in a figure in such a way to permit an estimate of the unit hydrograph parameters for an ungauged drainage area. Three unit-graph parameters were selected, namely; peak discharge, lag to peak from beginning of rain and total base time. The three predominant topographic characteristics were: Size of area, slope of area-elevation graph and stream pattern expressed by the number of major streams. The basic data consisted of 6-hr unitgraphs of 22 streams in Connecticut, ranging from 74 to 716 sq.mile.

iii) Snyder's Approach

Snyder(1938) correlated basin characteristics with peak flow, basin lag (i.e. time from the centre of mass of rainfall excess to the peak), and total time base of the unit hydrograph using the data from the Appalachian Highlands of the United States. The catchment considered were having the area ranging from 10 to 10,000 sq.miles. Snyder assumed that for storms of a given type on a particular catchment, the lag time t_p in hours was constant and defined by the expression:

$$t_p = C_t (LL_c)^{0.3} \qquad \ldots(6)$$

where L_c is the distance between the gauging station and the centroid of the catchment along the main channel in miles.

L is the total length of the catchment in miles.

C_t is an empirical coefficient, $1.8 \leq C_t \leq 2.2$ for Appalachain lands with an average value of 2.0

The peak discharge per unit area of the unit hydrograph, Q_p, was related to the time lag by a second empirical equation:

$$Q_p = \frac{C_p}{t_p} \qquad \ldots(7)$$

where , C_p is a second co-efficient, $360 \leq C_p \leq 440$, with an average value of 400. Finally, the time base T_B of the unit hydrograph in days was related to t_p by expression:

$$T_B = 3 + 3 \quad \left(\frac{t_p}{24}\right) \qquad \ldots(8)$$

Equations (6) to (8) were applied to a unit hydrograph of duration $\Delta t = \frac{t_p}{5.5}$. According to Johnstone and Cross (1949) this choice of duration arose from the division of the rising limb of the direct runoff hydrograph into six equal time steps. The time to peak was therefore 6 Δt which was also equal to $(t_p + \frac{\Delta t}{2})$ (see fig. 11(b)); t_p, was therefore 5.5 times the unit duration. In order to construct the unit hydrograph for a different duration of effective rainfall, $\Delta t'$, Snyder (1938) suggested a substitution of an adjusted lag time t_p' where

$$t_p' = t_p + 0.25 \; (\Delta t' - \Delta t) \qquad \ldots(9)$$

$$Q_p = C_p / t_p' \qquad \ldots(10)$$

The choice of the correction term $0.25(\Delta t' - \Delta t)$ is not fully explained in the original paper. Its justification is apparently purely empirical in that equation (10) allows for the reduction in the peak ordinate of the unit hydrograph as its duration increases (see fig.11(a)).

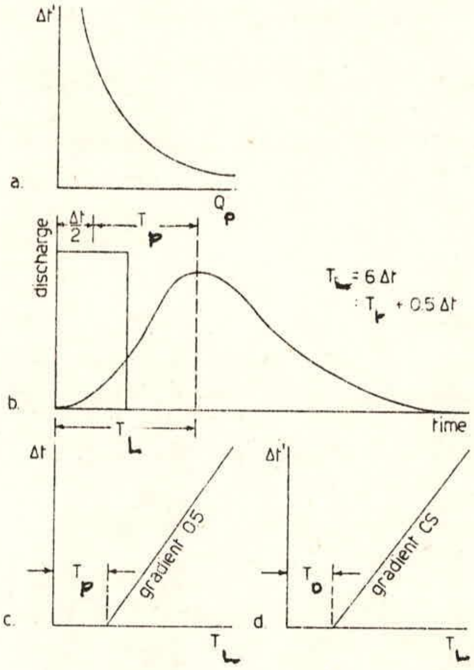

Figure 11- Snyder synthetic Unit hydrograph method

Linsley(1943), who applied the Snyder method to 18 drainage areas in the central valley of California, was found that basin lag was not a constant, the corollary to which is that a plot of time to peak against rainfall duration for selected storm events should be a straight line having a gradient of one half and intercept equal to the lag time (see fig.11(b),(c)). When such diagrams were constructed for the California catchments studied by Linsley, straight line relationships were obtained whose gradient C_s exceed 0.5 and were represented by the equation:

$$t_L = t_o + C_s \Delta t' \qquad \ldots(11)$$

where t_o is the intercept on the t_p axis (see fig.11(d) and $0.7 \leq C_s \leq 1.0$, with an average value of 0.85. Substituting $t_L = t_p + \Delta t'/2$ in equation(11), and replacing t_p by an adjusted lag time t_p.

$$t''_p = t_o + (C_s - 0.5) \Delta t' \qquad \ldots(12)$$

Equation(12) is similar in form to equation(9). Using the average value of C_s the correction term of equation(12) becomes $0.35 \Delta t'$. However, if Δt is assumed to be small t_p can be approximated by t_o and the correction term of equation (9) becomes $0.25\Delta t'$. These similar features led Linsley to suggest that equation(7) should be employed to compute the peak discharges for unit hydrographs corresponding to any rainfall duration. For the California catchments, $225 \leq C_p \leq 320$, with an average value of 270. However, the lag time of equation(6) was constrained to apply to a standard rainfall duration, and t_o, which was considered applicable to a very short storm, was adopted taking $0.3 \leq C_t \leq 0.7$, with an average value of 0.5

Study conducted by Linsley provided useful evidence for the general form of equations(6) to (9). The extrapolation of all such empirical equations to both other regions and other types and sizes of catchment area must be carried out with extreme caution.

Snyder and Linsley considered essentially rural drainage basins in their analysis. The question therefore arises as to whether the same relationships hold good for both urbanising and fully developed urban catchments, if so, whether appropriate values ot C_t and C_p can be found to characterise their behaviour,

It was Eagleson(1962) among the first to apply the Snyder method to fully Sewered urban areas. He considered 5 catchments ranging in size from 0.57 to 19.45 km^2 in his study, which are much smaller than those investigated by Snyder and Linsley. Therefore making the use of equation(8) for the computation of T_B was completely inappropriate. However,equation(6) and (7) were found to be applicable, with much smaller values of C_t and C_p towards the lower end of the range quoted by Snyder(1938).

Espey et al(1965) employed the time to peak of unit hydrograph as the principal determinant of unit hydrograph shape. Using data from 11 rural catchments ranginf from 0.35 to 18.2 km^2 and 22 urban drainage basins between 0.03 and 238.8 km^2 in an area located mainly in the eastern states of America, they have derived separate equations for the time to peak of the 30 min. unit hydrograph. The equations are :-

i) for the rural areas

$$TP_r = 2.65\ L^{0.12}\ S^{-0.52} \qquad \text{...(13)}$$

ii) For the urban areas

$$TP_u = 20.8\ L^{0.29}\ S^{-0.11}\ IMP^{-0.61} \qquad \ldots(14)$$

where,

L is the main channel length in feet,

S is the main channel slope(dimensionless)

TP_r is the time to peak of the unit hydrograph in minutes for rural catchments.

TP_u is the time to peak of the unit hydrograph in minutes.for urban catchments.

IMP is the percentage impervious area.

Although equation(14) explained 91% of the variance in TP_u, predicted values were found to overestimate measured values on catchments that had either extensive channel improvements carried out or storm water sewers installed. This performance was attributed to the inadequacy of IMP as an index of urbanization, and so an empirical factor PHI, was therefore introduced to account for the observed reductions in time to peak. The following classification was adopted for PHI:

PHI	Classification
0.6	Extnesive channel improvement and storm sewere system, cloged conduit channel system.
0.8	Some channel improvement and storm sewers, mainly cleaning and enlargement of existing channels.
1.0	Natural channel conditions, no urban development

Equation(14) was therefore written

$$TP_u = 20.8\ PHI\ L^{0.29}\ S^{-0.11}\ IMP^{-0.61} \qquad \ldots(15)$$

Further investigation of the available data showed that for both urban and rural catchments, the peak discharge of the 30 min unit hydrograph was a function of both the catchment area and the time to peak. A composite equation were derived combining all the data for the peak discharge per unit area Q_p:

$$Q_p = 40900\ TP^{-1.11} \quad \ldots(16)$$

where Q_p is measured in $ft^3/S/mile^2$. Equation(16) explained 90% of the variance in Q_p.

An analysis of hydrograph width showed that both catchment area and peak discharge per unit area consistently appeared as the independent variables. The equations derived by combining the data sets are :-

$$T_B = 318000\ Q_p^{-1.13} \quad \ldots(17)$$

$$W_{50} = 38800\ Q_p^{-1.025} \quad \ldots(18)$$

$$W_{75} = 10000\ Q_p^{-0.89} \quad \ldots(19)$$

The equations (17) to (19) were found to explain 95, 95 and 94% of the variance in the dependent variable respectively.

Espey et al (1969), in a subsequent study, used data sets of 17 rural and 33 urban catchments obtained from gauging stations in the vicinity of Houstan Texas. This analysis required the revision of the exponents and constants to several of the original equations. It was also observed that the seasonal variations in channel vegetation had an important influence on TP_u. The emperical factor PHI was redefined as the sum of two co-efficients, PHI1 and PHI2, where PHI1 was the original PHI and PHI2 was classified as follows :

PHI2	Classification
0	No vegetation
0.1	Light vegetation
0.2	Moderate vegetation
0.3	Heavy vegetation

using this revised definition the equation (15) becomes :

$$TP_u = 16.4 \; PHI \; L^{0.32} S^{-0.049} \; IMP^{-0.49} \qquad \ldots(20)$$

and equation (13) became :

$$TP_r = 2.68 \; L^{0.22} \; S^{-0.30} \qquad \ldots(21)$$

In order to predict the peak discharge for the 30 min unit hydrograph, the data sets were considered separately. The prediction equations developed for the urban and rural areas are given by equations (22) and (23) respectively:-

$$Q_p = 35000 \; TP_u^{-1.10} \qquad \ldots(22)$$

$$Q_p = 82500 \; A^{0.99} \; TP_r^{-1.25} \qquad \ldots(23)$$

For the rural drainage basins catchment area A(mile^2) was employed as an independent variable, and the peak discharge, Q_p, was taken in ft^3/sec.

(iv) Clark's Approach :-

Clark (1945) pointed out that the parameters T_c and K may be separately related with catchment characteristics Such relationships would provide the set of parameters T_c and K for ungauged catchments, which in addition to time area diagram could be used to derive the instantaneous unit hydrograph for the catchment.

Lucas (1949) (Quoted by Dickinson et al (1967)) related the Clark's parameters T_c and K to watershed parameters with regard to 7 watersheds between 139 amd 331 sq. miles. The relationships were obtained :

$$T_c = \frac{4.7}{r^2} \left(\frac{L}{\sqrt{S}} \right)^{1/2} \qquad \ldots(24)$$

$$K = 1.65 + 8.46 \frac{W}{R} \qquad \ldots(25)$$

Where L is the length of the main channel, in miles; S is the equivalent uniform slope of the channel ft/mi. and computed by using the equation.

$$S = \left(\Sigma_{i=1}^{n} l_i \sqrt{S_i} / \Sigma_{i=1}^{n} l_i \right)^2 \qquad \ldots(26)$$

where l_i and S_i are the length and slope of reach i, r is a dimensionless branching factor (i.e. ratio between the area under a curve depicting total area tributary to the main stream above a point, and the area under a curve depicting the total area that would be tributary if the stream were single branched and the drainage basin were of uniform width) W is the width of the drainage area, $\frac{A}{L}$, in miles, R is the general overland slope in ft. per mi. The branching factor played an insignificant role for basins less than 200 sq. miles. It was also suggested that the T_c and K relationship be used with caution and only for obtaining initial estimates.

HEC (1982) suggested that the combination of the parameters (T_c + K) could be related with one of the following parameters describing the catchment characteristics :

(a) A (catchment area)

(b) S (Average slope)

(c) $L / \sqrt{S}$

(d) $LL_c / \sqrt{S}$ e) $L\sqrt{A/S}$

where L represents length of the largest river course.

(v) Taylor and Schwarz Approach :-

Taylor and Schwarz (1952) (quoted by Dickinson et al (1967)) related the unit hydrograph lag and peak flow values to basin characteristics and to the duration of rainfall excess empirically, where the lag was defined from the centroid of the rainfall excess to the unitgraph peak. The most significant basin characteristics were found to be drainage area, length of longest water course, length to centre of area, and equivalent main stream slope defined as the slope of a uniform channel having the same length as the longest watercourse and an equal time of travel. The correlation studies were presented in the form of the graphs and a method for the computation of equivalent main stream slope was presented.

(vi) O'Kelly's Approach :-

O'Kelly's (1955) (Quoted by Dickinson et al (1967)) replaced the time-area diagram of the Clark Model by an isosceles triangle without loss of accuracy and with considerable saving of labour, gain of flexibility and convenience. Thus the IUH could be obtained by routing an isosceles triangular flow of the unit volume of bas length T_C hours through a single linear reservoir of storage coefficient K based on the O'Kelly's approach (Fig.(7)). Here the two parameters, T_C and K, are able to define the shape of the IUH. O'Kelly's assumed area and overland slopes as prominant physiographic characteristics. He also assumed that area could be allowed for by the Froude model law. Therefore all values of T_C and K were modified to correspond with a catchment of 100 sq. miles area. These modified values of T_c and K were plotted against the overland slope which was defined as the median value of the maximum slope occuring at the intersections of a grid of square mesh imposed on a map of the catchment. O'Kelly's conclusion was that the modified T_C and K could be expressed as nominal powers of the slope i.e. $T_C = AS^B$ and $K = C.S^D$ where S denotes the slope, and A,B,C, and D are emperically derived constants. If B and D were equal, then T_C/K would be a constant A/C. and the shape of the IUH would have been fixed. Infact O'Kelly used slightly different values of B and D and so obtained a basic shape which varied slightly with catchment slope, and consequently with the unit hydrograph parameter K.

(vii) Minshal Approach :-

Minshal (1960) used the two parameters, peak rate and time to peak, of the unit hydrograph and pointed out that these two parameters were dependent on rainfall intensity and storm pattern. He presented a method for constructing a synthetic unit hydrograph for small drainage basins involving emperical relationships for the percerntage of the peak rate at times before and after the peak rate in terms of the rainfall intensity and drainage area.

(viii) Nash Approach :-

Nash (1960) related the first and second moments of the IUH with the catchment characteristics for some English basins. He tried various forms of the relationships using different catchment characteristics. However, the following relationships were finally obtained :

$$m_1 = 20.7\ A^{0.3}\ S^{-0.3} \qquad \ldots(27)$$

$$m_2 = 1.0\ m_1^{-0.2}\ S^{-0.1} \qquad \ldots(28)$$

where m_1 is the first moment of IUH about the origin,

m_2 is the ratio of the second moment of IUH about the centroid to m_1^2 ,

A is the catchment area (mi^2) and S is a measure of overland slope.

The parameters of the model, n and K, were obtained using theoram of moments.

(ix) Gray's Approach :-

Gray (1961) used the two parameter gamma distribution equivalent to the expressions developed by Edson (1951) and Nash (1957), to fit the following form of the dimensionless unit hydrographs

$$\frac{Q_t}{P_R} = \frac{25.0}{\Gamma q} (\gamma')^q \left(e^{-\frac{\gamma' t}{P_R}}\right) \left(\frac{t}{P_R}\right)^{q-1} \qquad \ldots(29)$$

where $\frac{Q_t}{P_R}$ is the percentage of flow/0.25 P_R at any given t/P_R value.

P_R is the period of rise from the beginning of surface runoff to the peak discharge,

γ' is a dimensionless parameter equal to the product $\gamma\ P_R$,

q is a shape parameter,

γ is a scale parameter

Γ denotes the gamma function

e is the base of natural logarithm

The time of rise, P_R, was found to be a significant parameter. The storage factor, K or P_R/γ', was significantly correlated with the watershed characteristic $\frac{L}{\sqrt{S_C}}$, where L is the length of the stream and S_C is the channel slope. The relationships for three areas were approximately of the form,

$$\frac{P_R}{\gamma'} = C\left(\frac{L}{\sqrt{S_C}}\right)^{\frac{1}{2}} \qquad \ldots(30)$$

Then the parameter γ' was purely emperically related to the time of rise P_R. As a result, it was found that for uniformly distributed, short duration, high intensity storms over small watershed areas, the unit hydrographs could be derived from the watershed characteristics, $L / \sqrt{S_C}$.

(x) Application of Conceptual Models to Urbanising Catchments:-

The problem associated with sketching in a hydrograph shape that has the appropriate dimensions obtained from the regression equations and satisfies the constraint of unit volume may be avoided by the use of a standard form defined either by an equation or a simple geometrical approximation. Cruise and Contractor (1980) employed the two parameter gamma function, which was used by both Edson (1951) and Gray (1961) to describe the geometry of synthetic unit hydrographs for rural drainage areas, for catchments subjected to urban development. In this approach the IUH ordinates are given by the equation,

$$q(t) = (C(yt)^{x}\exp(-yt)) / \Gamma(x+1) \qquad \ldots(31)$$

where c is a conversion constant and Γ is the gamma function. According to Edson (1951), the parameter x depends upon the shape of the time area diagram of the catchment, and the parameter y is a recession constant. The peak and time to peak of the IUH, represented by equation (31), are given in terms of the parameters as :-

$$Q_p = [cy\ (\frac{x}{c})^x] \ / \ \Gamma(x+1) \qquad ...(32)$$

$$t_p = x/y \qquad ...(33)$$

Since x and y define Q_p and t_p completely, they may be considered as the dependent variables in a regression analysis on catchment characteristics. Cruise and Contractor (1980) performed the regression analysis, using data from 30 catchments in North Carolina and northern Virginia,where basin ratios and percentage impervious areas were considered as the independent variables. From the study they found that this regression model had no generality. However, the data set had to be devided according to geographical location before significant relationships could be obtained. After the study, they found that the parameter x was linearly related to the logarithm of the basin ratio and the percentage impervious area, but y depended only on the former.

The two parameter gamma distribution also describes the form of the IUH for a conceptual model consisting of a casacade of n linear reservoirs of equal storage constant K. If the parameters, x and y, are transformed according to $x=n+1$ $y=1/K$ equation(31) becomes identical to Nash Model. Rao et al(1972) applied this conceptual model and the simple linear reservoir model to urbanising catchments. They found considerable variations in model parameters from storm to storm. In order to take into account such variations they included the volume and duration of effective rainfall as independent variables in the prediction equations. They concluded from the study that a single linear reservoir model was able to describe the catchment behaviour adequately for areas of less than 13 km^2. The storage constant of this reservoir, which is also equal to the lag time T3, was obtained from the equation:

$$T3 = 0.831A^{0.458}(IMP+1)^{-1.66}Pe^{-0.267}\ D^{0.375} \qquad (34)$$

Where T3 is measured in hours

A is the catchment area(mile^2)

IMP is the portion of impervious area,

P_e is the volume of effective rainfall in inch and

D is the duration of effective rainfall in hours.

Based on 125 storms from 11 drainage areas, equation(34) explained 85.1% of the variance in T3.

For large catchments of the sizes between 13 and 52 km^2, the cascade of linear reservoirs was found to be the better model. Since for this model lag T3=nK, the parameters, n and K, could be found by using equation(34) for T3 and the following equation for K:

$$K = 0.575\ A^{0.389}(IMP+1)^{-0.22}\ P_e^{-0.106}D^{0.222} \qquad ...(35)$$

Equation(35) was able to explain 72.5% of the variance of K, which was measured in hours. The impervious area index (IMP+1), was found to be the most dominant independent variable.

(xi) Hall's Approach

Hall(1974,1977) assumed that unit hydrographs of same duration from a group of urbanising catchment areas can be represented in common dimensionless form. He applied this approach to 8 catchments in west Sussex and North London.

In both studies, the one hour unit hydrograph representing a particular state of development on individual catchments were made dimensionless by dividing their abscissae and multiplying their ordinates by the centroid to centroid lag time,T3. The functional form of each dimensionless unit hydrograph was therefore given by

$$u_t \; T3 = f(\; t/T3) \qquad \ldots(36)$$

where u_t is the ordinate of the unit hydrograph (reciporcal hours) at time t. Hall(1981) obtained representative responses for specified degress of urbanization using the combined data set of 187 events by fitting apolynomial function to each set of dimensionless unit hydrograph by the method of least squares. Denoting the product u_t T3 by Y and the quotient t/T3 by X, the fitted function was given by the expression:

$$Y = \sum_{j=0}^{m} C_j \; X^j \qquad \ldots(37)$$

where C_j,j=0,1....m, are the co-efficients of the polynomial of the order m. The same approach was applied to derive a general dimensionless 1 hour unit hydrograph for the whole data set, and an 8th order polynomial was found to afford the best compromise between the number of co-efficients, the root mean square residual and the area enclosed upto an abscissa of 3.5 T3.

The suitable relationships between the scaling parameter, T3, and catchment characteristics were developed for both rural and urban catchments in south east England. Those relationships are expressed as:

$$T3_r = 0.867 \; R^{0.42} \qquad \ldots(38)$$

$$T3_u = 0.212\ R^{0.50} \qquad \ldots(39)$$

where $R = 31.6 \frac{L}{\sqrt{S}}$ is the basin ratio

L is the main channel length in km, and

S is the main channel slope (m/km)

The slope S was defined as the altitude difference between two points located 10 and 85% of the main channel length upstream from the gauging site divide by 0.75 L. The subscript r and u denote rural and urban conditions respectively the latter corresponding to a condition with about 25% impervious area and some sewering and channel improvements. For intermediate states of development with a percentage impervious area IMP, the lag time, $T3_i$, was estimated by logarithmic interpolation between $T3_r$ and $T3_u$

$$\ln T3_i = \ln T3_r + 0.04\ IMP\ (T3_u/T3_r) \qquad \ldots(40)$$

xii) U.K.Flood Studies Approach

NERC(1975) represented the dimensionless one hour unit hydrograph by straight line rising and recessioon limbs. The unit hydrograph was completely defined in terms of time to peak, t_p by the equations:

$$t_p = 46.6\ S^{-0.48} RSMD^{-0.42}\ L^{0.14} (I+IMP)^{-1.99} \qquad \ldots(41)$$

$$Q_p t_p = 220 \qquad \ldots(42)$$

$$T_B = 2.525\ t_p \qquad \ldots(43)$$

where L is the length(km),

S is the slope(m/km) of the main channel

RSMD is the 5-year, 1-day rainfall excess (mm)

which is a function of average annual rainfall.

IMP is the fraction of the urbanised area in the catchment.

Q_p is the peak discharge of the unit hydrograph ($m^3/S/10^2$ km^2) and T_B is the time base of the unit hydrograph.

Equations (41) to (43) have also been applied by the Institute of Hydrology(1979) to synthesise the unit response of the urbanising catchment areas:

xiii) Sangvaree and Yevjevich's approach

Sangvaree and Yevjevich(1977) analysed 105 flood events of eight forest and 14 agricultural land use experimental catchments in the eastern and central united states in order to study the effects of forest and agriculautral land use on flood unit hydrograph. The parameters considered for the study can be categorised in three groups, namely

A. Unit Hydrograph parameters

- i) Q_p, the peak flow
- ii) T_r, the rise time
- iii) T_a, the average rise time
- iv) α, the shape factor

B. Rainstorm variables.

- i) T_e, the effective rainfall durations
- ii) I_e, the average effective rainfall intensity
- iii) M_1, the first moment of effective rainfall hyetograph
- iv) M_2, the second moment of effective rainfall hyetograph
- v) M_2. the second central moment of effective rainfall hyetograph
- vi) R_1, the first moment of observed hydrograph.
- bii) R_2, the second moment of observed hydrograph
- viii) R'_2 the second central moment of observed hyetograph.

C. Catchment physiographic factor

i) A, the catchment area
ii) H, the total fall
iii) L, the main stream length
iv) L_c, the length to centroid of area
v) S_1, the main stream slope
vi) S_2, the average slope
vii) Forest and agricultural types of land uses
viii) C_f, the percentage of forest or agricultural cover.
ix) F_1 or $LL_c/\sqrt{S}$, the shape factor
x) S_h , or H^2/A the relief factor.

In order to study the effects of land use on the shape of the unit hydrograph, the impact of the parameters related with catchments topography were removed prior to the study. They found that the unit hydrographs of small catchments were significantly affected by the landuse. For a given small catchment, the agricultural landuse increases the flood peaks while the forest landuse has the opposite effect. The peak flows of unit hydrographs of catchments with predominantly agricultural land use were approximately two to four times greater than the peak flows which result from catchments with the predominantly forest landuse. The stepwise multiple linear regression were performed considering the unit hydrograph parameters as dependent variable and physigographic climatic and landuse factors as independent variables so as to develop optimum relationships.

The method outlined permits the study of effects of other landuses on flood hydrographs, such as for the catchment which are predominantly grass covered, desert catchments, urban catchments, as well as the types of land cover other than the forest or the classical agricultural land use.

2.6 Regional Unit Hydrograph Studies conducted in India

(i) The small catchment directorate of CWC(1980), developed the following relationships between the one-hour UH parameters and physical characteristics of the catchments for Godavari basin subzone 3f:

$$t_p = 0.253\ (LL_c/\sqrt{S})^{0.45} \qquad \ldots(44)$$

$$Q_p = 1.968\ (t_p)^{-0.842} \qquad \ldots(45)$$

$$W_{50} = 2.30\ (Q_p)^{-1.108} \qquad \ldots(46)$$

$$W_{75} = 1.356\ (Q_p)^{-1.007} \qquad \ldots(47)$$

$$W_{R50} = 0.954\ (Q_p)^{-1.078} \qquad \ldots(48)$$

$$W_{R75} = 0.581\ (Q_p)^{-1.035} \qquad \ldots(49)$$

$$T_B = 4.572\ (t_p)^{0.90} \qquad \ldots(50)$$

where, the parameters Q_p, t_p, W_{50}, W_{75}, W_{R50}, W_{R75}, T_B, L, L_c and S are already defined in section 2.3. The one hour representative UH parameters and pertinent physiographic characteristics for 22 catchments of Godavari basin subzone 3F are given in table 1 and 2 respectively.

ii) CWC (1982) also developed the regional unit hydrograph relationships for Mahanadi basin subzone 3d analysing the data of 16 catchments of the basin. One hour UH parameters were considered for developing the following relationships.

$$t_p = 1.97\ (LL_c/\sqrt{S})^{0.24} \qquad \ldots(51)$$

TABLE 1. REPRESENTATIVE U.G. PARAMETERS SUB-ZONE 3-f

Sl. No.	Br. No.	t_p	Q_p	t_r	T_B	W_{50}	W_{75}	W_{R50}	W_{R75}
1.	807	4.5	650.0	1	17	2.9	1.7	1.2	0.6
2.	875	9.5	290.0	1	41	6.0	4.0	3.0	1.6
3.	224	9.5	214.0	1	40	7.5	4.0	3.8	1.8
4.	65	10.5	184.0	1	40	9.2	5.5	5.9	3.5
5.	228	4.5	280.0	1	20	3.3	2.0	1.3	1.0
6.	15	5.0	234.0	1	20	4.2	3.0	2.2	1.5
7.	184	11.5	60.0	1	44	15.3	7.0	7.2	3.4
8.	604	3.5	228.7	1	12	3.6	2.3	1.6	1.0
9.	269	3.5	140.8	1	14	4.4	3.1	1.2	1.0
10.	881	3.5	190.0	1	14	2.4	1.1	1.1	0.5
11.	969	2.5	179.0	1	12	2.8	1.7	1.1	0.7
12.	57	6.5	65.0	1	24	5.5	3.0	1.8	1.0
13.	36	4.5	80.0	1	15	3.9	2.3	1.5	1.0
14.	566	2.5	190.5	1	9	1.5	0.8	0.7	0.4
15.	494	3.5	65.1	1	13	4.8	3.4	1.8	1.3
16.	51	3.5	65.8	1	11	4.4	2.1	1.1	0.7
17.	59	2.5	66.5	1	6.5	2.1	1.3	1.1	0.8
18.	20	2.0	60.8	1	10	3.4	1.8	1.0	0.9
19.	161	2.5	41.0	1	12	2.9	1.6	1.4	0.7
20.	4	1.5	71.4	1	8	1.6	0.9	0.9	0.5
21.	491	1.5	43.5	1	8	2.3	1.3	0.8	0.4
22.	214	1.2	55.8	1	6	1.3	0.7	0.6	0.3

TABLE 2. BASIN CHARACTERISTICS SUB-ZONE 3-f

Sl. No.	Br.No.	A	L	Lc	Wc	S	$\frac{LLc}{\sqrt{S}}$
1.	807	824	67.2	25.8	12.9	2.3	1143
2.	875	750	61.1	29.0	20.1	1.8	1321
3.	224	750	61.1	23.8	17.7	1.4	1229
4.	65	731	92.3	43.1	21.6	2.0	890
5.	228	483	41.8	17.7	18.5	3.8	380
6.	15	459	33.1	8.4	16.6	1.3	244
7.	184	364	35.2	12.9	16.4	1.8	339
8.	604	341	45.0	20.5	14.5	1.9	669
9.	269	242	27.7	11.2	14.1	3.8	159
10.	881	233	24.1	10.1	11.3	9.1	81
11.	969	208	25.0	6.8	10.5	2.1	117
12.	57	163	29.0	15.3	8.1	1.6	351
13.	36	139	23.0	8.5	7.3	2.3	129
14.	566	137	19.6	8.4	9.3	4.9	74
15.	494	120	18.2	10.0	10.3	1.9	132
16.	51	87	33.7	20.0	5.1	1.3	296
17.	59	65	18.0	10.0	3.1	3.4	98
18.	20	60	17.7	8.1	5.6	5.0	64
19.	161	54	12.2	5.3	6.2	7.5	81
20.	4	50	12.2	5.3	6.2	7.5	24
21.	491	42	14.7	7.7	3.5	5.4	49
22.	241	35	10.1	7.4	2.2	8.8	25

$$Q_p = 1.12\ (t_p)^{-0.66} \qquad \ldots(52)$$

$$W_{50} = 2.195\ (Q_p)^{-1.1008} \qquad \ldots(53)$$

$$W_{75} = 1.221\ (Q_p)^{-0.95} \qquad \ldots(54)$$

$$W_{R50} = 0.995\ (Q_p)^{-0.94} \qquad \ldots(55)$$

$$W_{R75} = 0.532\ (Q_p)^{-0.93} \qquad \ldots(56)$$

$$T_B = 5.72\ (t_p)^{0.77} \qquad \ldots(57)$$

Table 3 and 4 respectively show the representat one hour unit hydrograph parameters and pertinent physiographic characteristics for Mahanadi Subzone 3d.

iii) Mathur & Vijay Kumar (1982) related the following physical parameters of 20 small and Medium catchments with an objective to find out the most effective physical parameters representing the regional unit hydrograph relationships.

L = length of main streams (km)

L_c = as defined in section 2.3

S = statistical stream slope

$$S = \left(L / \sum_{i=1}^{n} L_i / S_i^{\frac{1}{2}}\right)^2 \qquad \ldots(58)$$

where

L_i = length of the ith segment of the main stream (kms)

S_i = slope of ith segment of main stream (km/kms)

Sl = land slope defined by

$$Sl = \frac{\sum_{i=1}^{n} \frac{l_i + l_{i+1}}{2}\ (h_{i+1} - h_i)}{A} \qquad \ldots(59)$$

l_i = length of ith contour (km)

l_{i+1} = length of (i+1) the contour (km)

A = catchment area (Km^2)

TABLE.3. REPRESENTATIVE 1 HR U.G. PARAMETERS SUBZONE 3d

Sl. No.	Railway bridge no.	t_p hrs.	Q_P cumec	q_p cumec/ sq.km.	t_r hr.	T_B hr.	W_{50} hr.	W_{75} hr.	W_{R50} hr.	W_{R75} hr.
1.	7	16.50	559.44	0.18	1	57	10.97	5.25	6.17	2.60
2.	121	12.50	322.00	0.28	1	37	7.00	3.60	3.00	1.80
3.	489	8.50	271.59	0.33	1	29	6.00	3.00	2.00	1.50
4.	12	11.50	159.84	0.24	1	31	10.00	7.40	4.00	2.00
5.	195	10.50	123.00	0.20	1	38	11.20	5.05	4.00	2.30
6.	235	10.50	68.64	0.22	1	41	11.20	4.86	3.30	2.10
7.	332 (ii)	6.50	85.50	0.38	1	21	6.00	2.97	3.00	1.56
8.	385	7.50	58.20	0.30	1	24	7.75	4.50	3.20	1.80
9.	69	9.50	38.06	0.22	1	31	11.70	5.53	4.87	2.10
10.	59 (B)	6.50	40.80	0.30	1	31	6.48	3.48	3.40	1.39
11.	698	5.50	46.33	0.41	1	23	4.90	2.64	1.90	1.16
12.	48	7.50	20.71	0.19	1	38	12.80	6.85	4.20	2.60
13.	79	4.50	27.47	0.41	1	16	6.12	3.74	2.60	1.27
14.	37	5.50	24.32	0.38	1	18	6.67	3.40	2.20	1.30
15.	154	5.50	23.20	0.40	1	20	5.45	3.32	2.20	1.20
16.	59 (S)	5.50	17.39	0.37	1	28	5.30	2.20	2.70	1.20

TABLE 4 BASIN CHARACTERISTICS SUBZONE 3d

Sl. No.	Railway bridge no.	A Sq.km.	L km.	Lc km.	Wc km.	S m/km.	$\frac{LL_c}{\sqrt{S}}$
1.	7	3108	96.16	51.50	49.60	0.47	7304.00
2.	121	1150	80.50	38.14	16.14	3.22	1734.77
3.	489	823.00	64.40	25.74	16.57	3.10	941.49
4.	12	666.00	66.79	25.75	13.68	1.38	1463.66
5.	195	615.00	53.90	28.16	18.34	1.41	1278.24
6.	235	312.00	40.80	21.09	9.34	1.30	754.68
7.	332 (ii)	225.00	30.59	13.52	12.72	1.43	345.85
8.	385	194.00	39.36	15.13	6.76	5.31	258.43
9.	69	173.00	35.40	18.50	7.56	2.70	398.82
10.	59 (B)	136.00	28.16	11.26	4.99	4.27	153.90
11.	698	113.00	26.40	14.40	5.84	9.50	123.34
12.	48	109.00	19.32	10.46	8.13	2.68	123.44
13.	79	67.00	17.71	8.45	5.15	2.18	101.33
14.	37	64.00	17.70	7.24	6.36	7.66	46.30
15.	154	58.00	12.09	9.65	6.19	4.30	56.26
16.	59 (S)	47.00	13.07	8.29	5.23	3.78	55.73

SL_c = statistical stream slope from a point nearest to centroid.

W_c = Minimum width of the catchment from a point passing through centroid.

D = drainage density in km^{-1}

Table 5 shows the above physical parameters for 20 catchments. Multiple linear regression analysis of a total 31 combinations of physical parameters were considered, dropping one or several of them singularly and collectively. Table 6 shows the relationship between each parameter and basin lag. Relative importance of the individual parameters was determined by assigning them an order with respect to the coefficient of correlation. They have found that statistical stream slope, statistical stream slope from a point nearest to the centroid and drainage density are relatively more important than the other physical parameters.

iv) Huq et al (1982) developed generalized synthetic unit hydrograph relationships analysing the data of 21 bridge catchments in Lower Gangetic Plains, Mahanadi Basin, Krishna Basin and Brahmputra Basin. They have related the parameters of the representative unit hydrpgraphs with a suitable combination of the following physical characteristics of the catchments using regression analysis:

A, L, L_c, S are defined earlier in the text.

F = form factor which is the ratio of the square of the length of the main stream to the total catchment area i.e. $\frac{L^2}{A}$

W_c =Minimum width of the catchment measured through

TABLE 5: THE PHYSICAL PARAMETERS OF THE CATCHMENTS

Sl. No.	Bridge No.	Area 'A' km^2	Length L km	Lc km	S m/km	SL m/km	SLc m/km	D 1/km	Wc km	t_p hrs.
1	2	3	4	5	6	7	8	9	10	11
1.	12	665.13	66.79	25.75	1.38	80.65	1.47	0.82	3.50	11.50
2.	235	312.00	40.80	21.09	1.30	8.25	0.97	0.27	9.34	10.50
3.	195	615.00	53.90	28.16	1.41	11.53	0.83	0.50	18.34	10.50
4.	332(ii)	224.81	30.59	13.52	1.43	8.21	0.92	0.98	12.72	6.50
5.	385	194.25	39.36	15.13	5.31	124.50	3.01	2.10	6.78	7.50
6.	90	192.03	30.80	15.30	0.88	4.60	0.48	0.51	5.64	14.50
7.	69	172.78	35.40	18.50	2.70	41.52	2.23	0.46	7.56	9.50
8.	59(B)	135.70	28.16	11.26	3.58	44.62	1.74	1.53	4.99	6.50
9.	40(K)	115.25	23.09	8.05	8.13	101.98	3.09	2.45	6.68	2.50
10.	698	112.66	26.40	14.40	9.50	29.77	6.15	0.43	5.84	5.50
11.	48	108.52	19.32	10.46	2.68	52.58	1.24	0.96	8.13	7.50
12.	66K	154.13	23.21	14.63	6.90	54.50	5.33	3.81	10.17	3.50
13.	37	64.24	17.70	7.24	7.66	73.60	4.04	1.68	6.36	5.50
14.	154	58.09	12.09	9.65	4.30	48.30	2.67	1.88	6.19	5.50
15.	42	53.82	12.88	6.04	3.85	43.58	2.39	0.82	5.47	10.50
16.	79	66.56	17.71	8.45	2.18	21.25	1.38	1.48	5.15	4.50
17.	59(S)	46.50	13.07	8.29	3.78	73.44	2.06	2.29	5.23	7.50
18.	121	1149.98	80.50	36.14	3.22	30.00	0.51	0.43	10.14	14.50
19.	489	822.76	64.40	25.74	3.10	29.20	2.30	1.23	16.57	8.50
20.	7	3108.00	106.70	51.50	0.90	99.88	0.27	0.68	49.60	16.50

TABLE 6: RELATIONSHIP BETWEEN EACH PARAMETER AND BASIN LAG

Sl. No. 1	Parameters considered 2	Constant 3	Exponents 4	Correlation coefficient 5	Error sum of sequares 6	Order No. 7	Remarks 8
1.	L, t_p	1.7234	0.4397	0.5321	0.6028	6	
2.	Lc, t_p	2.3583	0.4244	0.6038	0.5343	5	
3.	S, t_p	12.7087	-0.4757	0.7123	0.4143	2	
4.	SL, t_p	12.8677	-0.1462	0.2784	0.7757	8	
5.	D, t_p	7.6190	-0.4749	0.7034	0.4248	3	
6.	Wc, t_p	3.5318	0.3587	0.4150	0.6960	7	
7.	A, t_p	1.9516	0.2571	0.6042	0.5339	4	
8.	SLc, t_p	9.4820	-0.4341	0.7481	0.3703	1	

the centroid of the catchment.

The relationships developed by regression analysis are :

$$Ft_p = 1.43 \left(\frac{LL_c}{W_c} \sqrt{\frac{A}{S}} \right)^{0.38} \qquad \ldots(60)$$

$$Q_p = 2.33\ A^{0.67}\ S^{0.38} \qquad \ldots(61)$$

$$W_{50} = 2.33\ (Q_p)^{-1.10} \qquad \ldots(62)$$

$$W_{75} = 1.321\ (Q_p)^{-1.22} \qquad \ldots(63)$$

Table 7 shows the physiographic characteristics of the catchments considered. However, the parameters of the derived unit hydrograph are compared with their estimated values in Table 8.

v) The small catchment directorate of CWC(1982) developed the following regional unit hydrograph relationships for Krishna and Penner Basins (subzone 3h)relating the physical parameters of 21 catchments with their one hour representative unit hydrograph parameters:

$$t_p = 0.258 \left(\frac{LL_c}{\sqrt{S}} \right)^{0.49} \qquad \ldots(64)$$

$$Q_p = 1.017\ (t_p)^{-0.52} \qquad \ldots(65)$$

$$W_{50} = 2.396\ (Q_p)^{-1.08} \qquad \ldots(66)$$

$$W_{75} = 1.427\ (Q_p)^{-1.08} \qquad \ldots(67)$$

TABLE 7: PHYSIOGRAPHIC CHARACTERISTICS OF CATCHMENTS CONSIDERED

Sl.No.	Br. No.	Physiographic Characteristics					Region
		A Km^2	L Km	Lc Km	Wc Km	S m/km	
1.	101(S)	19.94	6.44	3.62	4.03	5.32	Lower Ganetic Plains
2.	8	354.31	41.05	27.05	7.41	19.13	Brahamaputra Basin
3.	269	242.00	27.70	11.20	14.10	3.80	Lower Godavari Basin
4.	881	233.00	24.10	10.10	11.30	9.10	-do-
5.	566	137.00	19.60	8.40	9.30	4.90	-do-
6.	59	65.00	18.00	10.00	3.10	3.40	-do-
7.	20	60.00	17.70	8.10	5.60	5.00	-do-
8.	4	50.00	12.20	5.30	6.20	7.50	-do-
9.	491	42.00	14.70	7.70	3.50	5.40	-do-
10.	384	62.16	14.96	9.65	4.02	11.05	Krishna Basin
11.	123	64.75	16.09	7.24	6.11	3.65	-do-
12.	166	91.27	16.89	7.24	5.63	6.31	-do-
13.	353	118.25	26.54	15.69	7.24	4.71	-do-
14.	18	131.52	23.74	10.46	9.55	3.88	-do-
15.	215(I)	167.32	23.25	11.26	12.06	8.43	-do-
16.	202	171.70	19.30	9.85	11.46	5.19	-do-
17.	169	230.87	29.96	12.83	12.88	3.64	-do-
18.	98	348.40	31.38	15.29	15.20	7.93	-do-
19.	313	220.45	26.72	13.68	10.45	3.57	-do-
20.	40K	115.25	23.09	8.05	6.68	8.13	Mahanadi Basin
21.	66K	154.13	23.21	14.63	10.17	6.90	-do-

COMPARISON OF THE PARAMETERS OF THE DERIVED UNIT HYDROGRAPH WITH THEIR ESTIMATED VALUES

Table 8

Sl. No.	Bridge No.	t_p (Hrs) derived	t_p (Hrs) estimated	Q_p (cumec) derived	Q_p (cumec) estimated	W_{50} (Hrs) derived	W_{50} (Hrs) estimated	W_{75} (Hrs) derived	W_{75} (Hrs) estimated	Remarks
1	2	3	4	5	6	7	8	9	10	11
1.	101(S)	2.50	3.31	33.10	28.68	4.20		2.45		
2.	8	4.50	3.51	363.88	290.77	6.00		3.60		
3.	269	3.50	3.21	140.36	138.87	4.40	4.24	3.10	2.57	
4.	881	3.50	3.42	191.06	175.72	2.40	2.90	1.10	1.68	
5.	566	2.50	2.86	190.43	102.21	1.50	1.62	0.80	0.88	
6.	59	2.50	2.36	66.30	55.52	2.10	2.28	1.30	1.28	
7.	20	2.50	1.51	60.60	59.04	3.40	2.30	1.80	1.30	
8.	4	1.50	1.61	71.50	58.95	1.60	1.57	0.90	0.85	
9.	491	1.50	1.55	48.68	47.53	2.30	2.23	1.30	1.26	
10.	384	1.50	2.15	53.95	76.61	2.80	2.72	2.00	1.57	
11.	123	2.50	1.90	45.97	55.56	3.30	3.40	2.00	2.00	
12.	166	2.50	2.44	60.97	83.00	3.30	3.63	1.90	2.16	
13.	353	1.50	1.33	106.90	91.50	2.30	[illegible].60	1.60	1.49	
14.	18	2.50	1.79	87.59	89.01	3.80	[illegible].64	2.40	2.17	
15.	215(I)	2.50	2.52	111.94	137.43	3.85	3.63	2.48	2.16	
16.	202	2.50	3.74	115.55	121.03	3.95	3.60	2.50	2.14	
17.	169	2.50	2.88	116.59	132.83	5.00	4.94	3.50	3.04	
18.	98	2.50	3.96	204.16	221.03	4.50	4.19	2.60	2.53	
19.	313	3.50	3.10	108.68	128.03	4.90	5.07	2.40	3.13	
20.	40K	2.50	1.93	107.18	106.86	2.14	2.52	1.10	1.44	
21.	66K	3.50	2.88	117.14	122.56	2.60	3.15	1.40	1.84	

$$W_{R50} = 0.750\ (Q_p)^{-1.25} \qquad \ldots(68)$$

$$W_{R75} = 0.557(Q_p)^{-1.12} \qquad \ldots(69)$$

$$T_B = 7.193\ (t_p)^{0.53} \qquad \ldots(70)$$

The correlation coefficients obtained for the above equations are reasonable. The physical characteristics and one hour representative unit hydrograph parameters for 21 catchments of subzone 3h are given in table 9 and 10.

vi) The Small Catchment Directorate of CWC (1984) derived the following relationships relating the physical parameters of the 23 catchments of upper Indo-Ganga Plains (subzone 1.e.) with either representative 2 hour unit hydrograph parameters:

$$Q_p = 2.030\ \left(\frac{L}{\sqrt{S}}\right)^{0.649} \qquad \ldots(71)$$

$$t_p = 1.858\ (Q_p)^{-1.038} \qquad \ldots(72)$$

$$W_{50} = 2.217\ (Q_p)^{-0.99} \qquad \ldots(73)$$

$$W_{75} = 1.477\ (Q_p)^{-0.876} \qquad \ldots(74)$$

$$W_{R50} = 0.812(Q_p)^{-0.907} \qquad \ldots(75)$$

$$W_{R75} = 0.606(Q_p)^{-0.791} \qquad \ldots(76)$$

$$T_b = 7.744\ (t_p)^{0.779} \qquad \ldots(77)$$

TABLE 9. BASIN CHARACTERISTICS SUBZONE 3(h)

Sl.No.	Bridge No.	A Sq.Km.	L Km.	L_c Km.	W_c Km.	S m/Km.	$LL_c/\sqrt{S}$
1.	53(ii)	1689.92	54.06	22.53	32.18	2.04	852.75
2.	63	1357.15	56.32	27.35	32.18	2.09	1065.48
3.	200	555.37	41.83	20.91	15.12	5.20	383.57
4.	328	437.60	37.00	19.30	20.92	5.98	292.01
5.	601	398.60	36.20	16.73	18.83	2.28	401.08
6.	98	348.40	31.38	15.29	15.20	7.93	170.38
7.	16	270.60	35.40	13.84	11.26	1.44	408.28
8.	169	230.87	26.96	12.88	12.88	3.64	182.00
9.	313	220.45	26.72	13.68	10.46	3.57	193.46
10.	202	171.70	19.30	9.85	11.46	5.19	83.45
11.	215(i)	167.32	23.25	11.26	12.06	8.43	90.17
12.	18	131.52	23.74	10.46	8.45	3.38	135.07
13.	365	119.60	16.00	7.00	10.00	5.72	46.82
14.	353	118.25	26.54	15.69	7.24	4.71	191.87
15.	771	118.23	18.10	8.85	9.09	0.278	303.81
16.	53(i)	102.45	21.24	8.61	6.76	9.16	60.42
17.	253	100.98	16.49	8.05	8.85	3.10	75.39
18.	166	91.27	16.89	7.24	5.63	6.31	48.68
19.	123	64.75	16.09	7.24	6.11	3.65	60.97
20.	384	62.16	14.96	9.65	4.02	11.05	43.43
21.	404	29.78	10.70	6.44	4.02	1.22	62.38

TABLE 10 REPRESENTATIVE 1 - HR. U.G. PARAMETERS SUB - ZONE 3 (h)

Sl.No.	Bridge No.	tp (hr.)	Qp (Cumecs)	tr (hr.)	T_B (hr.)	W_{50} (hr.)	W_{75} (hr.)	W_{R50} (hr.)	W_{R75} (hr.)
1.	53(ii)	7.5	496.70	1	24	9.0	5.8	3.7	2.5
2.	63	7.5	533.88	1	22	6.8	4.0	2.8	1.6
3.	200	4.5	312.00	1	15	4.2	2.2	2.4	1.4
4.	328	6.5	133.98	1	21	8.6	4.8	2.8	1.9
5.	601	5.5	153.92	1	18	6.8	3.9	2.8	1.8
6.	93	2.5	204.00	1	10	4.5	2.8	1.5	1.0
7.	16	4.5	117.00	1	15	6.1	4.0	2.9	2.1
8.	169	2.5	116.58	1	12	5.0	3.5	1.4	0.9
9.	313	3.5	108.70	1	15	4.9	2.4	0.8	0.5
10.	202	2.5	115.70	1	10	3.95	2.5	1.6	1.1
11.	215(i)	2.5	112.00	1	11	3.85	2.5	1.5	1.1
12.	18	2.5	87.59	1	11	3.8	2.4	1.5	1.1
13.	365	1.5	86.89	1	9	3.6	2.0	1.2	0.8
14.	353	2.5	107.00	1	10	2.8	1.6	0.8	0.5
15.	771	4.5	72.38	1	15	4.2	2.6	1.8	1.2
16.	53(i)	2.5	58.94	1	13	4.0	2.5	1.6	1.2
17.	253	1.5	72.54	1	11	3.3	1.8	0.8	0.6
18.	166	2.5	61.00	1	14	3.3	1.9	0.7	0.5
19.	123	2.5	46.00	1	10	3.3	2.0	1.2	1.0
20.	384	1.5	54.27	1	9	2.8	2.0	1.2	1.0
21.	404	1.5	22.42	1	10	3.2	1.6	0.8	0.6

The coefficient of correlation for the above equations are in the range of 0.80 to 0.99

The physical characteristics and 2 hour representative unit hydrograph for 23 catchments of upper-Indo Ganga plains (subzone ie) are given in table 11 and 12 respectively.

vii) Singh (1984) developed the regional unit hydrograph relationship relating the physical parameters of five catchments of Godavari basin subzone 3f with the average parameters of Nash Model and Clark Model for those catchments. The physical parameters of five catchments of Godavari basin subzone 3f are given in table 13. However, the average parameter of Nash and Clark models for those catchments are given in table 14 and 15 respectively. The variation of n K with ($\frac{LL_c}{\sqrt{S}}$) is shown in fig.12. Figure 13 shows variation of k with main stream length L. The Clark Model parameter T_c was related with $\frac{LL_c}{\sqrt{S}}$ as shown in figure 14. A fixed value of the ration $R/(T_c+R)$ along with T_c v/s $\frac{LL_c}{\sqrt{S}}$ plot was used to establish the regional unit hydrograph relationships, based on Clark Model. However, figure 12 and 13 were used to develop the regional unit hydrograph relationships based on Nash Model.

TABLE 11. BASIN CHARACTERISTICS OF SUBZONE -1(e)

Sl. No.	Br. No.	A Sq.km.	L km.	S(q) m/km	$\frac{L}{\sqrt{S}}$
1	20	2425.54	96.60	0.629	121.82
2	104 (i)	2072.0	125.19	0.870	134.21
3.	400	1908.00	200.80	0.257	396.09
4.	Ghaggar	1126.00	81.42	5.14	35.91
5.	181	911.68	144.90	0.901	152.61
6.	89	814.75	97.40	0.39	155.96
7.	124	511.53	54.74	0.465	88.23
8.	1244	440.00	64.50	6.280	25.74
9.	1307	322.20	56.32	3.65	29.48
10.	99(i)	296.61	49.88	0.422	76.78
11.	65	190.11	32.2	11.43	9.52
12.	229	187.96	47.75	0.974	48.38
13.	166	165.76	27.48	0.61	35.18
14.	288	160.06	36.70	0.492	52.32
15.	93(ii)	140.66	28.60	3.60	15.07
16.	2	106.40	61.98	0.361	183.16
17.	104(ii)	104.58	23.90	4.363	11.44
18.	291	96.41	36.20	1.08	34.83
19.	315	73.04	28.34	0.128	79.21
20.	Khar	55.00	17.00	5.8	7.06
21.	1231	49.47	16.19	2.41	10.43
22.	184	35.87	9.45	4.37	4.53
23.	50	25.26	15.0	2.0	10.61

TABLE -12: REPRESENTATIVE 2-HOUR U.G.PARAMETERS SUBZONE 1(e)

Sl. No.	Br.No.	tp hrs	Qp Cumecs	qp Cumec/ Sq.Km.	tr hr.	T_B hr.	W_{50} hr.	W_{75} hr.	WR_{50} hr.	WR_{75} hr.
1.	20	25	226.50	0.093	2	86	26.00	14.00	7.5	5.00
2.	104 (i)	23	237.00	0.114	2	80	17.60	10.80	8.80	5.60
3.	400	27	141.40	0.074	2	104	31.20	16.00	11.20	6.40
4.	Ghaggar	7	289.00	0.257	2	36	8.50	4.50	3.00	1.80
5.	181	27	37.50	0.041	2	188	53.00	23.00	13.00	5.00
6.	89	25	55.70	0.068	2	127	36.10	15.20	11.10	5.20
7.	124	27	70.20	0.137	2	74	15.00	10.00	5.00	4.00
8.	1244	13	114.50	0.260	2	40	7.70	4.10	3.20	2.10
9.	1307	7	140.45	0.436	2	24	4.30	2.70	2.20	1.50
10.	99(i)	45	24.39	0.082	2	120	26.00	12.50	9.00	4.00
11.	65	6	84.22	0.440	2	21	5.20	2.98	2.60	1.68
12.	229	6	70.00	0.372	2	28	5.80	2.90	2.20	1.30
13.	166	8	28.00	0.169	2	54	13.00	5.60	1.00	0.60
14.	288	32	10.80	0.067	2	177	27.50	13.00	7.00	4.00
15.	93(ii)	5	66.00	0.469	2	15	5.40	3.50	2.35	1.70
16.	2	39	6.50	0.061	2	144	36.50	26.50	17.00	11.55
17.	104 (ii)	1	120.00	1.147	2	9	2.10	1.60	0.60	0.40
18.	291	6	53.50	0.555	2	21	3.30	1.90	1.40	1.00
19.	315	33	4.24	0.058	2	138	38.50	17.00	10.10	4.60
20.	Khar	4	16.19	0.294	2	25	7.80	5.00	2.70	2.00
21.	1231	8	14.65	0.296	2	29	7.40	3.80	2.40	1.60
22.	184	1	35.62	0.992	2	8	2.50	1.90	0.70	0.50
23.	50	9	4.5	0.178	2	56	11.20	5.60	2.00	1.20

TABLE 13: CATCHMENT CHARACTERISTICS SUBZONE 3f

Catch.No.	Catchment Area (A)	Length of main stream (L)	Distance of C.G. to outlet(Lc)	Slope S	$LL_c/\sqrt{S}$
	km^2	km	km	m/m	x 10^4
A	823.62	67.20	25.75	0.00228	3.624
B	86.76	23.74	10.06	0.001299	0.663
C	340.52	45.95	20.44	0.00193	2.138
D	208.49	24.94	6.76	0.00207	0.371
E	483.03	42.00	18.00	0.0038	1.23
F	137.21	19.55	8.37	0.004917	0.233

TABLE 14
NASH MODEL- AVERAGE PARAMETERS AND UNIT HYDROGRAPH PEAK AND TIME TO PEAK

BR No.	n	k	nk	U.G.peak	U.G.time to peak	Remark
		hrs	hrs	(m^3/s)	(hrs)	
807/1	3.96	1.41	5.58	36	5	
51	2.33	1.34	3.122	5.3	2	
604/2	3.175	1.15	3.65	20.5	3	
969/1	2.02	1.36	2.747	14.6	2	
228	3.55	1.74	6.177	18.3	5	
566	2.91	0.789	2.296	11.9	2	

TABLE 15: CLARK MODEL - AVERAGE PARAMETERS AND UNIT HYDROGRAPHS

Bridge No.	T_c (hrs)	R (hrs)	T_c+R (hrs)	U.G.Peak (m^3/sec)	U.G.time to peak (hrs)	Remarks
807/1	2.03	4.96	6.99	35	3	$\frac{R}{T_c+R}$ =0.71 is fixed for the region
51	1.21	2.96	4.17	6	2	
604/2	1.38	3.38	4.76	19	2	
969/1	1.13	2.76	3.89	15	2	
228	2.89	7.06	9.95	14	4	
566	1.05	2.57	3.62	10	2	

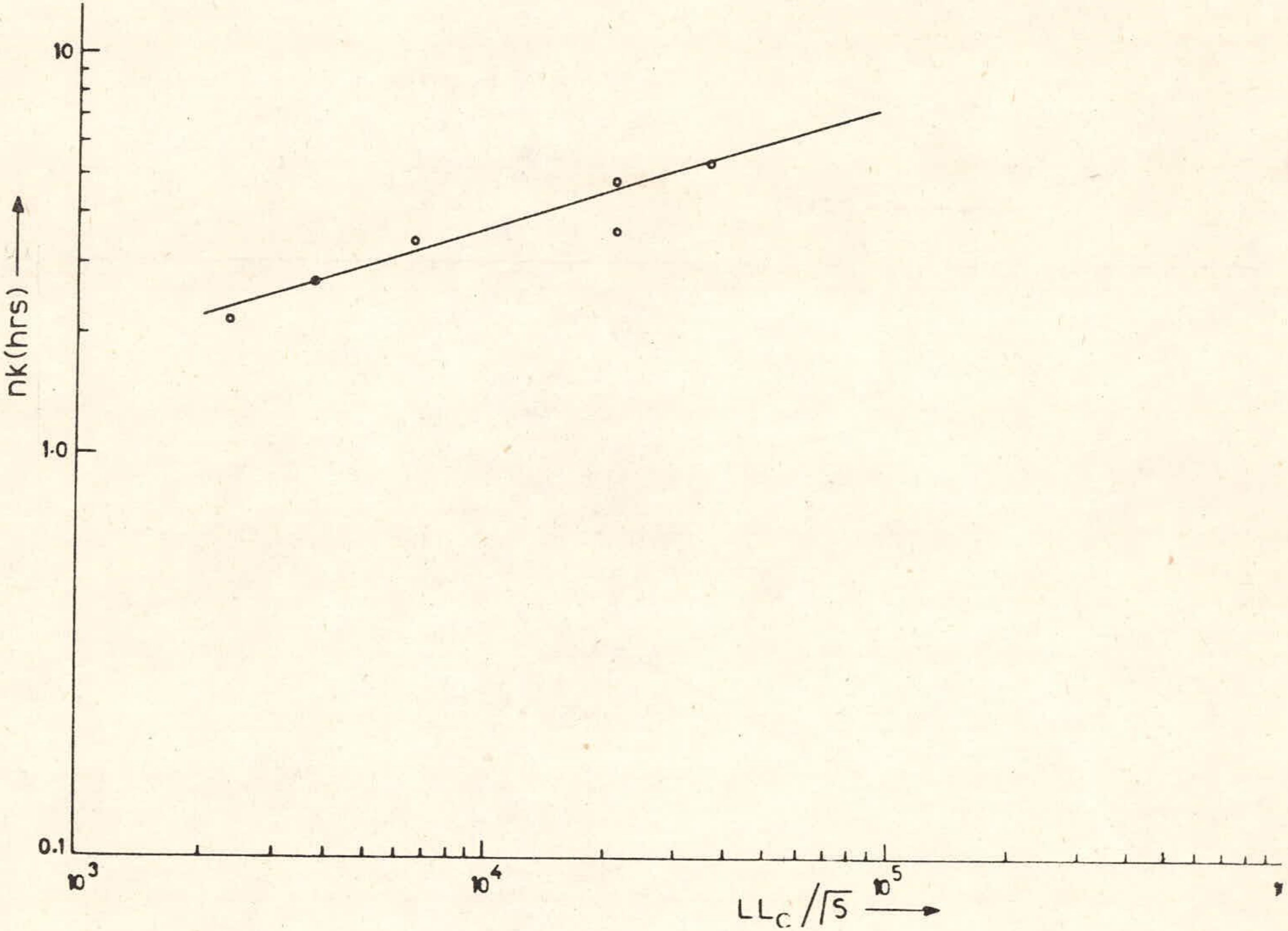

Figure 12- Plot between nK and LL$_c$ / $\sqrt{S}$

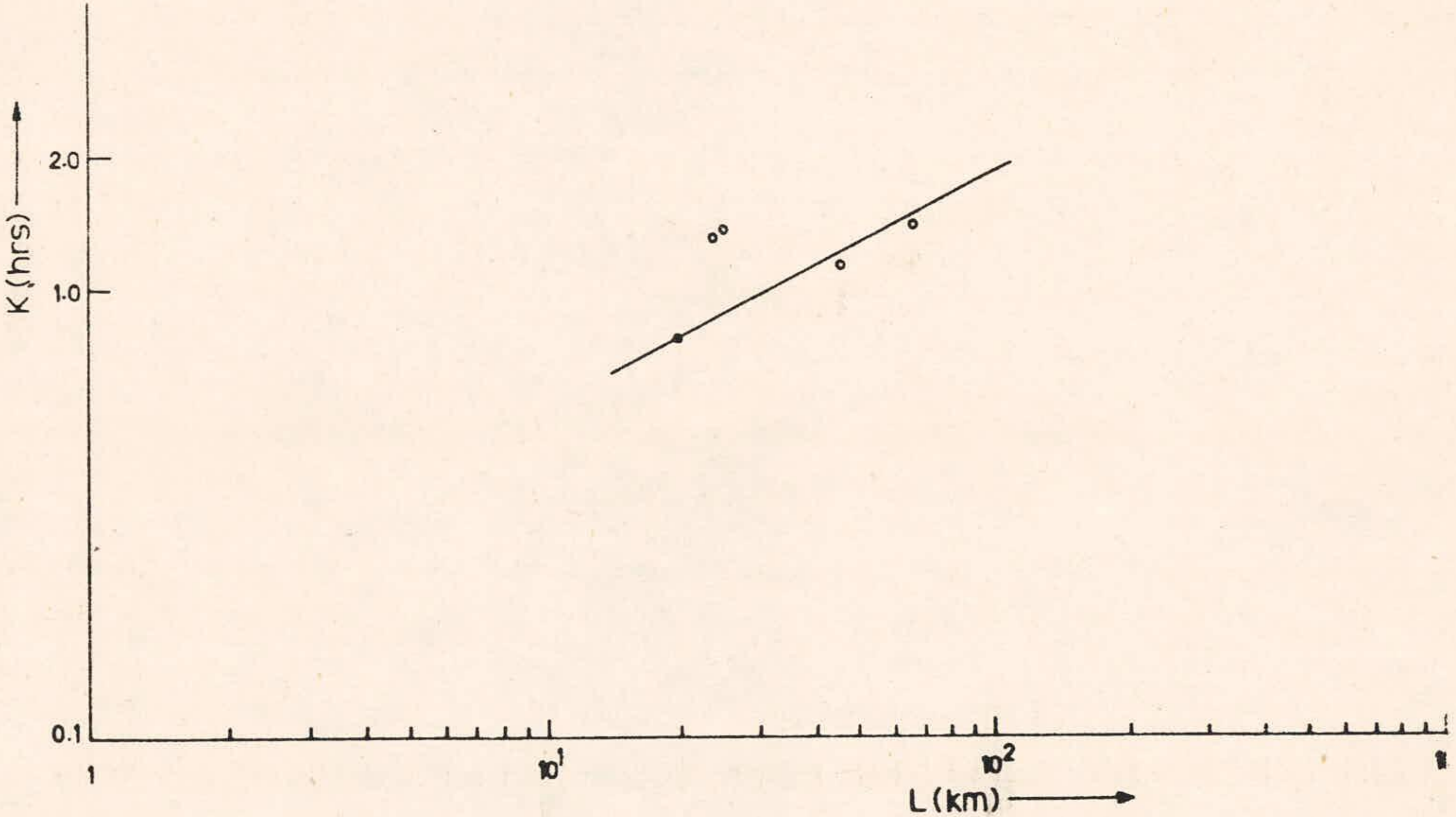

Figure 13 - Plot between K and L

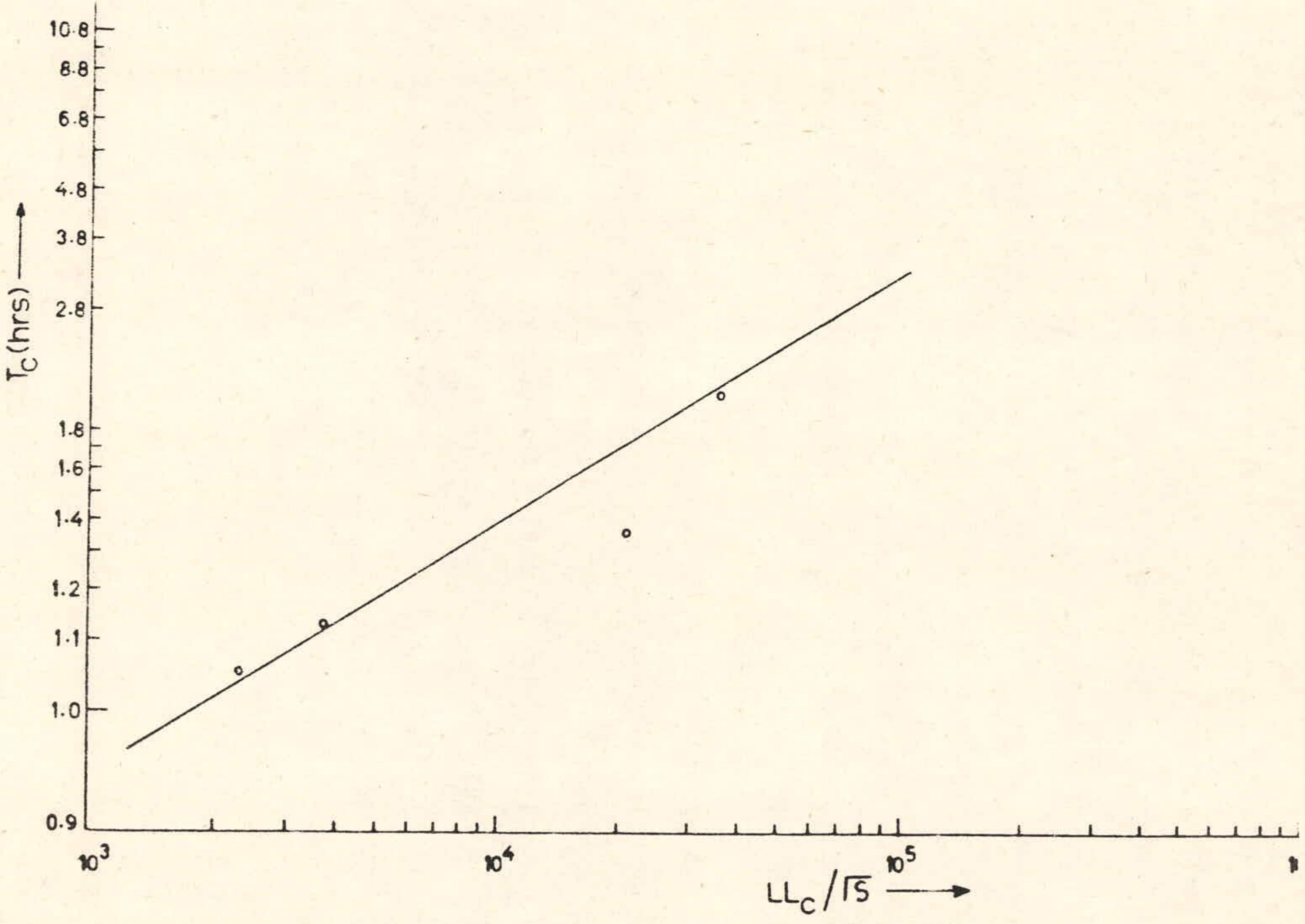

Figure 14- Plot between T_c and LL_c / $\sqrt{S}$

3.0 CONCLUSIONS

A critical review of the different regional unit hydrograph studies, conducted in India as well as in abroad, reveals the following conclusions

i) Regional Unit Hydrograph relationships provide most effective means to derive the unit hydrograph for ungauged catchments located in hydrometeorologically homogeneous region.

ii) For developing the regional unit hydrograph relationships, the multiple linear regression analysis seems to be most popular approach.

iii) The conceptual models define the standard shape of unit hydrograph using the minimum no. of parameters. These parameters of the models can be related with the pertinent physiographic characteristics of the catchments in some way or other to develop regional unit hydrograph relationships. It avoids the subjective sketching of unit hydrograph shape through the appropriate dimensions (Q_p, t_p, W_{50}, W_{75}, W_{R50}, W_{R75} etc.), obtained from regression equations in order to satisfy the constraints of unit volume.

Different conceptual models have been used by many investigators abroad for developing the regional unit hydrograph relationships. However, very little work has been done in India for developing such relationships using the conceptual models. The superiority of the conceptual models over the conventional methods for unit hydrograph derivation points out the need for carrying out the regional unit hydrograph study for Indian basins using some well known conceptual models such as Nash ,Clark etc.

(iv) The effects of forest, agricultural,urbanisation as well as of the other land uses on the shape of the unit hydrograph should be studied using the catchments of different geographic conditions. Such investigations should reveal whether the extrapolations are permitted beyond the ranges of the catchment areas, flood peaks, and other factors. Further, the effects of the additional characteristics such as geologic formation, water storage properties on the shape of the unit hydrograph should also be examined.

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