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Rainfall-Runoff Modelling of Morel Catchment for Design Flood Estimation

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ABSTRACT

The computations of flood hydrographs have always been one of the major concerns of the water resources engineers and scientists. Either the empirical, statistical or deterministic approaches have been quite often used for these purposes. Deterministic approach has the advantage over other two approaches as it provides complete shape of hydrograph.

For the purpose of rainfall-runoff process simulation, mathematical modelling is often resorted to. Continued research in this field has resulted in numerous types of rainfall-runoff models. For simulation and design flood evaluation, conceptual models and physically based models are widely used. The linearity principle of unit hydrograph theory has been widely applied for the simulation of rainfall-runoff process, particularly for small and medium sized catchments. For the gauged catchments the unit hydrographs can be derived by analysing the historical rainfall-runoff records. However, for ungauged catchments some indirect approaches have been used for the derivation of the unit hydrographs. Due to scarcity of data, particularly for small and medium sized catchments, physically based models are very difficult to be implemented. For these catchments, emphasis is either to use the regional information or to use the geomorphological characteristics of the basin for estimation of floods. Geomorphological instantaneous unit hydrograph (GIUH) is one among the various approaches available for the simulation of flood events, especially for the ungauged catchments.

In the present study, design flood estimation of Morel catchment, of Rajasthan state is computed using the Snyder approach, regional relationships as proposed by Central Water Commission, using the Clark model, SCS method and using the GUIH based approach.

To estimate the parameters of Clark model, relationships between time of concentration and catchment area and time of concentration and ratio of length of stream channel to the equivalent slope have been developed for the region. Ratio of storage coefficient to the sum of time of concentration and storage coefficient is worked out for each catchment of the region and based on this a median value of this ratio is assigned to the region. Design flood for the basin is computed based on Clark model and GIUH approach being the more realistic and more appropriate for ungauged catchment.

INTRODUCTION

The problem of transformation of rainfall into runoff has been a very active area of research throughout the evolution of the subject of hydrology. In the past, many investigators have tried to relate runoff with the different physiographic and climatic characteristics. The simplest theory proposes to multiply the rainfall with some factor (called the runoff coefficient) to get the runoff. A better way to transform rainfall into runoff is to apply conceptual models in which the various interrelated hydrological processes are conceptualized. More sophisticated procedures are also evolved which are based on the physical concept of the process and try to model this hydrological phenomenon on the basis of physical laws governing them. Actually, many more factors, besides the accuracy, e.g., the availability of data, computing facility, time, resources etc. govern the applicability of a model.

Hydrologic models are required not only for deciding about water yields or design parameters, but also for understanding and evaluating effects of developmental and other activities on hydrological regime of river basins. For comprehensive planning of water resources projects besides data in respect of various uses, adequate hydrological information is necessary. The use of modelling approach can provide such information and could also incorporate scenarios of proposed/ likely land use changes in the river basin for use in planning/ operation of water resources projects.

Correct estimation of the design flood is one of the most important aspect of the water resources development planning. Earlier practice for the design flood estimation was mainly restricted to the use of empirical formulae of course, the lack of sufficient data was a major hurdle in adoption of the different available techniques elsewhere. Today, with availability of more data and the growing awareness for the accuracy in design flood estimation, the unit hydrograph, flood routing and flood frequency analysis are commonly used to predict flood flows.

If information about runoff at site is available, the estimation of design flood hydrograph can utilise that information. However, in rare cases the available runoff data are adequate for the complete hydrologic analysis. For such cases the available information of the nearby catchment or the information of the region can be used to carry out the further analysis. This approach attempts to establish relationships between model parameters and physically measurable watershed characteristics for gauged catchments. These relationships are then assumed to hold for ungauged watersheds having similar hydrologic characteristics. Rainfall-runoff relationships for ungauged watersheds have been developed along two complimentary lines: (1) Empirical equations have been developed to relate some individual runoff hydrograph characteristics to watershed characteristics (2) Procedures have been developed to synthesize the entire runoff hydrograph from watershed characteristics. Bernard (1935) model is perhaps the first attempt to synthesize the unit hydrograph (UH) from watershed characteristics. It assumes that the peak of the UH is immensely proportional to the time of concentration, which in turn is assumed to be proportional to a watershed factor. A distribution graph establishes relation between the effective percentage area contributing and the watershed factor for different days of the storm. Snyder (1938) established a set of formulae relating the physical geometry of the watershed to three basic parameters of the unit hydrograph. Mc Carthy (1938) related three parameters of 6-hour UH, including the time of rise, the peak discharge, and the base length, to watershed characteristics such as area, overland slopes expressed as the average slope of the hypsometric curve and stream pattern. Taylor and Schwarz (1952), in addition to the watershed characteristics employed by Snyder (1938), introduced the average slope of the main channel. The method of hydrograph synthesis employed by the Soil Conservation Service (SCS) (1971), U.S. Deptt. of Agriculture, uses an average dimensionless hydrograph derived from an analysis of a large number of natural UHs for watersheds varying widely in size and geographical locations. Among different approaches used to estimate discharges of extreme floods are the index flood and regional regression methods (National Research Council (NRC), 1988).

Clark (1945) developed a technique to compute the unit hydrograph of any desired unit period using the concept of instantaneous unit hydrograph. This method utilises the two parameters only i.e. the time of concentration, T_c and storage coefficient R. This storage coefficient has been related with the catchment characteristics. The time of concentration was considered to equal the time interval between the end of rain and the point of contraflexure of the hydrograph recession limb. This time base was measured from the recorded floods and not related to watershed characteristics. Nash (1960) model has two parameters n and K. Nash showed that these parameters were related to the first and second moments of the IUH about the origin. These moments were then correlated empirically with watershed characteristics.

In early years, in India, the design discharges for very small and medium catchments were used to be calculated by well known empirical formulae viz. Dickens, Ryves, Inglis, Ali Nawaz Jung, etc. Later on, to evolve a method of estimation of design flood peak of desired frequency for small catchments, the unit hydrograph approach has been adopted by the Central Water Commission. For this purpose, the country has been divided into 7 major zones which are sub-divided into 26 hydrometeorologically homogeneous subzones. For most of these sub-zones, Central Water Commission has already developed regional formulae for different sub-zones for the derivation of the synthetic unit hydrograph. The unit hydrograph characteristics such as peak (Q_p), time to peak (t_p), width of hydrograph at 50% of peak volume (W_{50}), width of hydrograph at 75% of peak volume (W_{75}), width of the rising side of unit hydrograph in hours at ordinate equal to 75% of UH peak (W_{R50}), width of the rising side of unit hydrograph in hours at ordinate equal to 75% of UH peak (W_{R75}), time base (t_B) etc. have been computed on the basis of physiographic features. These regional formulae enable computation of unit hydrograph for ungauged catchments of the sub-zones.

Boyd (1978, 1982) developed the linear watershed bounded network (LWBN) model for synthesis of the IUH employing geomorphologic and hydrologic properties of the watershed. The model divides a watershed into sub-areas bounded by watershed lines using large-scale topographic maps. The model has a large number of lumped storage parameters. Most of these parameters are deduced from geomorphologic properties.

Rodriguez-Iturbe and Valdes (1979) developed an approach for derivation of the IUH by explicitly incorporating the characteristics of drainage basin composition (Horton, 1945; Strahler, 1964; Smart, 1972). The approach coupled the empirical laws of geomorphology with the principles of linear hydrologic systems. Rodriguez-Iturbe and his associates have since extended this approach by explicitly incorporating climatic characteristics and have studied several aspects including hydrologic similarity. Gupta, Waymire and C.T.Wang (1980) examined this approach, and reformulated, simplified and made it more general.

The effect of climatic variation is incorporated by having a dynamic parameter velocity in the formulation of Geomorphological IUH (GIUH). This is a parameter that must be subjectively evaluated. It is shown (Rodriguez-Iturbe, et.al., 1979) that this dynamic parameter "velocity" of the GIUH can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. This transforms the time invariant IUH throughout the event into a time invariant IUH in each storm occurrence.

In the derivation of GIUH one of the greatest difficulties involved is the estimation of peak velocity. This is a parameter that must be evaluated for each flood event. Rodriguez et.al. (1982) rationalised that velocity must be a function of the effective rainfall intensity and duration and proceeded to eliminate velocity from the results. It leads to the development of geomorphoclimatic instantaneous unit hydrograph. The governing equations consists of the terms such as the mean effective rainfall intensity, Manning's roughness coefficient, average width, and slope of the highest order stream.

Janusz Zelazinski (1986) gave a procedure for estimating the flow velocity. It involves the development of the relationship between the velocity and corresponding peak discharge. A methodology based on trial and error procedures has been suggested for estimating the maximum value of the velocity for each flood event.

Panigrahi (1991) estimated the velocity using the Manning's equation. The methodology involves the estimation of equilibrium discharges and subsequently the estimation of the velocity corresponding to it using Manning's equation. It requires the intensity of each rainfall block for the event for the computation of equilibrium discharge. The channel cross-section at the gauging site, longitudinal slope and Manning's roughness are also required during the computation of the velocity. The methodology has been applied to estimate the velocity to derive the Nash model parameters using GIUH approach for the Kolar sub-basin of Narmada basin.

Development of GIUH has potential applications for the estimation of runoff, flood forecasting and design flood estimation, particularly for the ungauged catchments or for the catchments with limited data.

In the present report, design flood estimation of Morel catchment, of Rajasthan state is computed using the Snyder approach, regional relationships as proposed by Central Water Commission, using the Clark model, SCS method and using the GUIH based approach.

THE CATCHMENT

Morel river rises from the Kukas hill ranges of Jaipur. The Dhund tributary, which is a major tributary of Moral river, joins after traversing a distance of about 95 kilometers. Morel river joins the Banas river after traversing a distance of about 160 kilometers, which is a major tributary of Chambal basin.

Total drainage area of Morel catchment is approximately 3320 sq. km. and is regular in shape. The upper part of the basin lies at higher altitude varying between 300 meter and 600 meter while lower part lies at an average altitude of about 150 meter. Soils of the basin can be classified as alluvial with red and yellow soils being predominant in the eastern part of the basin. The existing Morel dam site lies at latitude 26°-26′-36″ N and longitude 76°-20′-15″ E. The catchment map showing the dam site and locations of raingauge stations in and around the basin is given in Figure 1.

The Morel drainage basin lies in the eastern part of Rajasthan. Climatologically, the area is semi-arid (IMD, classification) with large variations in temperature and rainfall. The region is influenced by the south-west monsoon. The mean annual rainfall is about 600 mm. Although, the region is semi-arid, it has received some of the worst rainstorms during the last 100 years. The heavy rainfall associated with these storms, caused considerable damages to the existing dams leading to occasional breaches.

METHODOLOGY

At the dam site, observation of short interval gauges during high flood are being done. It is very difficult to measure reservoir stages during high flood accompanied by strong wind and waves. Moreover, dam breached during the high flood of 1981 and as such no record of flow of that period is available. Therefore, in the current analysis, methods based on empirical relationships, regional relationships and geomorphological characteristics are used to develop a unit hydrograph for the catchment.

Heavy storms occurred in the past in this region as mentioned by Dhar and later got analysed by Rajasthan Irrigation Department (1994), are used for computation of design rainfall. Based on this, the most intense storm has been identified and is used for subsequent analysis. The duration of storm has been decided based on the recommendations of CWC (1993). Using this storm rainfall and developed unit hydrograph, design flood hydrograph for the catchment is computed. Following sections describe in details the step by step computations involved.

Unit hydrograph derivation based on regional relationships developed by CWC

CWC derived the regional unit hydrograph relationships for different sub-zones of India relating to the various unit hydrograph parameters with some prominent physiographic characteristics. The general forms of the relationships are as given below:

$$t_p = a_1 (LL_{ca}/\sqrt{S})^{b_1} \quad \text{....(1)}$$
$$q_p = a_2 (t_p)^{b_2} \quad \text{....(2)}$$
$$W_{50} = a_3 (q_p)^{b_3} \quad \text{....(3)}$$
$$W_{75} = a_4 (q_p)^{b_4} \quad \text{....(4)}$$
$$WR_{50} = a_5 (q_p)^{b_5} \quad \text{....(5)}$$
$$WR_{75} = a_6 (q_p)^{b_6} \quad \text{....(6)}$$

$t_b \quad = a_7\ (t_p)^{b_7}$ ....(7)

where L is the length of main stream in Km.

L_{ca} is the distance from outlet to centre of area of catchment along the stream in Km.

S is stream slope in metre/kilometre

t_p is time from the centre of unit rainfall duration to the peak of unit hydrograph in hours

q_p is peak discharge of UH in cumec/sq.km.

t_b is base period

W_{50} is width of hydrograph at 50% of peak

W_{75} is width of hydrograph at 75% of peak

WR_{50} is the width of the rising side of UH in hours at ordinate equal to 50% of UH peak, and

WR_{75} is the width of the rising side of UH in hours at ordinate equal to 75% of UH peak.

Application to Morel catchment

Morel catchment lies in the Chambal basin therefore regional relationship developed for this region could be used for this catchment. Information from CWC Report of sub zone 1-b (1988), prepared for Chambal basin, is used for further analysis. In this report 19 representative bridge catchment in the Chambel basin have been analysed. Locations of these catchments along with location of Morel catchment are shown in Figure 2. The size of catchment varies from 25 Sq. Km. to 2500 sq. Km. Table 1 shows these details. Calculations are shown as below:

Calculation of unit hydrograph by Regional relation developed by CWC

Length of longest main stream (L) = 111.6 km

Equivalent stream slope S_e = 1.30 m/km

$t_p \quad = 0.339\ (L/\sqrt{S})^{0.826}$

$\quad\quad = 0.339(111.6/\sqrt{1.3})^{0.826}$

$\quad\quad = 14.95$ hours

$q_p \quad = 1.251\ (t_p)^{-0.61}$

$\quad\quad = 1.251\ (14.95)^{0.61}$

$\quad\quad = 0.24$ cumecs/ sq km

$Q_p \quad = 0.24 \times 3320$

$\quad\quad = 796.8$ say 800 cumecs

T_b = 35 hours

From above, peak discharge works out as 800 cumecs, time to peak as 15 hours and base period as 85 hours.

Development of unit hydrograph using Snyder's method

Snyder (1938) gave some empirical relationships for development of synthetic unit hydrograph for a ungauged catchment based on his studies carried out in USA for several catchments in the Appalachian Highland relating shape of the UH to physiographic characteristics of the catchment and information of the nearby gauged catchments. Those relationships were originally developed in FPS system.

The relationships in metric unit to be used to derive t_r' - hour unit hydrograph characteristics using this approach are given below :

Time Lag (hrs) or Basin Lag (hrs)

$t_p = C_t (LL_{ca})^{0.30}$ ....(8)

where t_p = Basin Lag (or time lag) in hours
L = Length of main stream in Km.
L_{ca} = Distance from outlet to centre of area of catchment along the stream in Km.
C_t = A coefficient for different regions

Unit Hydrograph Duration (hrs)

$t_r = t_p / 5.5$ hour ....(9)

where t_r = Unit hydrograph adopted unit duration

Peak of UH (cumec)

$Q_p = (C_p \, CA) / t_p$ ....(10)

where Q_p = Peak of UH in cumec
CA = Catchment area in sq Km
C_p = A coefficient varying from 0.31 to 0.93

Base width of UH (t_b)

For large catchments

$t_b = 3 + 3 (t_p'/24)$ (in days) ....(11)

For small catchments

$t_b = 5\,(t_p' + t_r'/2)$ (in hours) ....(12)

The UH peak, basin lag time and t_b are used to define the shape of UH preserving the unit volume equal to one cm.

Application to Morel catchment

Catchment area of Morel dam is 3320 sq. km. Values of coefficients C_t and C_p are to be calculated from known unit hydrographs of the neighbouring catchments. These coefficients for the nearby bridge catchments Nos. 94, 519, 72, 283 and 198 as shown in Figure 2, have been computed using relevant formulae by Govt of Rajasthan (1995) and are reproduced here in the form of Table 2. Looking at the table, it is observed that for bridge nos. 519, 72 and 283 the variations in the values of C_t and C_p are within reasonable limits and therefore the mean of these values, i.e. $C_t = 0.91$ and $C_p = 2.65$ is adopted for the purpose of further calculations of unit hydrograph for Morel catchment. Unit hydrograph calculations are shown below. It gives time to peak as 16 hours, peak ordinate as 650 cumecs and base period as 110 hours.

Calculations of unit hydrograph by Snyder's Method

A = 3320 sq km

L = 111.6 km

L_{ca} = 62.0

t_r = 1.0 hr (adopted unit period)

C_t = 0.91

C_p = 2.65

$t_p = 0.91 \times (111.6 \times 62.0)^{0.3}$

= 12.91 hours say 13 hours

$t_r = t_p/5.5 = 13/5.5 = 2.36$ hours

$t_{pr} = 13 + (1.0 - 2.36) \times 0.25$

= 12.56 hour

$T_p = 0.5 + 12.56 = 13.06$ hours

Adjusting T_p to nearest even number = 14 hours

$T_{pr} = 14.0 - 0.50 = 13.50$ hours

$Q_p = (2.65 \times 3320) / 13.5 = 651.7$ cumecs say 650 cumecs

$T_b = 3 + 3{*}t_p/24$ days

= 109.67 hours say 110 hrs.

Development of unit hydrograph using SCS method

The method developed by Soil Conservation Service (SCS) is based on a dimensionless hydrograph. This dimensionless hydrograph is the result of an analysis of a large number of natural unit hydrographs obtained from different geologic locations of varying sizes. The method needs to know the time to peak and the peak discharge by the following equations and Figure. 3, developed by Mockus (1957).

$$t_{pr} = t_r/2 + t_p \qquad \text{...(13)}$$

$$q_p = 5.36CA/t_{pr} \qquad \text{...(14)}$$

Where t_{pr} = time from the beginning of rainfall to the peak discharge (h)
t_r = duration of rainfall (h)
t_c = time of concentration (h)
t_p = time from the centroid of the rainfall to the peak discharge (h)
q_p = peak discharge (cumec)
CA = drainage area (sq. km.)

t_p can be estimated from the size of the catchment area.

Application to Morel catchment

To determine the value of tp for Morel catchment, a relationship between catchment area and tp on log-log paper for the nearby bridge catchment of sub zone 1-b is developed as shown in Fig. 8. From this figure, the equation of best fit line comes out as $t_p = e^{0.803\ln(CA)-3.32}$. Substituting CA = 3320 sq. km., catchment area of Morel catchment, t_p works out to be 24.5 hours.

Development of one hour unit hydrograph (t_r = 1 hour)

$$t_{pr} = t_r + t_p \qquad \text{...(15)}$$

$$t_{pr} = 1/2 + 24.5 = 25 \text{ hours.} \qquad \text{...(16)}$$

$$Q_p = 5.36 \times 3320 / 25 = 715.8 \text{ cumecs, say } 715 \text{ cumecs} \qquad \text{...(17)}$$

The peak flow occurs at $t/t_{pr} = 1$ or at t = 25 hours.
Time base of hydrograph = $5t_{pr} = 5 \times 25 = 125$ hours.

Development of unit hydrograph using Clark model

Clark's Unit Hydrograph

Clark (1945) developed a technique to compute the unit hydrograph of any desired unit period using the concept of instantaneous unit hydrograph. In this method, the travel time of water particles from the farthest point in the basin to the outlet of the basin is first computed. The whole catchment area is sub-divided into smaller units or sub-areas by drawing isochrones of equal time of concentration. This represents a portion of the catchment that will contribute at that time interval. This runoff of a particular sub-area is then routed through a linear reservoir to account for storage effect of basin and channels. The total time of concentration, T_c represents the time interval between the end of effective rainfall and the point of inflexion on the recession limb of the flood hydrograph. This method utilises the two parameters only i.e. the T_c and storage coefficient R.

The routing equation takes the following form:

$$O_i = CI_i + (1-C)\, O_{i-1} \qquad \text{...(18)}$$

Where, O_i = Outflow in cumecs from catchment at the end of the period i,
I_i = Inflow in cumecs from each area at the end of the period i and
C = Dimensionless routing constant.

The value of constant C is given by,

$$C = \frac{t}{R + 0.5t} \qquad \text{...(19)}$$

Where, t= Computational time interval in hours and
R=Storage coefficient in hours.

R can be assigned average value of Q/dQ/dt at the point of inflexion computed from observed flood hydrographs.

Application to Morel catchment

Computation of T_c and R values

As inflow hydrograph at the dam site is not available it is not possible to compute the values of T_c and R from the observed records. In the absence of any information, data of CWC report "Flood Estimation for Chambal Basin sub zone - 1(b)" published in the year 1988, has been used for computation of T_c and R for the Morel catchment. Using physiographic characteristics of the catchments and region based relationships, various unit hydrograph parameters i.e. time to peak, peak discharge, base length, W_{50}, W_{75},

WR_{50} and WR_{75} have been derived by CWC. The meaning of these terms is explained in Figure 4 and values of these parameters for all 19 catchments and other relevant details are given in Table 3. All the 19 catchments are used in the analysis

Looking at the Figure 2 it is found that Morel catchment is located just at the north boundary of the sub-zone 1-b. To explore the regional values of T_c and R further, bridge catchments of nearby sub-zones namely 1-a and 1-e, laying nearer to the boundary of Morel catchment, are also investigated. Details of selected bridge catchments used in the study and, the parameters estimated are given in Table 4.

Following sections discuss in detail, methodology adopted for computation of regional values of T_c and R using the given unit hydrograph parameters of :

Case I- (a) all 19 bridge catchments of sub zones 1-b and,
Case II- (b) selected 9 bridge catchment of sub zones 1-b, 1-e and 1-a.

Computation of regional values of T_c and R

To each representative bridge catchment selected, initial values of T_c and R are assigned and assuming the time area diagram for the catchment as an equilateral triangle having base equal to time of concentration T_c, resulting unit hydrograph is computed. Now using the Rosenbrock (1960) optimization technique, value of T_c and R values are optimised in such a way so that resulting unit hydrograph has values of W_{50}, W_{75}, WR_{50}, WR_{75}, t_b, t_p and Q_p close to these given values for this catchment. The optimized values of T_c and R, so found, are given in the Table 3, for subzone 1-b (Case- I) and in Table 4 for the selected bridge catchments of sub zone 1-b, 1-e and 1-a (Case- II).

Regional relationship for time of concentration T_c

Having known T_c values for these catchments, a relationship on log-log paper between catchment area and T_c is developed. Similarly, relationships between T_c and L/ sqrt(s) (where L= length of the longest main channel upto the dam site and S= equivalent stream slope) and Catchment area and L/sqrt(s) are also developed. These graphs are shown in Figures 5 to 7 for Case- I and in Figures 8 to 10 for the Case- I. The best fit equation used, has the following form :

$$Y = \exp[A \times \ln(X) + C] \qquad ...(20)$$

Where, A is intercept and C is a constant.

Parameters of the best fit line are given in Table 5.

Regional relationship for Storage coefficient (R)

It was tried to develop a relationship between R and Catchment area or R and L/sqrt(s) but so significant correlations were observed. Therefore, for further analysis a median value of ratio of $R/(T_c + R)$, which, should be constant for a catchment and should not vary much for a region, has been considered from Tables 3 and 4.

For sub zone 1-a i.e. Case- I, median value of ratio of $R/(T_c + R)$ has been computed as 0.18 while for Case-II its values has been found out as 0.25.

To see whether developed regional relationship holds good for the region or not, based on L/sqrt(S) and T_c relationship, for each catchment of sub zone 1-b, based on its L/sqrt(S) value, value of T_c is computed. Having known T_c and value of ratio $R/(T_c + R)$, R is computed. Using these values and Clark model, for each catchment one hour unit hydrograph is developed. For each catchment of sub zone 1-b, this unit hydrograph and the unit hydrograph obtained by using optimised values of T_c and R is plotted. Figures 11a to 11e show these plots.

Use of regional relationship for computation of T_c and R values for Morel catchment

Catchment area (CA) of Morel catchment has been computed as 3320 sq. Km., length of longest main stream upto dam site = 111.6 km. and equivalent stream slope S=1.30 m/km. Value of L/sqrt(S) is worked out as 98.67. Based on the above relationships between Tc and CA and Tc and L/sqrt(S) and using the values of CA and L/sqrt(S), for Morel catchment value of T_c has been computed for both the cases. These computed values of T_c are substituted in the relation $R/(T_c+R)$ to get R values. Table 6 shows these computed values.

For the Case-I, average values of T_c and R are considered as 24 hours and 5.27 hours respectively. Similarly, for the Case-II, these values are adopted as 20 hours and 6.79 hours respectively.

Computation of unit hydrograph for Morel catchment

Having known the values of Clark model parameters time of concentration, T_c and storage coefficient, R, time area diagram needs to be calculated. Based on natural channel network, T_c and time area diagram have been computed as shown in Table 7. It gives the time of concentration, T_c as 23 hours. Now, having known the catchment area and shape of time area diagram, for T_c = 24 hours and Tc = 20 hours, area contributed at every hour is computed from cumulative time area diagram.

Using the T_c, R, catchment area and time area diagram details, ordinates of one hour unit hydrograph are computed for both the cases. Table 8 shows these details. From this table, values of T_p, T_b and Q_p for both the cases, are worked out as 16 hrs., 51 hrs. and 549 cumecs and 14 hrs., 58 hrs. and 560 cumecs.

Development of unit hydrograph using GIUH approach

Rodriquez-Iturbe and Valdes (1979) first introduced the concept of geomorphologic instantaneous unit hydrograph, which led to the renewal of research in hydrogeomorphology.

The expression derived by Rodriquez-Iturbe and Valdes (1979) yields full analytical, but complicated, expressions for the instantaneous unit hydrograph. Rodriquez-Iturbe and Valdes (1979) suggested that it is adequate to assume a triangular instantaneous unit hydrograph and only specify the expressions for the time to peak and peak value of the IUH. These expressions are obtained by regression of the peak as well as time to peak of IUH, derived from the analytic solutions for a wide range of parameters with that of the geomorphologic characteristics and flow velocities.

The expressions are given as:

$$q_p = 1.31\ R_L^{0.43}\ V/L_\Omega \qquad \text{...(21}$$

$$t_p = 0.44(L_\Omega/V)(R_B/R_A)^{0.55}(R_L)^{-0.38} \qquad \text{...(22)}$$

where;

L_Ω = the length in kilometers of the main stream
V = the expected peak velocity, in m/sec.
q_p = the peak flow, in units of inverse hours
t_p = the time to peak, in hours
R_B,R_L,R_A = the bifurcation, length and area ratios given by the Horton's laws of stream numbers, lengths and areas respectively.

Empirical results indicate that for natural basins the values for R_B normally ranges from 3 to 5, for R_L from 1.5 to 3.5 and for R_A from 3 to 6 [Smart (1972)].

On multiplying eq. (21) and (22) we get a non-dimensional term q_p x t_p as under.

$$q_{pg} \times t_{pg} = 0.5764\,(R_B/R_A)^{0.55}\,(R_L)^{0.05} \qquad \text{...(23)}$$

This term is not dependent upon the velocity and thereby on the storm characteristics and hence is a function of only the catchment characteristics. This is also apparent from the expression given above.

For the dynamic parameter velocity (V) , Rodriquez et. al. (1979) in their studies assumed that the flow velocity at any given moment during the storm can be taken as constant throughout the basin. The characteristic velocity for the basin as a whole changes throughout as the storm progresses. For the derivation of GIUH, this can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin.

Application to Morel catchment

For application of GIUH approach, catchment area, time area diagram, R_B,R_L,R_A ratios and velocity V are need to be known. These geomorphological characteristics for a basin, other than the velocity may easily be derived using a Geographical Information System (GIS). GIS is a computer based system for storage, retrieval, manipulation, analysis and display of spatial and associated attributes of a catchment. The input to a GIS may be remotely sensed data, digital models of the terrain, or point or aerial data compiled in the forms of maps, tables or reports. GIS provide a digital representation of watershed characterisation used in hydrologic modelling. Hydrological modelling is one of the most important application of a GIS system.

Computation of the parameters required for geomorphologic study using manual methods like area measurement using dot grid method or using planimeter and length measurement using curvimeter are very tedious and time consuming. Also, an important drawback is that these detailed manual measurements of the attributes are difficult to be scrutinised for any error at a later date. It is much more difficult if the map is on higher scale like 1:50,000 and 1:25,000. On the other hand, by using a GIS, one has the detailed measurements available on the computer media which may easily be retrieved any time and modified for any type of error made earlier. Also, all the digitized information may be displayed on the monitor or printed for verifying if the various attributes have been correctly taken. The scope of the manual error is thus brought to a minimum level by employing a GIS. In the present work the stream ordering, calculation of various geomorphological characteristics like numbers, lengths, areas of each order are found using GIS technique. In GIS environment the derivation of time-area diagram is significantly easier. The time area diagrams in non-dimensional form was prepared by assuming that the time of travel between any two points is proportional to the distance and inversely proportional to the square root of the slope between them. Starting from the basin outlet, the relative time of travel of various points over the catchment is thus progressively calculated. The values of the relative time of travels for all these points are then denoted on the map and were transferred in the digital form in GIS. Using interpolation technique a map of relative time distribution was then drawn through these points.

Use of GIS has not only made this task relatively easy but accurate as well. ILWIS package is used in this study because of its versatility, efficiency in digitizing and attribute entry, editing capabilities etc. Various geomorphologic parameters calculated for Morel catchment using ILWIS package are shown in Table 9. To calculate the average stream area corresponding to a stream order, graphs between stream order and log of average stream length, stream order and log of stream numbers are plotted and slope of the best fit lines passing through these points is computed. For stream number this slope is nothing but R_B, while for stream length it is R_L. To compute average area for each stream order, the relationship between area andlength in terms of Horton's laws of drainage-network composition, as proposed by Hack (1957) has been used. The relationship relates the area A_u of a basin of order u with the bifercation ratio R_B and R_{LB}, the ratio of length ratio to bifurcation ratio as follows.

$$A_u = \bar{A}_1 R_B^{u-1} \frac{R_{LB}^u - 1}{R_{LB} - 1} \qquad ...(24)$$

Finally a graph between stream order and average area is plotted and the slope of the best fit line passing through these points is computed (R_A). These graphs are shown as Figure 12.

For ungauged catchments like the present case, the peak discharge is not known and so the criteria for estimation of velocity based on peak discharge cannot be applied. For the present case, for each representative bridge catchment velocity is estimated based on available length (L) and computed time of concentration T_c (Tables 3 and 4) for both the cases using the following relationship

$$V = 0.2778 \times L / T_c \qquad ...(25)$$

Computed values of velocity V in metre/sec are tabulated in Tables 3 and 4. A significant variation in the values of V has been observed. Also from geomorphological analysis, T_c value for the Morel catchment has been worked out as 22.6 hours and length of longest stream channel as 111.4 kilometers. Using these values, velocity comes out as 1.37 m/sec. This appears to be considerable low during high floods. Based on the cross sectional details of Morel river at the dam site, its area (11275 sq. m) and wetted perimeters (4100 m) are calculated and assuming Manning's roughness coefficient as 0.035, and slope of water profile is assumes and equivalent bed slope (1.3m/km), velocity comes out as 2.3 m/sec. Discharge based on this velocity and cross sectional area comes out as 24900 cumecs. However, in the absence of sufficient data, for Morel catchment velocity has been assumed as 2.5 m/sec for further analysis.

Using the above equation, values of various geomorphological parameters and velocity, time to peak and peak ordinates of instantaneous unit hydrograph are computed. A Clark model is fitted in such a way so that IUH of Clark model and IUH of GIUH give similar peak discharges and also similar product of time to peak and peak discharge. Time to peak and peak discharge of unit hydrograph using the GIUH approach comes out as 9 hours and 607 cumecs. Table 8 provides the details of the GIUH based unit hydrograph.

FINALISATION OF UNIT HYDROGRAPH FOR THE MOREL CATCHMENT

Time to peak and peak discharge of one hour unit hydrograph computed for Morel catchment using various approaches are tabulated in Table 10. Now, keeping in mind the methodology adopted in each case, it is clear that methods namely Snyder, SCS or CWC regional relationships are purely based on regional relationships. Clark model approach uses the parameter values T_c and R computed for the region. GIUH based approach uses geomorphological characteristics of the basin with the limitation of determination of velocity. Morel catchment being a comparatively large catchment, variability in rainfall and physiography within the catchment is bound to effect the runoff. However, as proposed by Leopold and Maddock (1954), for basins of larger size the routing of flow through channel network dominates the peak flow. Therefore, for picking up the unit hydrograph for this catchment, unit hydrographs as developed by using Clark model and GIUH approach have been considered for computation of design flood hydrograph. Moreover as GIUH approach considers the peak velocity in determination of time to peak and peak discharge, it automatically adjusts the time to peak corresponding to the velocity. These selected one hour unit hydrographs are shown in Figure 13.

DETERMINATION OF DESIGN RAINFALL

Details of existing storms in the catchment

During the past, many heavy storms have occurred in this region. As mentioned in the paper by Dhar, one day and two days DAD values and storm period of these storms are reproduced here in Table 11.

Based on this table and the area of Morel catchment it appears that the storm of 18-19th July, 1981 has been the severe most for this catchment. This storm was centred in the catchment of the Morel dam. Daily rainfall data of the raingauge stations for the storm period has been got analysed by Govt. of Rajasthan in their report (1995) and after examining the data same has been adopted. Two bell per day, distribution of rainfall is considered appropriate here and incremental and critical distribution of rainfall is given in Table 12.

COMPUTATION OF DESIGN FLOOD HYDROGRAPH FOR MOREL CATCHMENT

For computation of design flood hydrograph, apart from rainfall and unit hydrograph details, information about the design loss rate and baseflow rate are also needed. Based on the CWC reports of sub zones, design loss rate has been assumed as 2 mm per hour and base flow as 0.05 cumecs per sq. km of catchment area. Thus, baseflow works out as 167.25 cumecs.

Design rainfall considering the two days and four bell pattern as already discussed in earlier section is superimposed on the selected one hour unit hydrographs for the basin. Resulting design flood hydrographs are shown in Figure 14 and ordinates are given in Table 8. From this table, for first case (Case-I), Tp and Qp work out as 32 Hours and 22663 cumecs respectively. For second case (Case-II) corresponding values are 31 hrs and 22387 cumecs respectively. Similarly, resulting flood hydrograph obtained using GIUH unit hydrograph gives Tp and Qp as 27 Hours and 21585 cumecs respectively.

DISCUSSIONS

Some commonly used methods have been tried to get representative unit hydrograph for the Morel catchment. In the absence of observed data, Regional relationship as developed by CWC, the Snyder method, SCS method, Clark method and GIUH based method have been tried. Parameters of Clark model have been estimated utilising regional information of other gauged catchments. Clark model has the advantage over other methods as it completely defines the shape of the unit hydrograph while other methods provide information about discharge and time at some specific locations only. Based on the analysis, it is difficult to mention which approach is the best and should be adopted for computation of design flood, however, as mentioned earlier, Clark model which utilises two parameters , time of concentration and storage coefficient only, apart from time area diagram, can be considered more reliable and scientific. Time area diagram and time of concentration can be estimated accurately from the topographic details without much difficulty. Flood hydrograph as computed using Clark model and GIUH based approach, give similar peak discharges, therefore for further use these values can be adopted for the catchment. As in the present analysis, regional values of Clark model parameters have been proposed, for other ungauged catchments, located in this region, unit hydrograph can be computed using these values.

For the present analysis, regional relationships developed for sub-zones 1-b, 1-a and 1-e have been used. Regional relationships so developed using information of small catchments has following limitations :

(i) The catchment 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.

(ii) While establishing such regional relations, the inherent limitations of the unit hydrograph theory are also being carried out with it. As a result the prevailing method of predicting the discharge hydrograph for a design storm by using the average unit hydrograph will not be appropriate, since the average unit hydrograph does not necessarily reproduce the actual response due to such inherent limitations.

(iii) The relationship evolved are based upon the gauged observations in number of catchments in the region. It is practically very difficult to always have gauged catchments available in adequate numbers in a region to enable the development of such relationships.

(iv) Generally, the data for intense and short duration storms are not available for the derivation of average unit hydrograph for gauged catchments. Hence the average unit hydrograph derived from minor flood events is considered for the regionalisation. It may result in the under estimation of design flood for ungauged catchments.

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Table : 1 Locational and other details of selected bridge catchments of sub zone 1-b

Sr. No.	Name of stream	Name of section where bridge is located	Railway bridge no.	Latitude	Longitude	catchment Area (Sq.Km.)
1	Kali Sindh	Ujjain -Bhopal W/R	94	23° 21′ 05′	76° 26′ 30′	2297.33
2	Chambal	Ajmer-Khandwa W/R	519	23° 01′ 50′	75° 31′ 00′	1613.60
3	Sipra	Indore-Ujjain W/R	72	22° 55′ 20′	75° 58′ 35′	662.81
4	Chakan	Nagda-Mathura W/R	283	25° 48′ 10′	76° 16′ 14′	587.63
5	Dhund	Jaipur-Bandikui W/R	198	26° 50′ 30′	75° 56′ 30′	419.13
6	Chopan	Guna-Maksi W/R	221	24° 31′ 00′	77° 10′ 08′	361.05
7	Kadmali	Ajmer-Khandwa W/R	272	24° 36′ 30′	74° 42′ 35′	349.13
8	Ghorapa Chhar	Guna-Mkasi W/R	140	24° 03′ 40′	76° 57′ 45′	274.33
9	Maleni	Ajmer-Ratlam W/R	437	23° 31′ 25′	75° 05′ 08′	237.14
10	Gudla	Jaipur-Swaimadhopur W/R	39	26° 16′ 20′	76° 00′ 00′	145.45
11	Baitlii	Kota-Bina W/R	51	24° 38′ 10′	76° 58′ 10′	140.43
12	Kilor	Nagda-Mathura W/R	44	23° 59′ 55′	75° 38′ 02′	108.78
13	Tributory of Chambal	Ajmer-Khandwa W/R	495	23° 06′ 35′	75° 19′ 45′	66.30
14	Sarwani	Ajmer-Khandwa W/R	406	23° 43′ 40′	75° 06′ 28′	47.44
15	Iatia	Jaipur-Kota W/R	1	26° 00′ 39′	76° 21′ 00′	44.75
16	Dhobi	Ratlam-Nagda W/R	306	23° 26′ 15′	75° 16′ 25′	43.77
17	Khinjra	Nagda-Kota W/R	118	24° 30′ 45′	75° 54′ 15′	41.44
18	Iliyakhal	Ujjain-Bhopal W/R	35	23° 23′ 42′	76° 41′ 40′	39.52
19	Paranga	Ratlam -Ajmer W/R	77	26° 06′ 24′	74° 41′ 21′	26.18

Table : 2 Coefficients C_t and C_p for some neighbouring catchments

Bridge No.	CA (sq km)	L(km)	L_{ca}	t_p	Q_p	C_t	C_p
94	2297.33	111.0	66.0	22.5	316.0	1.50	3.09
519	1613.60	90.0	46.0	10.5	395.0	0.86	2.57
72	662.81	47.0	28.0	8.5	180.3	0.98	2.31
283	587.63	30.0	14.0	5.5	330.0	0.90	3.09
198	419.13	38.0	20.0	4.5	320.0	0.61	3.44

Table : 3 **Representative one hour unit hydrograph parameters, catchment area and other details of selected catchments sub zone 1-b**

Bridge No.	Area in Sq. Km.	Tp in Hrs.	Qp in cumecs	Tb in Hrs.	L in km.	L/ sqrtS	Tc in Hrs	R in Hrs.	R/ (Tc +R)	velocity in m/sec
94	2297	22.5	316	47	111	110	37	2.5	0.06	0.84
519	1614	10.5	395	40	89.8	81.3	16	3.56	0.18	1.56
72	663	8.5	180	32	46.7	38.6	15	3.33	0.18	0.00
283	588	5.5	330	18	30	24.6	8.9	2.45	0.22	0.94
198	419	4.5	320	15	37.8	25.9	8.1	1.33	0.14	1.30
221	361	3.5	280	12	38.6	22.3	6.5	0.96	0.13	1.64
272	349	3.5	233	12	30.6	19.9	6	1.3	0.18	1.42
140	274	3.5	300	9	23.2	16.9	6	0.74	0.11	1.07
437	237	3.5	135	12	28.3	16.2	6.9	1.27	0.16	1.14
39	145	2.5	90	13	14.5	9.75	3.2	2.1	0.40	1.26
51	140	2.5	80.6	11	29.4	19.2	3.5	1.74	0.33	2.33
44	109	2.5	90	12	15.8	8.64	3.8	1.58	0.29	0.00
495	66.3	4.5	33.3	15	19.8	14.9	7.6	1.58	0.17	0.73
406	47.4	1.5	54	8	10.8	5.45	2.1	1.05	0.33	1.43
1	44.8	1.5	58	7	17.2	7.34	2.8	0.61	0.18	1.72
306	43.8	1.5	20	14	13.7	7.78	1.6	2.83	0.64	2.38
118	41.4	1.5	31.1	13	12.6	6.3	1.6	2	0.55	2.18
35	39.5	2.5	30	9	12.8	12.7	4.6	0.87	0.16	0.77
77	26.2	1.5	20	10	7.56	4.56	1.9	2.15	0.53	1.09

Table : 4 **Representative one hour unit hydrograph parameters, catchment area and other details of selected catchments of sub zones 1-b, 1-e and 1-a**

Sub zone & Bridge No.	Area in Sq. Km.	Tp in Hrs	Qp in cumecs	Tb in Hrs.	L in km.	L/ sqrtS	Tc in Hrs.	R in Hrs.	R/ (Tc +R)	velocity in m/sec
283	587.6	5.5	330	18	30	24.6	8.91	2.45	0.22	0.94
1-b,198	419.1	4.5	320	15	37.8	25.9	8.05	1.33	0.14	1.30
1-b,39	145.5	2.5	90	13	14.5	9.75	3.2	2.1	0.40	1.26
1-b,77	26.18	1.5	20	10	7.56	4.56	1.93	2.15	0.53	1.09
1-b,1	44.75	1.5	58	7	17.2	7.34	2.77	0.61	0.18	1.72
Mot-3	380	3.5	280	13	60.3	35.07	5.2	1.28	0.20	3.22
527	70.55	1.5	130	7	15.8	8.09	2	0.68	0.25	2.19
672	18.49	1.5	36.8	8	7.08	3.16	1.76	0.84	0.32	1.12
184	35.87	1	35.6	8	9.45	4.53	1.02	1.58	0.61	2.57

Table : 5 Parameters of the best fit line

Sr.No.	Y	X	A	C	R^2
Considering sub-zone 1-a					
1.	L/sqrt(S)	Catchment Area	0.60404	-0.3386	0.88
2.	Tc	L/sqrt(S)	0.92	-0.8943	0.89
3.	Tc	Catchment Area	0.5628	-1.363	0.81
Considering nearby catchments					
1.	L/sqrt(S)	Catchment Area	0.644	-0.66	0.94
2.	Tc	L/sqrt(S)	0.825	-0.835	0.79
3.	Tc	Catchment Area	0.563	-1.525	0.83

Table : 6 Computed values of Tc and R for Morel catchment

Description	Value of Tc using		R/(Tc+R)	Value of R using	
	CA	L/sqrt (S)		CA	L/sqrt(S)
Considering catchments of suz-zone 1-a only	24.63	24.03	0.18	5.41	5.28
Considering nearby catchments also	20.9	19.16	0.25	7.10	6.51

Table : 7 Ordinates of time area diagram for Morel catchment

Time in Hrs	0	5	7	9	11	13	15	17	20	23
Ordinates in Km^2	0	48.5	189.2	332.7	472.4	760.3	811.9	461.6	173.7	49.4

Table : 8 **Ordinates of one hour unit hydrograph and design flood hydrograph for Case-I, Case-II and GIUH based approach.**

One hr (10 mm) unit hydrograph				Design flood hydrograph			
Time in Hrs	Ordinates in cumecs			Time in Hrs	Ordinates in cumecs		
	Clark model		GIUH		Clark model		GIUH
	Case-I	Case-II			Case-I	Case-II	
0	0	0	0	0	168.25	168.25	168.25
1	0.7	0.79	7.1	1	168.51	168.25	169.1
2	3.45	3.88	24.1	2	170.17	168.25	171.15
3	8.75	9.89	72.5	3	175.78	168.25	178.83
4	16.38	18.63	156.7	4	188.42	170.4	201.39
5	26.13	29.89	284.3	5	213.55	181.87	249.65
6	37.81	43.49	445.6	6	260.46	214.28	340.61
7	51.23	59.28	571.8	7	341.71	283.07	494.46
8	66.25	77.09	606.9	8	472.52	407.03	725.45
9	82.71	96.78	584.3	9	668.44	605.67	1054.1
10	100.49	118.22	546.6	10	943.23	896.88	1529.8
11	119.47	141.28	502.2	11	1307.3	1294.99	2209.2
12	139.54	165.85	459	12	1766.41	1809.16	3117.2
13	160.6	191.82	419.5	13	2316.22	2437.4	4224.2
14	182.56	219.09	383.4	14	2946.92	3170.16	5452.3
15	205.34	247.58	350.4	15	3659.11	4004.33	6684.1
16	228.86	277.18	320.3	16	4465.77	4943.47	7785.6
17	253.06	307.83	292.7	17	5383.18	5990.35	8676.5
18	277.88	339.44	267.5	18	6422.74	7142.77	9362.5
19	303.26	371.96	244.5	19	7586.11	8392.21	9953
20	329.15	405.31	223.5	20	8863.11	9724.92	10701
21	355.5	438.66	204.2	21	10231.82	11122.69	11892
22	382.27	469.63	186.7	22	11657.05	12559.3	13590
23	409.42	496.05	170.6	23	13094.78	14008.39	15612
24	436.93	517.44	155.9	24	14504.85	15454.32	17687
25	464.05	534.17	142.5	25	15862.42	16875.03	19531
26	488.71	546.56	130.2	26	17161.86	18228.09	20890

27	509.03	554.93	119	27	18399.39	19461.71	21585
28	524.7	559.56	108.8	28	19552.53	20525.82	21547
29	536.15	560.72	99.4	29	20581.45	21376.75	20899
30	543.75	558.64	90.9	30	21441.82	21980.86	19922
31	547.85	553.57	83.1	31	22093.47	22317.79	18906
32	548.78	545.71	75.9	32	22505.97	22387.78	18062
33	546.81	535.27	69.4	33	22662.76	22215.22	17498
34	542.21	522.42	63.4	34	22565.63	21829.49	17185
35	535.22	507.33	57.9	35	22240.63	21257.38	17007
36	526.05	490.18	53	36	21730.14	20536.63	16838
37	514.91	471.09	48.4	37	21080.92	19713.16	16570
38	501.97	450.22	44.2	38	20329.35	18828.65	16126
39	487.39	427.68	40.4	39	19493.78	17917.13	15475
40	471.33	403.6	37	40	18588.74	17006.26	14654
41	453.91	378.08	33.8	41	17632.45	16116.52	13771
42	435.26	352.01	30.9	42	16645.71	15261.56	12962
43	415.49	327.01	28.2	43	15650.09	14443.49	12315
44	394.7	303.79	25.8	44	14666.17	13656.45	11820
45	372.99	282.21	23.6	45	13713.09	12896.93	11403
46	350.44	262.17	21.5	46	12809.88	12162.84	10996
47	327.12	243.55	19.7	47	11969.81	11449.83	10561
48	303.11	226.25	18	48	11194.02	10752.21	10077
49	278.46	210.18	16.4	49	10473.01	10066.35	9534.1
50	253.94	195.25	15	50	9787.9	9391.88	8930.8
51	230.94	181.39	13.7	51	9119.62	8731.05	8285.2
52	210.02	168.5	12.6	52	8458.59	8087.11	7629.2
53	191	156.54	11.5	53	7803.83	7462.77	6992.7
54	173.7	145.42	10.5	54	7158.79	6859.7	6395.7
55	157.96	135.09	9.6	55	6529.34	6276.6	5849.3
56	143.65	125.5	8.8	56	5921.67	5710.75	5355.2
57	130.64	116.58	8	57	5343.82	5160.35	4906.9
58	118.81	108.3	7.3	58	4801.2	4628.38	4498.3

59	108.05	100.61	6.7	59	4293.88	4122.06	4125.6
60	98.26	93.46	6.1	60	3817.69	3647.89	3785.1
61	89.36	86.83	5.6	61	3368.52	3211.06	3473.8
62	81.27	80.66	5.1	62	2946.61	2814.17	3189.4
63	73.9	74.93	4.7	63	2556.23	2458.95	2929.4
64	67.21	69.61	4.3	64	2202.32	2145.92	2691.8
65	61.12	64.67	3.9	65	1884.49	1872.91	2474.6
66	55.59	60.07	3.6	66	1601.64	1636.32	2276.2
67	50.55	55.81	3.3	67	1355.39	1431.76	2094.8
68	45.97	51.84	3	68	1145.36	1255.28	1929
69	41.81	48.16	2.7	69	969.21	1103.25	1777.5
70	38.02	44.74	2.5	70	823.13	972.55	1639
71	34.58	41.56	2.3	71	702.74	861.51	1512.5
72	31.45	38.61	2.1	72	604.36	765.23	1396.8
73	28.6	35.87	1.9	73	525.77	679.79	1291.1
74	26.01	33.32	1.7	74	462.46	604.64	1194.4
75	23.65	30.95	1.6	75	410.67	538.86	1106.1
76	21.51	28.76	1.4	76	368.29	481.62	1025.4
77	19.56	26.71	1.3	77	332.59	432.24	951.67
78	17.79	24.82	1.2	78	301.94	390.1	884.26
79	16.18	23.05	1.1	79	276.16	354.72	822.64
80	14.71	21.42	1	80	254.62	326.54	766.33
81	13.38	19.9	0.9	81	236.83	303.67	714.87
82	12.17	18.48	0.8	82	222.34	284.39	667.83
83	11.07	17.17		83	210.74	268.14	624.84
84	10.06	15.95		84	201.89	253.55	585.28
85	9.15	14.82		85	195.68	239.98	549.26
86	8.32	13.77		86	190.78	227.89	516.19
87	7.57	12.79		87	186.73	217.27	485.97
88	6.88	11.88		88	182.29	208.12	457.92
89	6.26	11.04		89	178.55	200.4	431.99
90	5.69	10.25		90	175.45	194.07	407.86

91	5.18	9.52		91	173.02	189.26	385.51
92	4.71	8.85		92	171.22	186.05	364.94
93	4.28	8.22		93	169.74	183.47	346.15
94	3.89	7.64		94	168.87	181.26	329.11
95	3.54	7.09		95	168.37	178.41	313.83
96	3.22	6.59		96	168.3	175.89	300.89
97	2.93	6.12		97	168.2	173.71	288.79
98	2.66	5.69		98	168.2	171.94	276.33
99	2.42	5.28		99	168.2	170.6	264.09
100	2.2	4.91		100	168.2	169.44	252.35
101	2	4.56		101		168.76	241.33
102	1.82	4.24		102		168.35	231.26
103		3.93		103		168.3	222.34
104		3.65		104		168.25	214.75
105		3.4		105			209.22
106		3.15		106			205
107		2.93		107			201.43
108		2.72		108			198.39
109		2.53		109			195.27
110		2.35		110			191.85
111		2.18		111			188.49
112		2.03		112			185.3
113		1.88		113			182.4
114		1.75		114			179.86
115		1.63		115			177.72
116		1.51		116			176.15
				117			175.28
				118			174.6
				119			173.98
				120			172.86
				121			171.8
				122			170.82

				123			170
				124			169.35

Table : 9 Geomorphological characteristics of the Morel catchment

Basin	Order	No. of Streams	Average Length (kms.)	Average Area (sq.kms.)	Value of Constants
Morel Catchment Area=3320 sq. km. L=111.6 kms.	1	219	3.061	7.91	$R_b=3.00$
	2	64	4.689	34.15	$R_l=1.35$
	3	21	8.309	115.85	$R_a=3.30$
	4	7	12.097	363.52	
	5	2	19.715	1105.92	
	6	1	10.000	3320.03	

Table : 10 Time to peak, peak ordinate and base period of one hour unit hydrograph (10 mm) computed using various approaches

Sr. No.	Approach used		Peak (cumecs)	Time to peak (hrs.)	Base period (hrs.)
1.	Regional relation developed by CWC		800	15	85
2.	Snyder approach		650	13	110
3.	SCS Approach		715	25	125
4.	Clark Model	Sub zone 1b (Case-I)	540	16	51
		Nearby catchments (Case-II)	550	14	58
5.	GIUH based Unit Hydrograph		607	9	83

Table : 11 **One day and two days DAD values and storm period of observed storms for Morel catchment**

Sr. No.	Storm Period	Area in Sq. Kilometers						
		Point	259	518	777	1295	2590	3885
One Day Duration								
1.	27/7/1913	371	363	358	353	343	323	310
2.	30/6/1937	488	455	422	401	376	333	316
3.	29/6/1945	383	376	373	368	363	348	334
3.	19/7/1981	560	550	545	540	528	500	472
Two Day Duration								
1.	27/7/1993 -28/7/1913	478	467	462	455	442	411	391
2.	30/6/1937 - 1/7/1937	904	831	794	760	701	610	554
3.	29/6/1945- 30/6/1945	452	442	429	419	409	386	370
4.	18/7/1981 - 19/7/1981	840	822	801	783	745	680	645

Table : 12 **Incremental and critical design rainfall values for Morel catchment**

Values in mm

Time in Hours	Percentage	Incremental distribution				Critical distribution			
		Ist day		IInd day		Ist day		IInd day	
		Ist bell	IInd bell	Ist bell	IInd bell	Ist bell	IInd bell	Ist bell	IInd bell
1	14	51.0	26.3	20.7	10.6	3.7	7.3	4.4	10.2
2	28	51.0	26.2	20.6	10.7	3.8	10.9	8.8	10.6
3	41	47.3	24.4	19.2	10.2	5.6	29.1	16.3	10.7
4	54	47.4	24.4	19.2	9.8	5.7	40.1	19.2	9.8
5	65	40.0	20.6	16.2	8.4	11.2	47.3	20.7	8.4
6	76	40.1	20.7	16.3	8.4	15.0	51.0	20.6	8.4
7	84	19.1	15.0	11.8	6.0	20.6	51.0	19.2	6.0
8	90	21.9	11.7	8.8	4.6	24.4	47.4	16.7	4.6
9	93	10.9	5.7	4.5	2.3	26.3	40.0	11.8	2.3
10	96	10.9	5.6	4.4	2.3	26.2	21.9	4.5	2.3
11	98	7.3	3.7	2.9	1.5	24.4	10.9	3.0	1.5
12	100	7.3	3.8	3.0	1.5	20.7	7.3	2.9	1.5

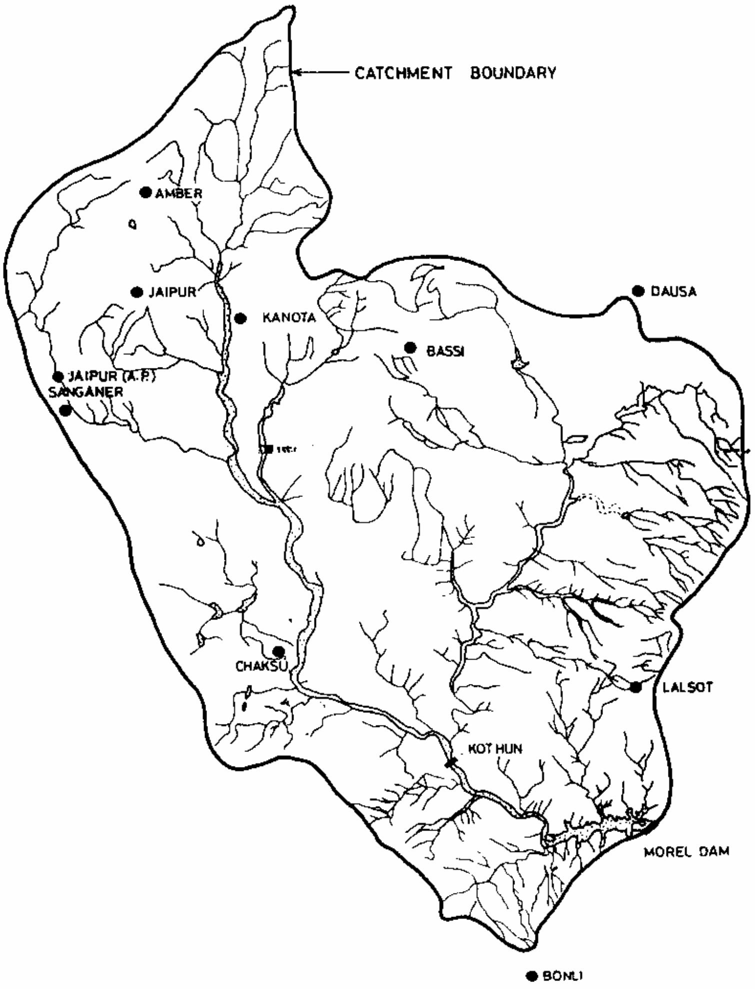

Figure 1 : Catchment map of Morel dam

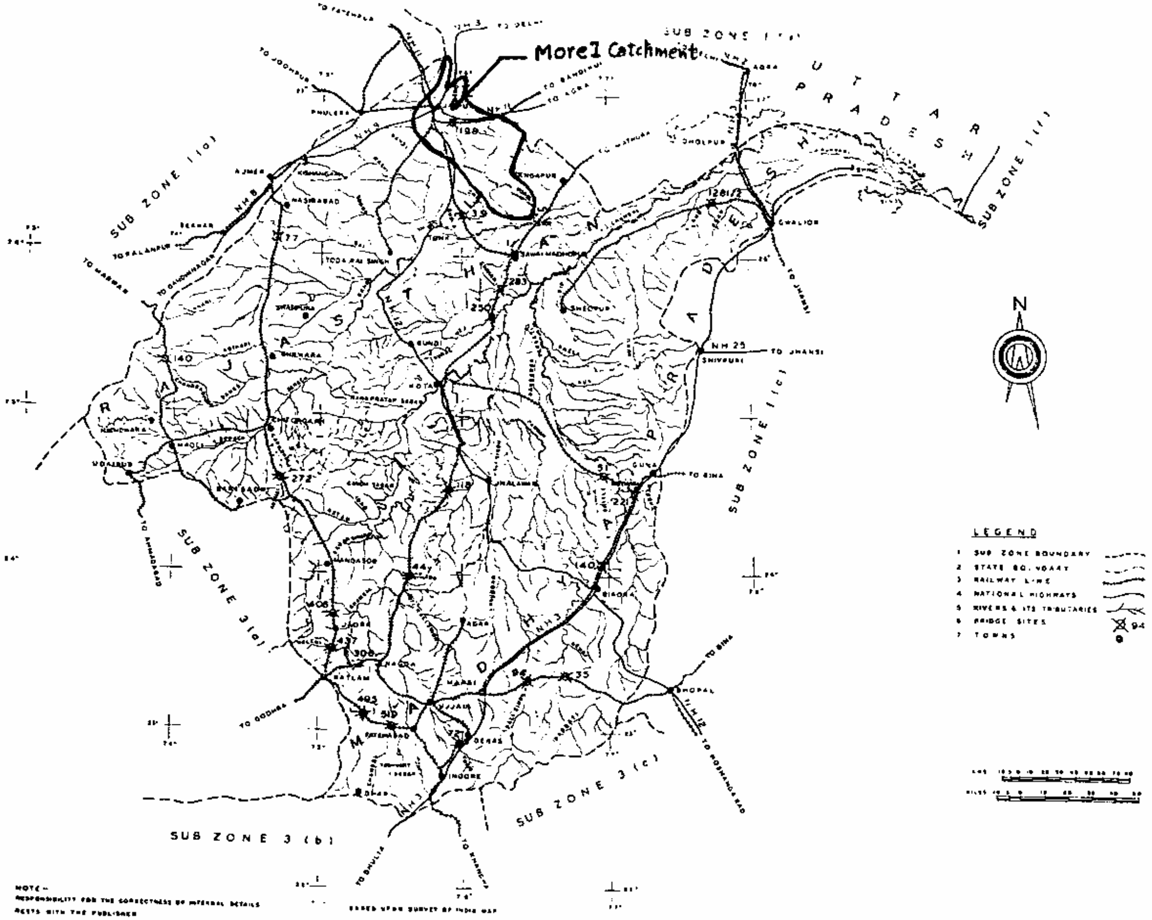

Figure 2: Map of Chambal sub zone 1-D along with location of Morel catchment

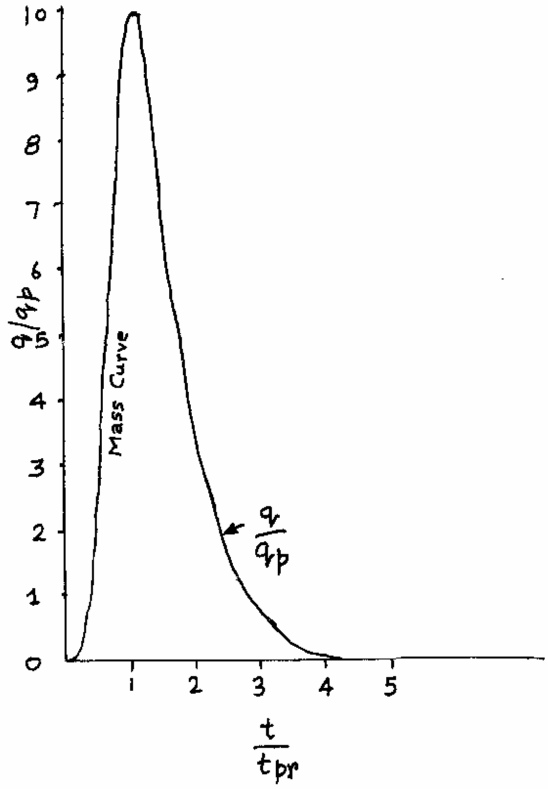

Figure 3: Dimensionless unit hydrograph used for SCS method

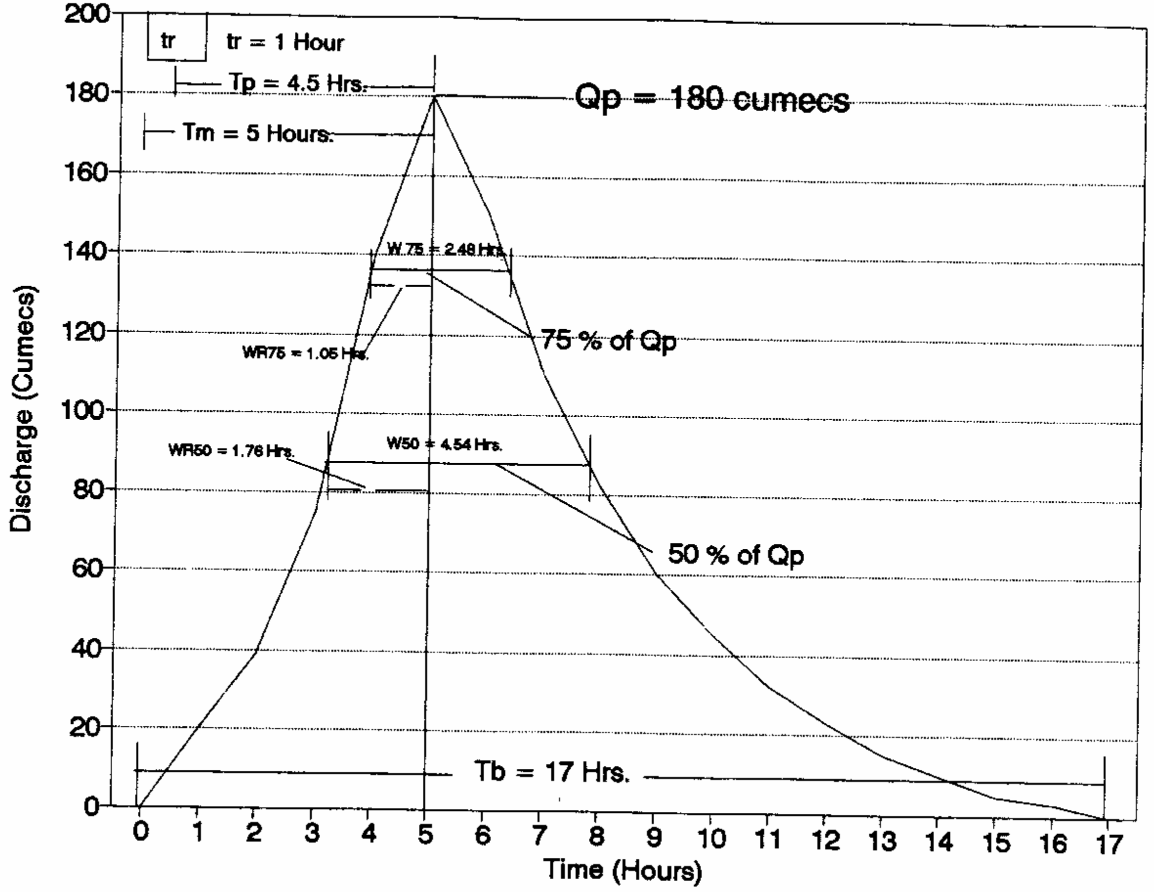

Figure 4 : Unit hydrograph characteristics

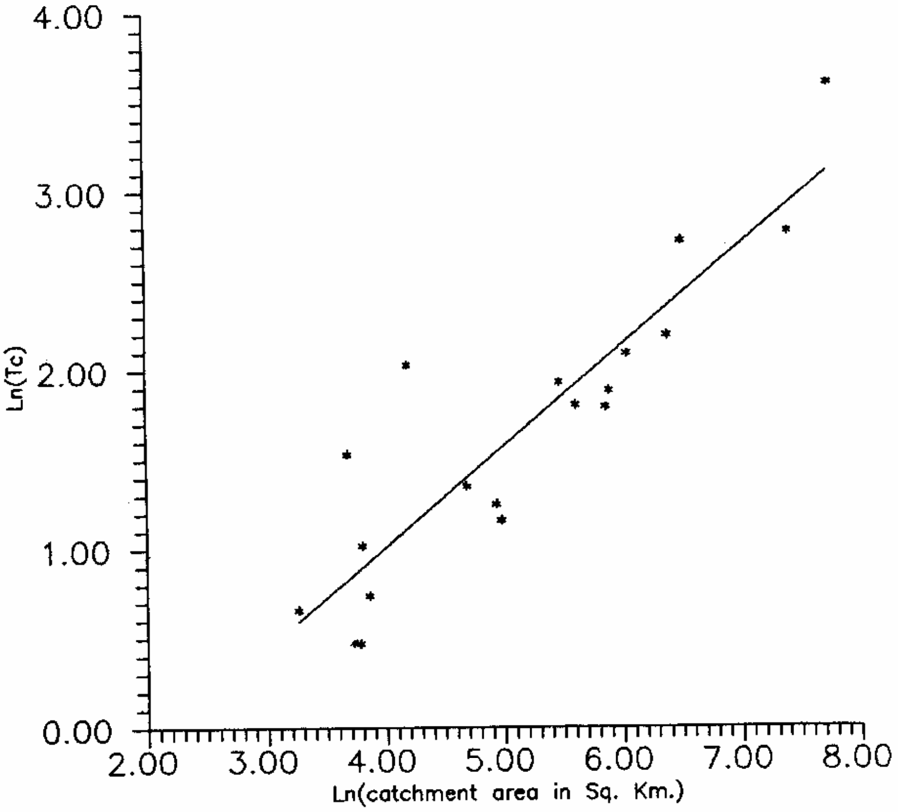

Figure 5: Best fit line between catchment area and T_c for sub zone 1-b

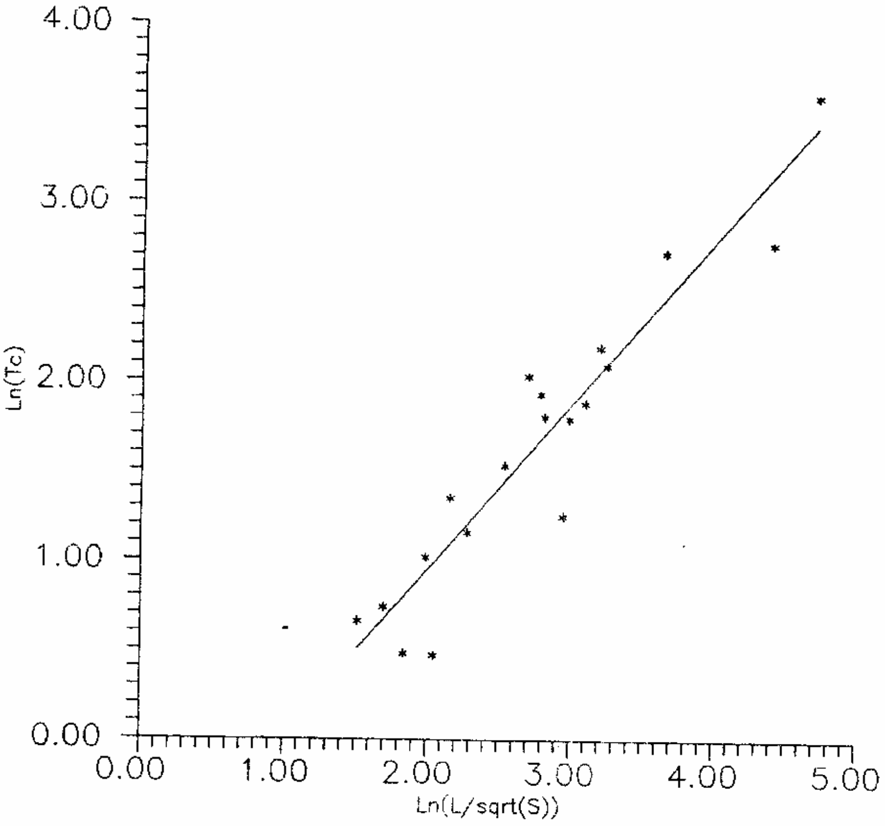

Figure 6: Best fit line between L/sqrt(S) and T_c for sub zone 1-b

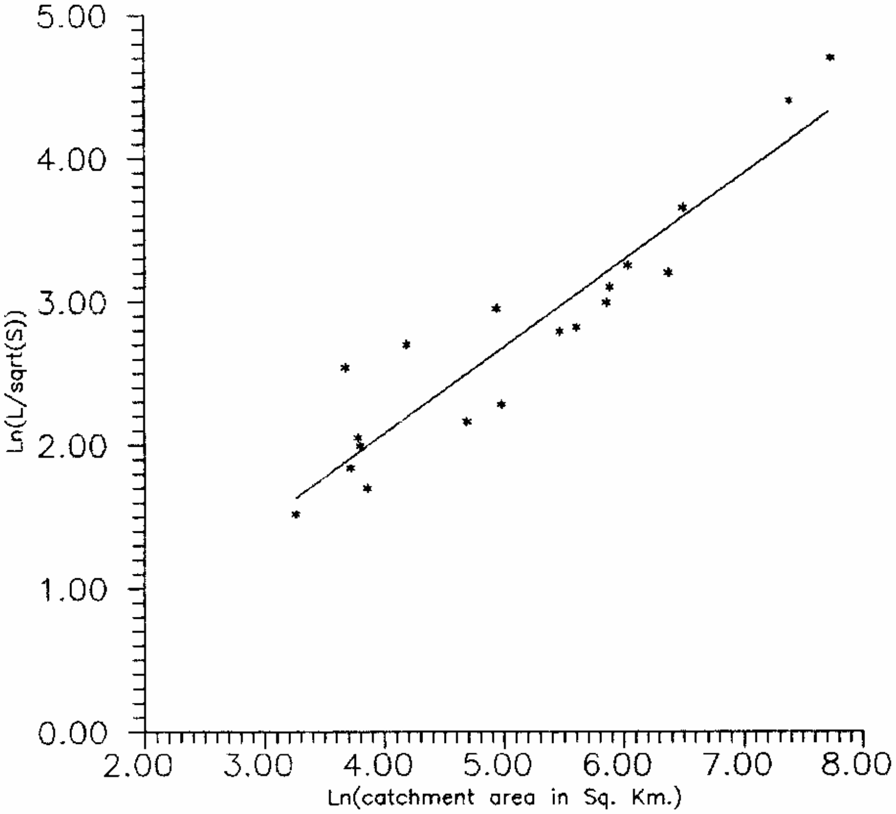

Figure 7: Best fit line between catchment area and L/sqrt(S) for sub zone 1-b

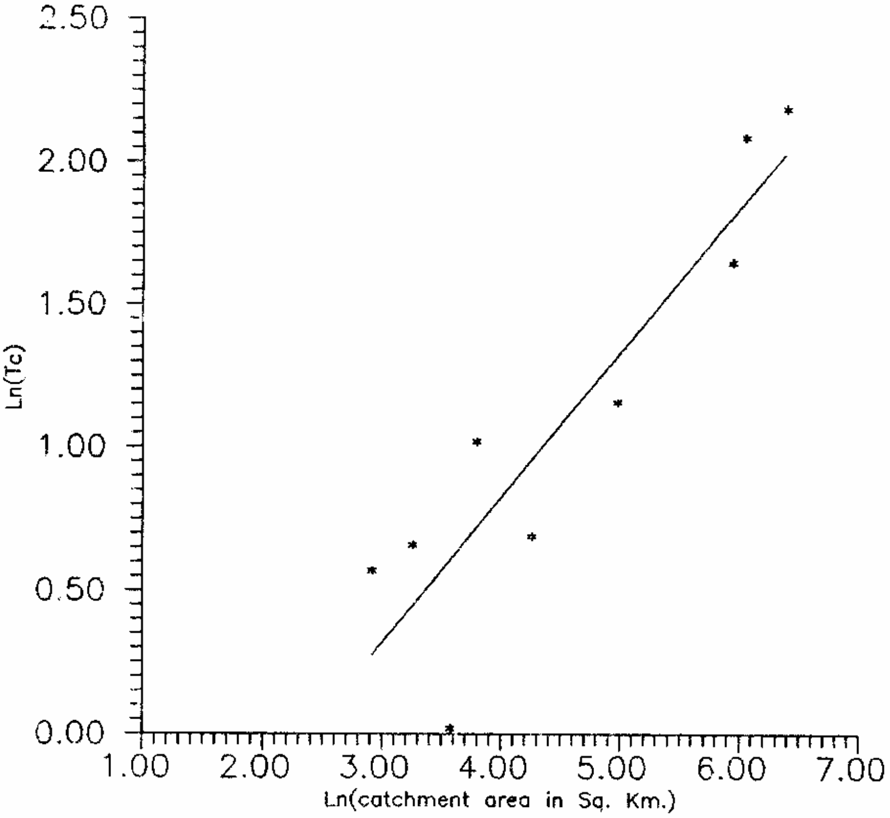

Figure 8: Best fit line between catchment area and T_c for some selected catchments of sub zones 1-b, 1-e and 1-a

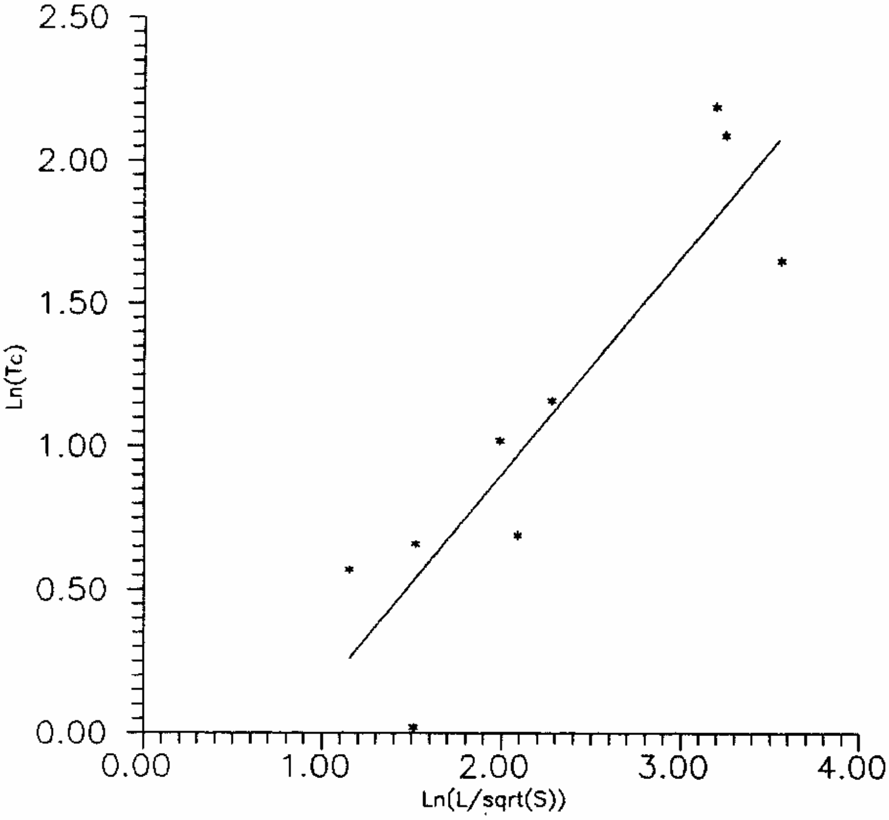

Figure 9: Best fit line between L/sqrt(S) and T_c for some selected catchments of sub zones 1-b, 1-e and 1-a

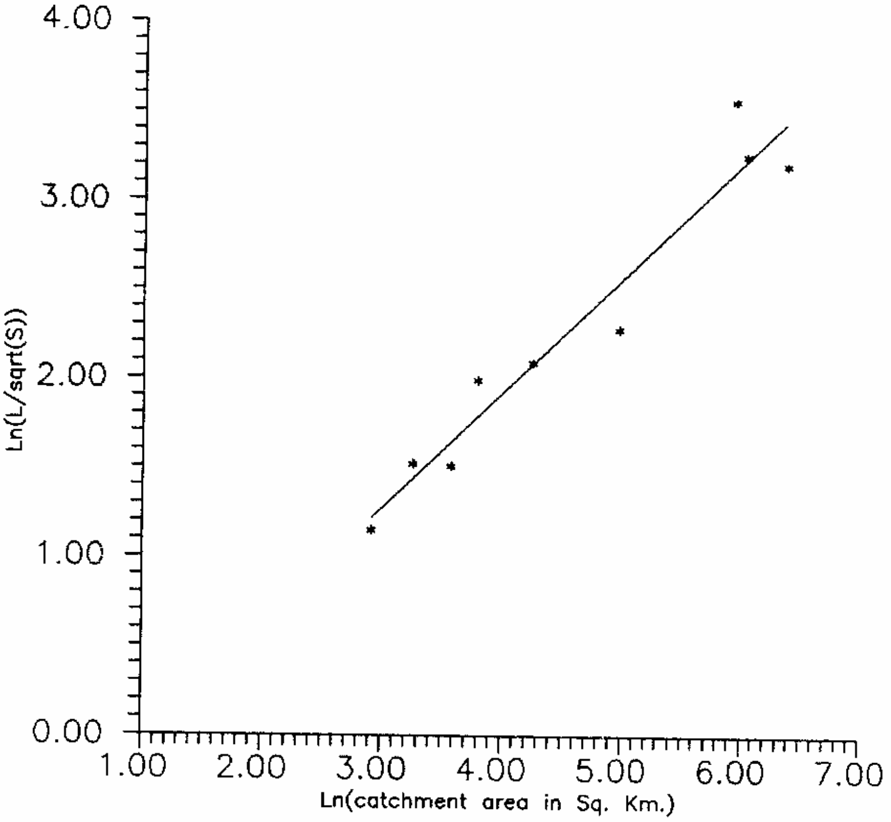

Figure 10: Best fit line between catchment area and L/sqrt(S) for some selected catchments of sub zones 1-b, 1-e and 1-a

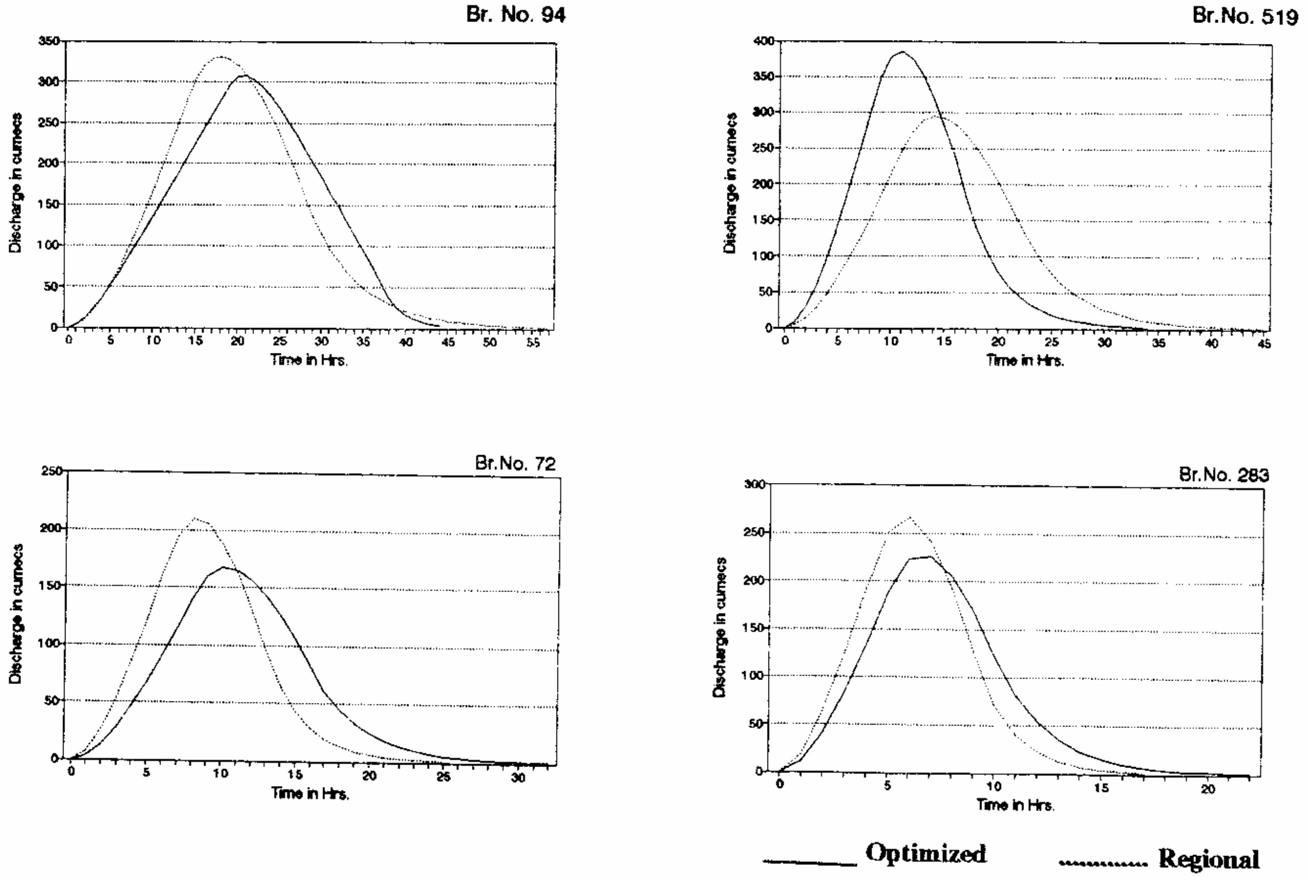

Figure IIa: One hour unit hydrograph obtained using Clark model and optimized and regional values of Tc and R for Bridge nos. 94, 519, 72 and 283

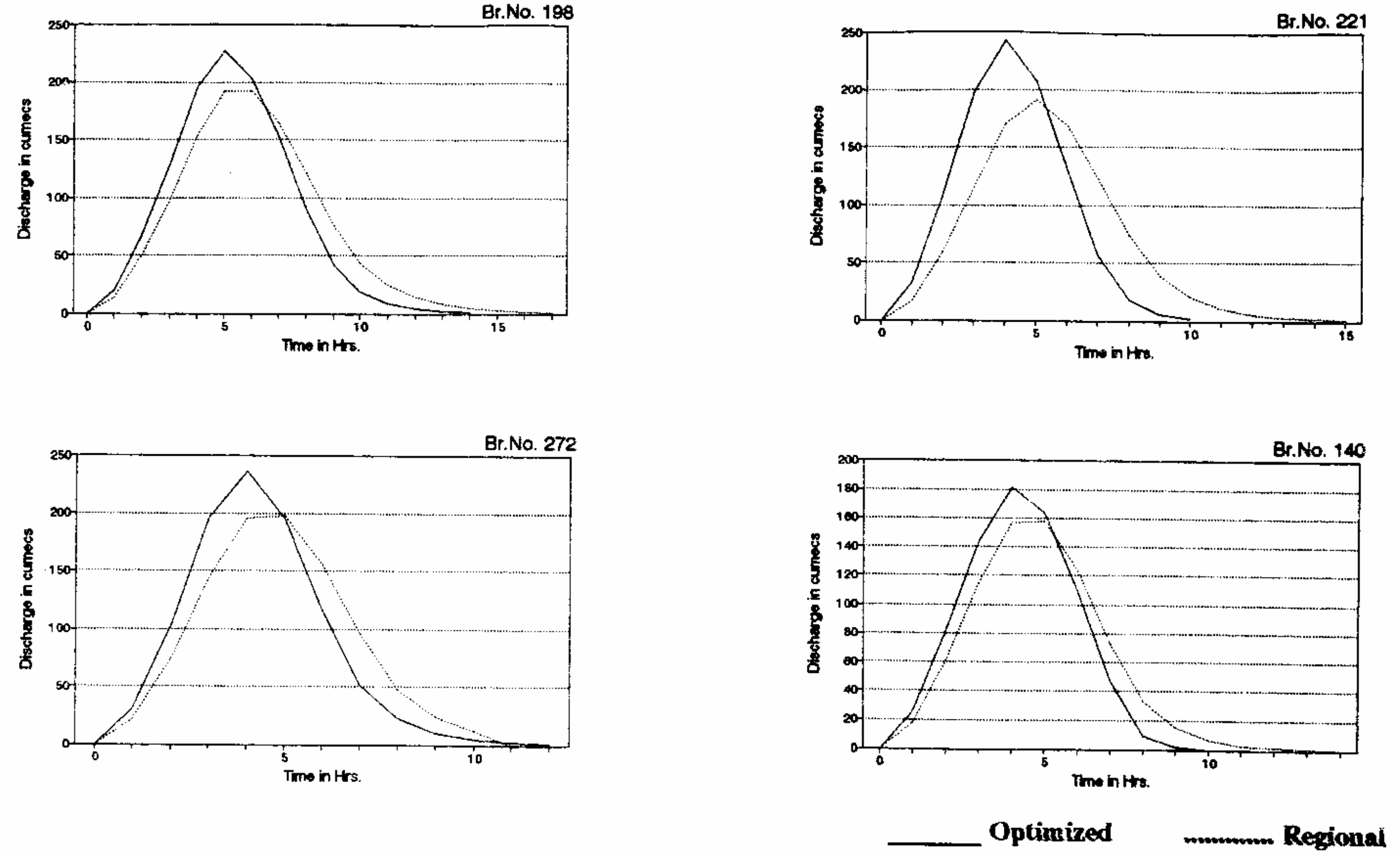

Figure IIb: One hour unit hydrograph obtained using Clark model and optimized and regional values of Tc and R for Bridge nos. 198, 221, 272 and 140

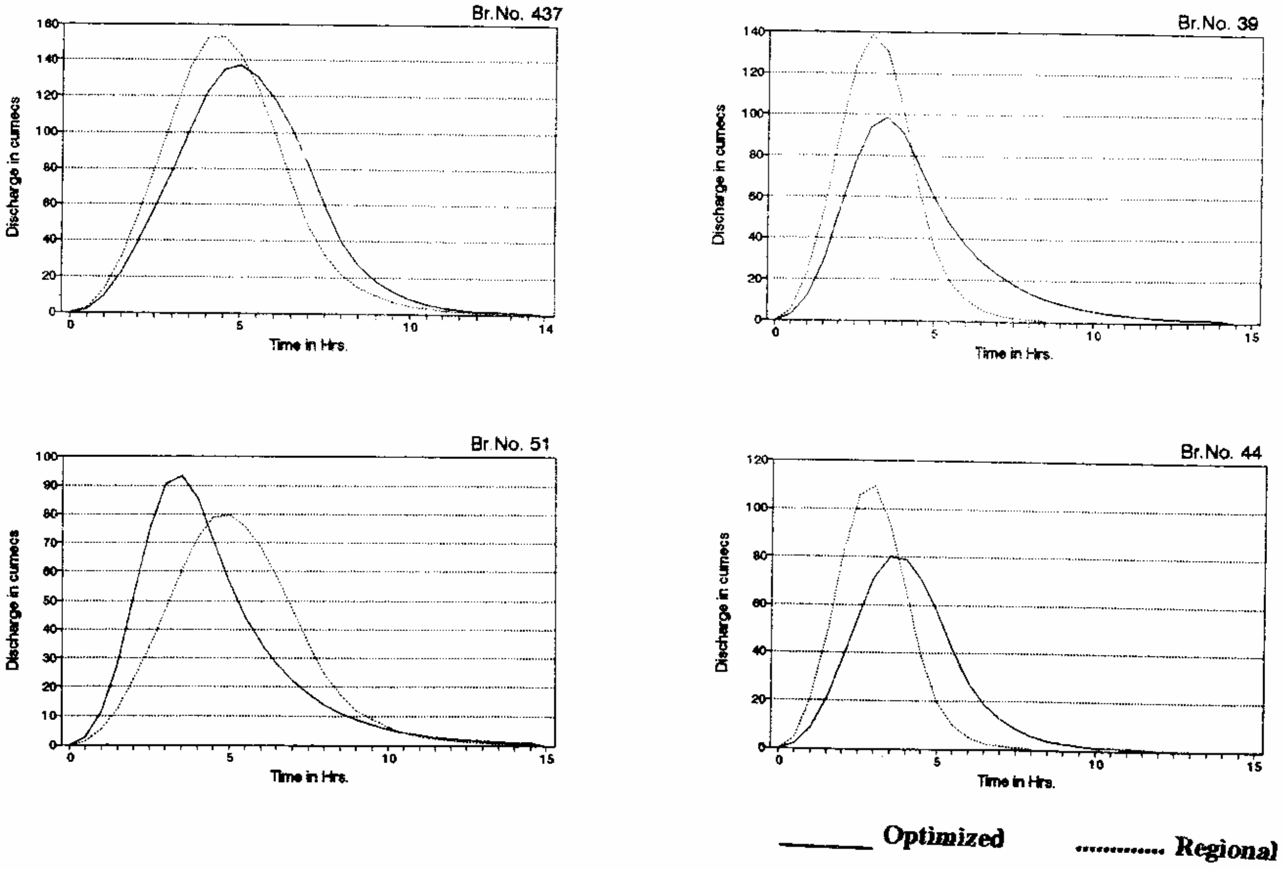

Figure 11c: **One hour unit hydrograph obtained using Clark model and optimized and regional values of Tc and R for Bridge nos. 437, 39, 51 and 44**

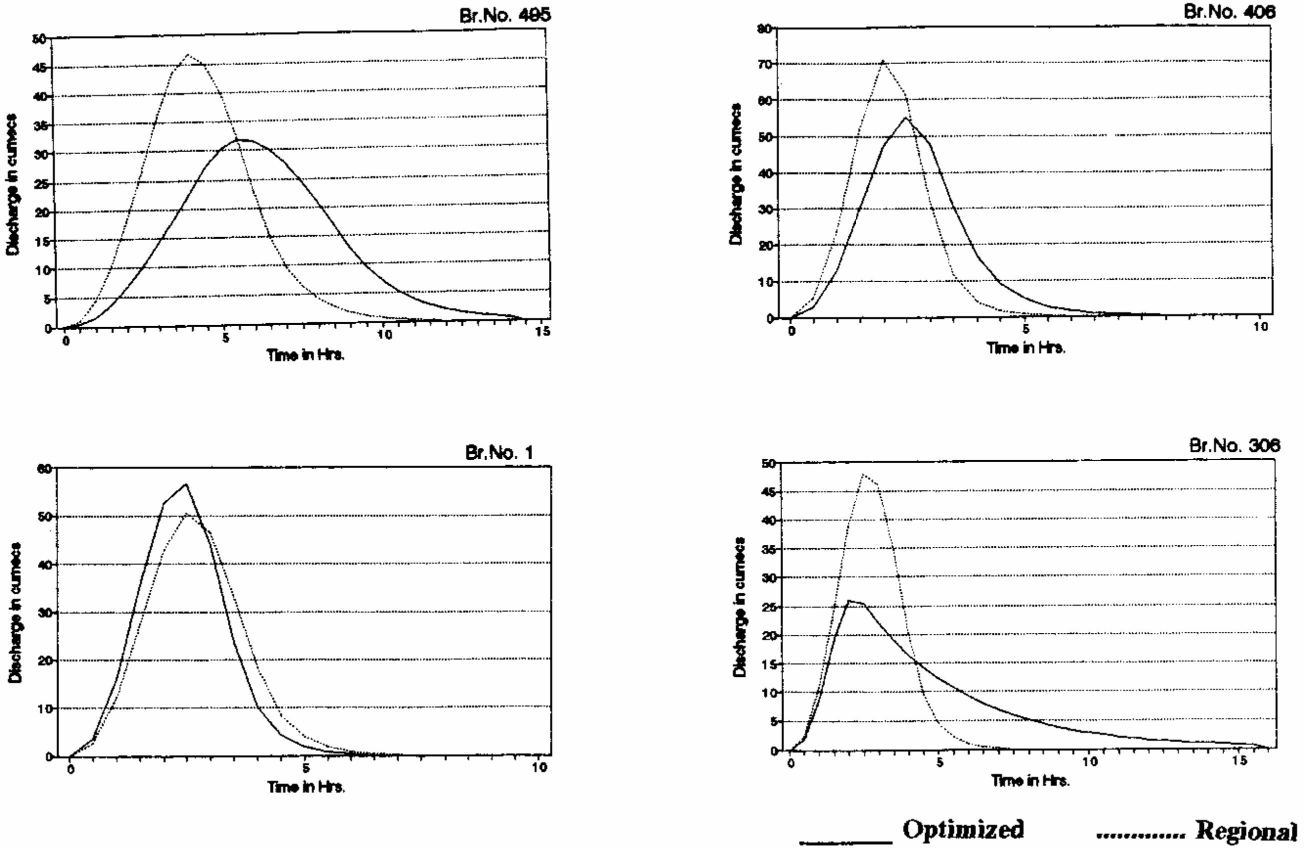

Figure IId: One hour unit hydrograph obtained using Clark model and optimized and regional values of Tc and R for Bridge nos. 495, 406, 1 and 306

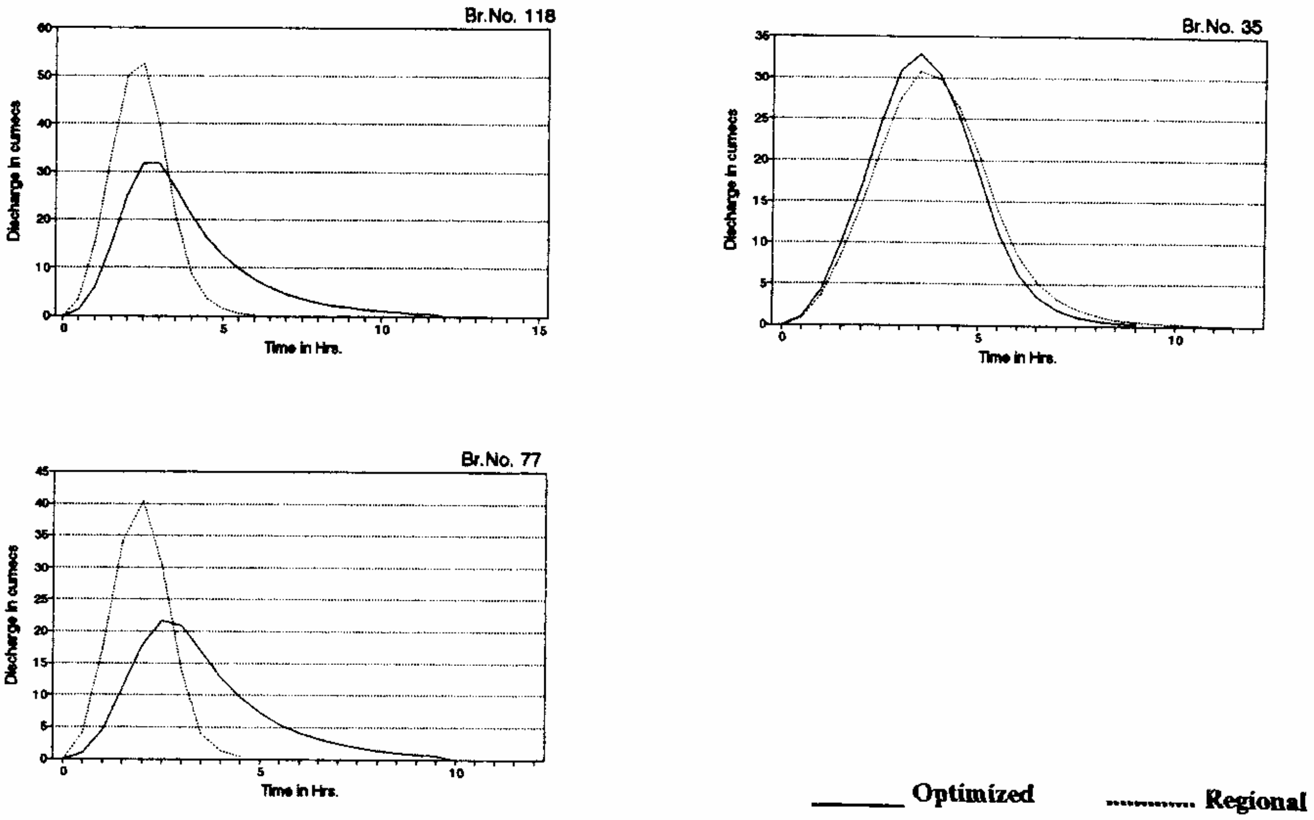

Figure IIe: **One hour unit hydrograph obtained using Clark model and optimized and regional values of Tc and R for Bridge nos. 118, 35 and 77**

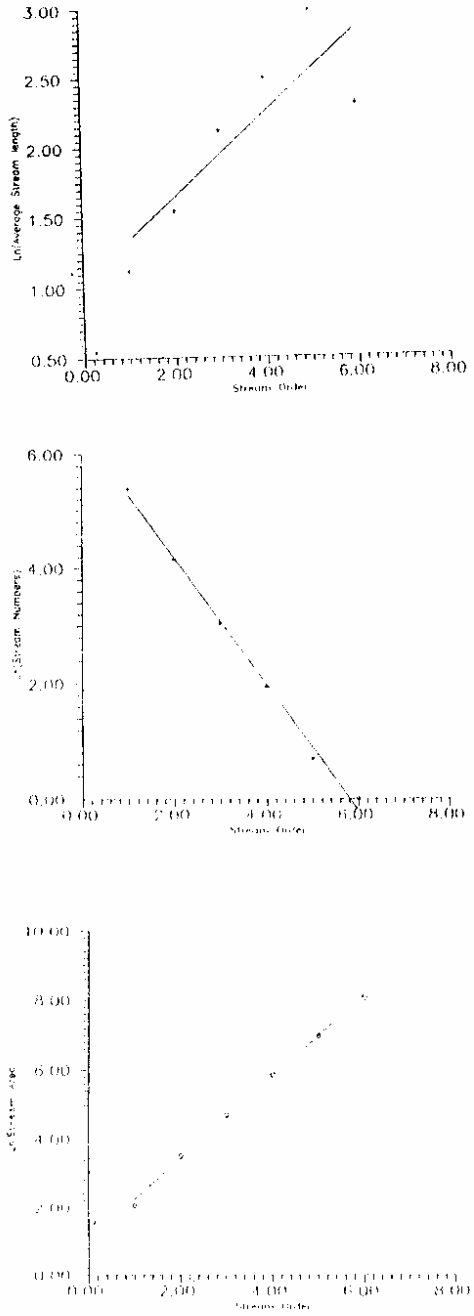

Figure 12: Relationships between stream order and average stream area, stream numbers and stream length for Morel catchment

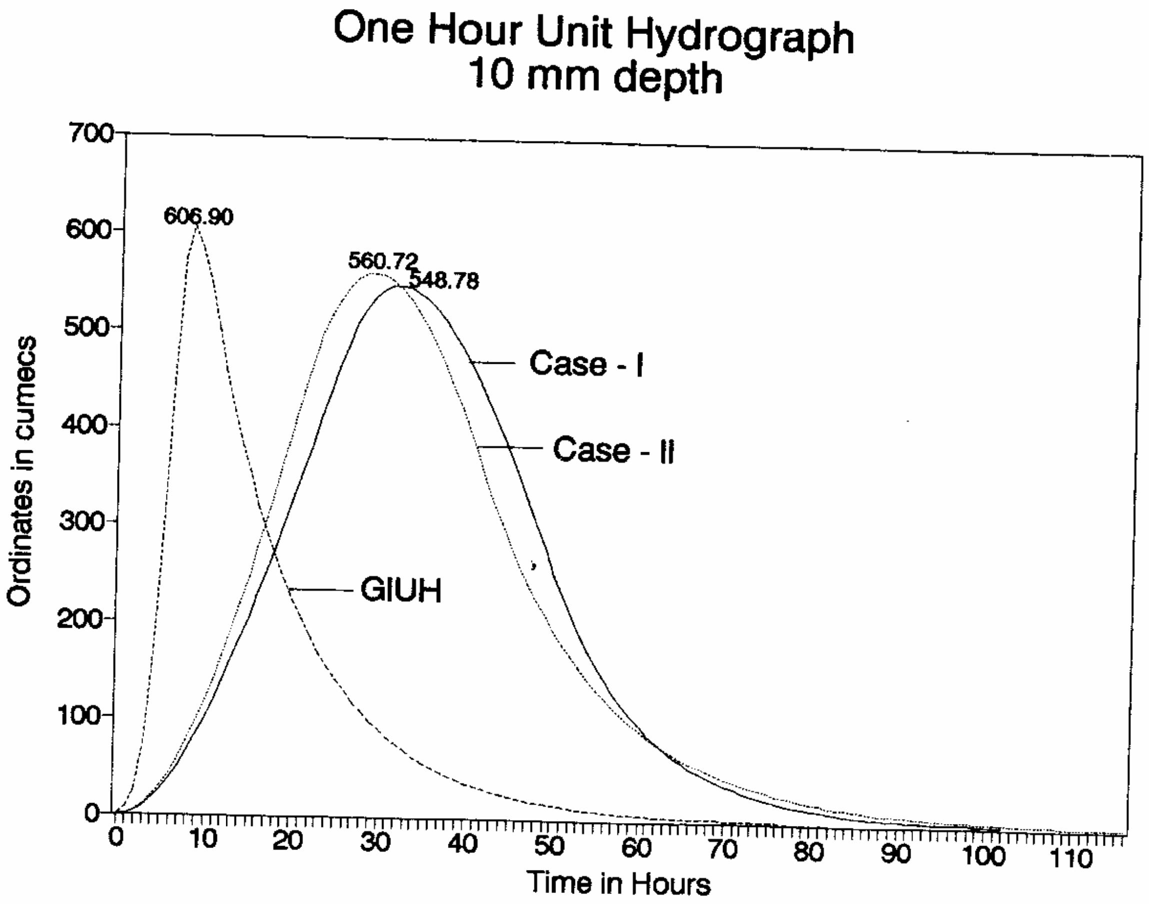

Figure 13: Representative one hour (10 mm) unit hydrographs for Morel catchment developed using Clark model and GIUH approach

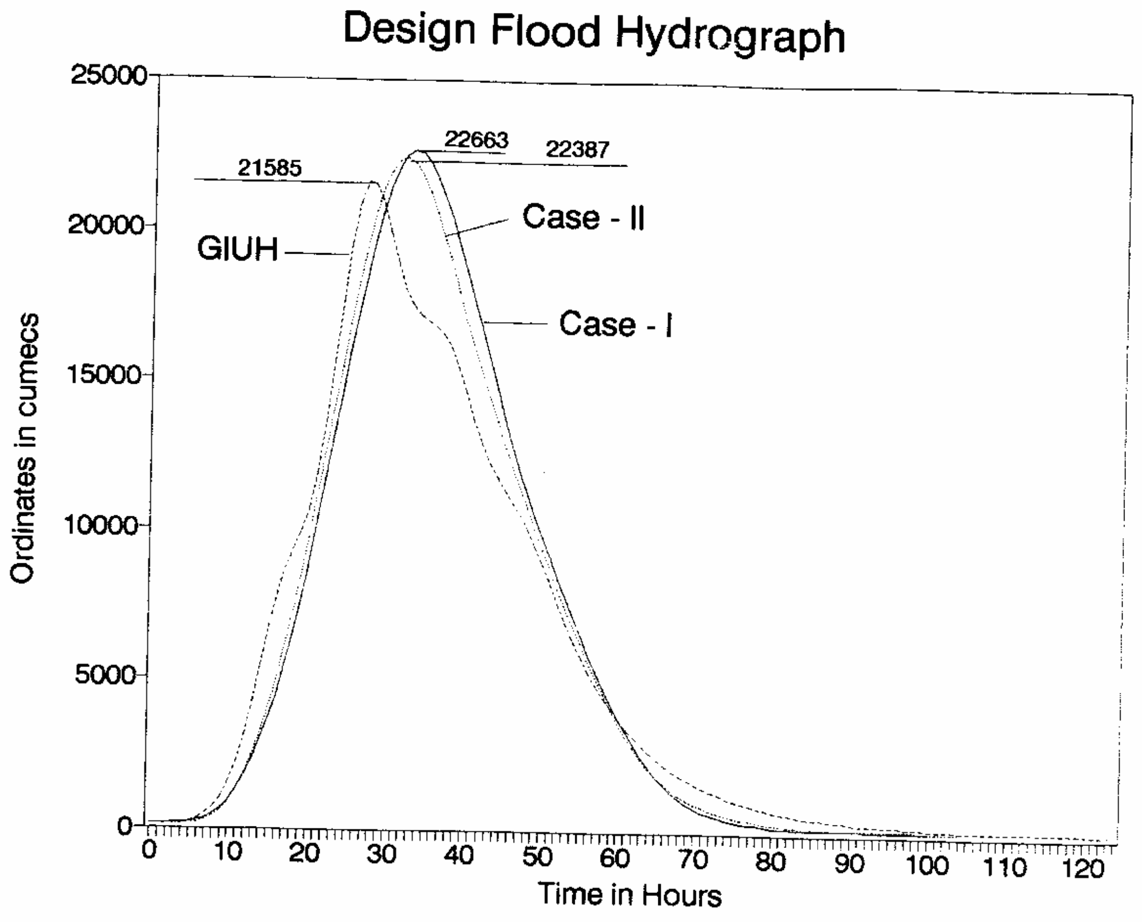

Figure 14: Design flood hydrographs for Morel catchment computed using design rainfall and developed unit hydrograph

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