RAINFALL-RUNOFF MODELLING USING GIUH APPROACH

1.0 INTRODUCTION

Simulation of rainfall-runoff process for ungauged catchments is one of the important areas of research in the sphere of surface water hydrology. The problem of transformation of rainfall into runoff has been a very active area of research throughout the evolution of the subject of hydrology. Through their intuition, many investigators have tried to relate runoff with the different characteristics which affect it. 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. Never it is inferred that, a particular model is the best for rainfall-runoff transformation. Actually, many more factors, besides the accuracy, e.g., the availability of data, computing facility, time, resources etc. govern the applicability of a model. The search for suitable models for different conditions still continues and thus more and more mathematical models are being suggested.

There are a number of well established techniques like unit hydrograph, conceptual or physically based modelling which are employed for the purpose of rainfall-runoff process simulation for the catchments. All such techniques require a certain amount of historical data for establishing various parameters. However, due to very sparse gauging network available in most of the Indian catchments, particularly for small catchments it becomes very difficult for such techniques to be directly applicable. In such situations of very poor data availability, the options available are, either to go for regionalization of parameters based on the data available for the gauged catchments in nearby hydro-meteorologically similar regions or by using the morphological details available for the ungauged catchments for modelling their hydrological response. Regionalisation of the parameters is, however, a very tedious task to accomplish since the hydrological behaviour of many nearby catchments have to be ascertained before being confident about the values of the parameters. Although number of such relations are developed with the hope that they will yield satisfactory results when applied to the ungauged basin, these approaches have 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 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.

On the other hand, the geomorphological approach has many advantages over the regionalization techniques as it avoids the requirement of flow data and computations in the neighbouring gauged catchments in the region. As a first step in the direction of using geomorphologic characteristics with the conviction that the search for a theoretical coupling of quantitative geomorphology and hydrology is an area which will provide some of the most exiting and basic developments of hydrology in the future, the concept of Geomorphologic Instantaneous Unit Hydrograph (GIUH) was introduced. This technique, though appears to be tempting to the practitioners for its use in areas of insufficient or inexistent hydrologic data, is very difficult if needed to be applied without making a few assumptions.

A new approach, in which the conceptual modelling of instantaneous unit hydrograph (IUH) is combined with the geomorphologic instantaneous unit hydrograph approach, has been developed at the National Institute of Hydrology. This technique may be applied for the simulation of the flood hydrographs and for the evaluation of the design flood specially for the small to medium sized catchments which are ungauged. By this way, the estimation of parameters of the conceptual model of IUH is not required to be carried out through the tedious regionalisation process. This hybrid approach is developed by linking the Clark's model parameters with the peak characteristics of the geomorphological instantaneous unit hydrograph. The proposed method is called GIUH based Clark model here-in-after in this text. The methodology has been applied by simulating storm events in Kolar sub-basin of river Narmada (NIH, 1993) and eighteen small catchments of Upper Narmada & Tapi subzone (Subzone 3c) - Part I (NIH, 1995) & Part II (NIH, 1996).

2.0 GEOMORPHOLOGICAL PARAMETERS

The quantitative analysis of channel networks begins with Horton's (1945)method of classifying streams by order. Strahler (1957) revised Horton's classification scheme such that the ordering scheme is unlike Horton's, purelytopological, for it refers to only the interconnections and not to the lenghts, shapes, or orientation of the links comprising a network. Fig. 1 shows a hypothetical river network. The network has a single outlet (root or trunk). Inner nodes are points where lines or river segments join. Outer nodes are sources with one line or stream segment originating from them. Links are segments between nodes. Interior links connect interior nodes. Exterior links are between a source (outer node) and a downstream interior node. Based on the above representation Strahler classified streams according to the following procedure:

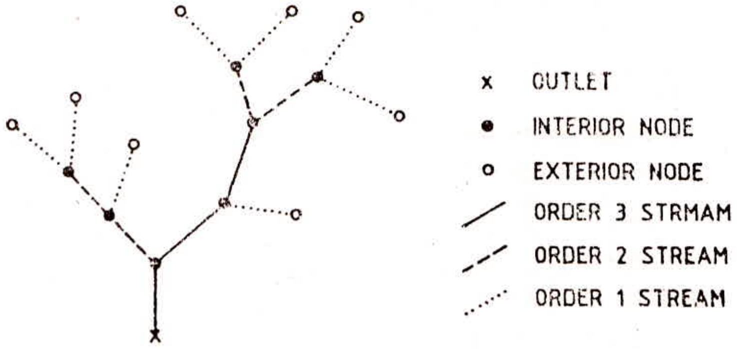

Fig.1 : Hypothetical River Network Illustrating Strahler's Stream-Ordering System

(i) Channels that originate at a source are defined to be first-order streams;
(ii) When two streams of order ω join, a stream of order $(\omega+1)$ is created;
(iii) When two streams of different order merge, the channel segment immediately downstream is taken to be the continuation of the higher order stream; and
(iv) The order of the basin is the highest stream oder Ω.

Note that Strahler streams of order higher than 1 may be composed of several links.

Horton (1945) first developed a somewhat different stream-ordering scheme and suggested several empirical laws; the law of stream numbers and the law of stream lengths. These results have been confirmed many times using Strahler's ordering system. Schumm (1956) proposed a Horton-type law of stream areas.

The law of stream numbers states that the number of streams of a given order follows an inverse geometric relationship with stream order :

$$N_\omega = R_B^{\Omega-\omega} \qquad \text{(i)}$$

where Ω is the order of the highest-order stream in the network, ω is the order of interest, and R_B is a constant for a given network. R_B is called the bifurcation ratio. A plot of the logarithm of N_ω versus order ω will approximately yield a straight line with negative slope. The magnitude of that slope is the logarithm of R_B. Fig. 2 illustrates that result.

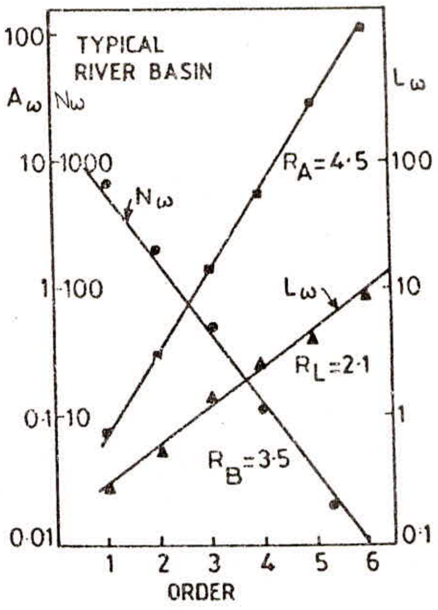

Fig. 2 : Stream Numbers, Lenths, and Areas Vs. Stream Order Illustrating Horton's Laws for a Typical Basin

It is to be noted that the above Eq. (12.1) leads to the conclusion that the total number of streams in the network is

$$\sum_{\omega=1}^{\Omega} N_\omega = 1 + R_B + R_B^2 + \ldots + R_B^{\Omega-1} = \sum_{\omega=1}^{\Omega} R_B^{\Omega-\omega} = \frac{R_B^{\Omega} - 1}{R_B - 1} \qquad \text{(ii)}$$

Also that

$$R_B = \frac{N_{\omega-1}}{N_\omega} \qquad \text{(iii)}$$

which implies that on the average there are R_B streams of order Ω - 1.

The concept of the laws of stream numbers, the ratios of the series being the length ratio R_L and the area ratio R_A, respectively. R_L and R_A are calculated using the following quantities : the average stream lengths of each order $\bar{L}_\omega$ are given by

$$\bar{L}_\omega = \frac{1}{N_\omega} \sum_{i=1}^{N_\omega} L_{\omega i} \qquad \text{(iv)}$$

where $L_{\omega i}$ is the length of a stream of order ω, and the average stream area of each order $\bar{A}_\omega$ is given by

$$\bar{A}_\omega = \frac{1}{N_\omega} \sum_{i=1}^{A_\omega} A_{\omega i} \qquad \text{(v)}$$

where, $A_{\omega i}$ is the area contributing runoff to a stream of order ω and its tributaries. The quantitative expressions of Horton's laws are summarized below :

Law of stream numbers $$\frac{N_{\omega-1}}{N_{\omega}} = R_B \qquad \text{(vi)}$$

Law of stream lengths $$\frac{\bar{L}_{\omega}}{\bar{L}_{\omega-1}} = R_L \qquad \text{(vii)}$$

Law of stream areas $$\frac{\bar{A}_{\omega}}{\bar{A}_{\omega-1}} = R_A \qquad \text{(viii)}$$

Empirical results indicate that for natural basins the value for R_B normally ranges from 3 to 5, for R_B form 1.5 to 3.5, and for R_B from 3 to 6. Fig. 2 also shows plots of $\bar{L}_{\omega}$ and $\bar{A}_{\omega}$ versus ω.

3.0 GIUH BASED CLARK MODEL

3.1 General

The conceptual rainfall-runoff models invariably require calibration of their parameters. This calibration is carried out on the basis of some observed events. For the case of ungauged catchments, where no such observed events are available for the calibration purpose, regionalization on the basis of nearby gauged catchments is resorted to. Such an exercise becomes very tedious considering the computational effort required. Also, it is to be repeated from time to time whenever more observations become available.

Rainfall-runoff modelling based on the geomorphological details of the basin is a new concept in hydrology. Analytical procedures have been established for the derivation of the geomorphological instantaneous unit hydrograph. Such approach may be advantageously applied even for the ungauged catchments as it does not require the observed runoff data. However, these procedures have been tried for basin of smaller stream orders only. For basins of four or higher stream order this type of analytical procedure becomes highly complicated and has not been applied so far. Two formulae for the peak characteristics of the geomorphological instantaneous unit hydrograph (GIUH) have been suggested. But these formulae are not adequate to describe the shape of the instantaneous unit hydrograph (IUH) fully.

A new approach of rainfall-runoff modelling has been developed at the National Institute of Hydrology (NIH, 1993) in which the conceptual modelling has been clubbed with the GIUH approach. This has enabled to determine the complete shape of the IUH by using the formulae given for the peak characteristics of the GIUH. Simultaneously on the other hand, it has been possible to use the conceptual modelling approach without even required to calibrate its parameters on the basis of the observed runoff data. The conceptual model used in this new approach is the Clark model. Various steps in involved in this approach are given here under.

The topographic map of the catchment is required for findind out the geomorphological parameters. The maps on a scale of 1:50,000 may be used for this purpose as it provides adequate details for catchments of about 50 to 1000 sq. kms.. On larger scale the work involved may be tremendous whereas on smaller scale the details are lost. However, the subjectivity if any in using maps at different scales remains in finding out the geomorphological parameters.

Rainfall data is also required for the event to be simulated. For obtaining a relation between velocity and discharge at the catchment outlet sufficient observations are needed for discharge at different depths covering the expected range. In case the simulated flows are to be validated then the discharge observations of the event is also required to be taken.

3.2 Computation of Excess Rainfall

When the rainfall occurs over the catchment not all the rain contribute to the direct surface runoff. A part of the rainfall is abstracted as interception, evapotranspiration, surface depression storage and infiltration. The remainder of the rainfall termed as excess rainfall contributes to the direct surface runoff. Thus the computation of excess rainfall is required for the estimation of direct surface runoff by separating the hydrological abstractions from the rainfall hyetographs. Although number of techniques are available for the computation of excess rainfall but the ϕ-index method is one of the simple and most commonly used technique. Among the other techniques SCS curve number method is being widely used for the estimation of the excess rainfall particularly when the catchment is ungauged. When using ϕ-index method the volume of the excess rainfall for a given storm event is assumed to be known. It is computed as the volume of direct surface runoff hydrograph for a given event. The direct surface runoff hydrograph is computed by separating the baseflow from the observed hydrograph ordinates. Here the observed direct surface runoff is used only for the estimation of excess rainfall hyetograph and is not used further for the derivation of instantaneous unit hydrograph. However, the use of the observed direct surface runoff for the estimation of excess rainfall has to be avoided for the ungauged catchment as no runoff records would be available for such catchments. In such situations the values of ϕ-index can be estimated by analysing the rainfall-runoff records of flood events of the same period of the neighbouring catchments having similar hydro-meteorological characteristics. Alternatively, other methods such as SCS method may be applied to estimate the excess rainfall provided that the land use, soil type, treatment class, hydrologic condition and antecedent soil moisture condition are known for the estimation of runoff curve number.

3.3 Preparation of Time-Area Diagram

Time of travel between any two points in the stream , t , is considered proportional to $L / \sqrt{S}$

or $$t = K L / \sqrt{S} \qquad (1)$$

where:

t ⇒ time of travel
L ⇒ length of the stream. between the two points
S ⇒ slope of the stream between the two points
and, K ⇒ proportionality constant.

Using eq.(1) we may get the time of travel between any point in the catchment on the river layout and the outlet of the catchment as:

$$K L / \sqrt{S_A} = K \sum_{i=1}^{NR} (L_i / \sqrt{S_i}) \qquad (2)$$

where:

L ⇒ the total length of the main stream
L_1 ,L_2 ⇒ the lengths of each individual segments
S_A ⇒ average slope of main stream
S_1,S_2 ⇒ average slope of individual segment slopes.
NR ⇒ no. of segments considered in the main stream.

Assuming some arbitrary value of K, eq.(2) may be used to calculate time of travel between any two points on the river layout in the catchment. Starting from the basin outlet the time of travel of various points over the catchment is thus progressively calculated.

All the values of the time of travels for different points are then denoted on the map at their respective locations. Curves of specified time of concentration called the "Isochrones" are then drawn through these points by making use of linear interpolation and consideration of elevation contour pattern and stream layout. Fig. 3 shows a typical catchment showing different isochronal areas.

From this map having contours of equal time of travel the inter isochronal areas may be obtained by using planimeter etc.. The cumulative isochronal area with respect to the cumulative time of travel may thus be obtained. To eliminate the effect of assumed value of K, each value of time of travel corresponding to cumulative isochronal areas is divided by the largest time of travel to express it in percent form. Thus, a non-dimensional relation between cumulative isochronal area and percent time of travel may be obtained. This may also be expressed in graphical form by plotting percent time of travel on x-axis and cumulative isochronal area on y-axis. Fig. 4 gives such a plot for a typical catchment.

3.4 Derivation of Clark Model IUH and D-hour Unit Hydrograph

The Clark model concept suggests that the IUH can be derived by routing the unit inflow in the form of time-area diagram, which is constructed from the isochronal map, through a single reservoir. For the derivation of IUH the Clark model uses two parameters, time of concentration (T_c) in hours, which is the base length of the time-area diagram, and storage coefficient (R), in hours, of a single linear reservoir in addition to the time-area diagram.

The governing equation of IUH using this model is given as :

$$u_i = C I_i + (1-C)\, u_{i-1} \tag{3}$$

where;

u_i ⇒ ith ordinate of the IUH
C & (1-C) ⇒ the routing coefficients.
and C ⇒ $\Delta t / (R+0.5\Delta t)$
Δt ⇒ computational interval in hours
I_i ⇒ the ith ordinate of the time-area diagram

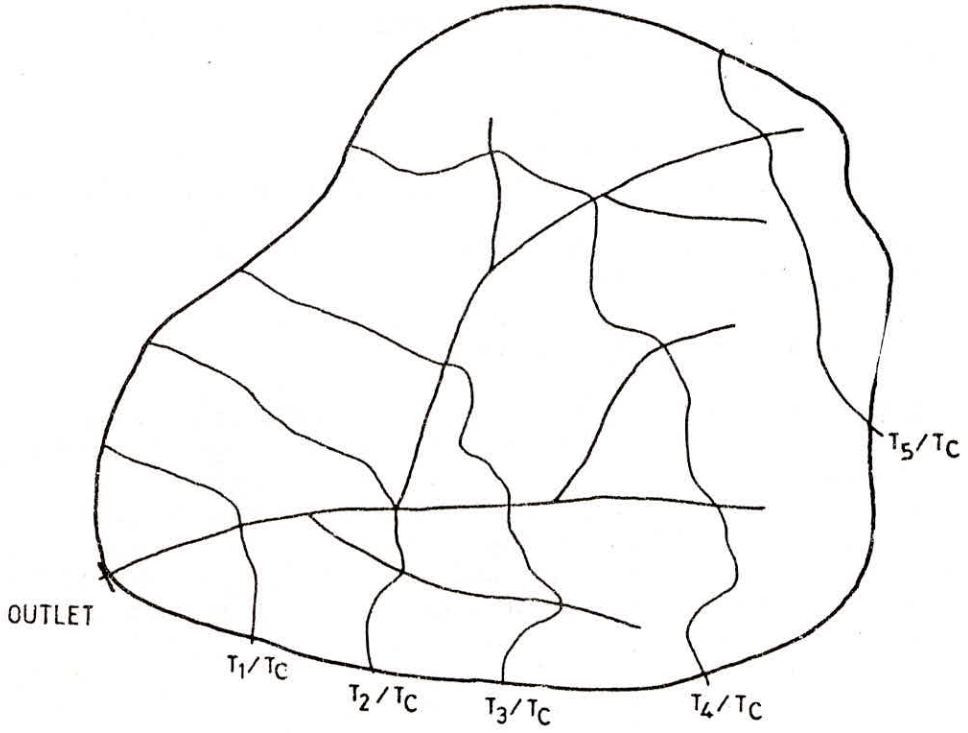

FIG. 3. A TYPICAL CATCHMENT MAP SHOWING ISOCHRONAL AREAS

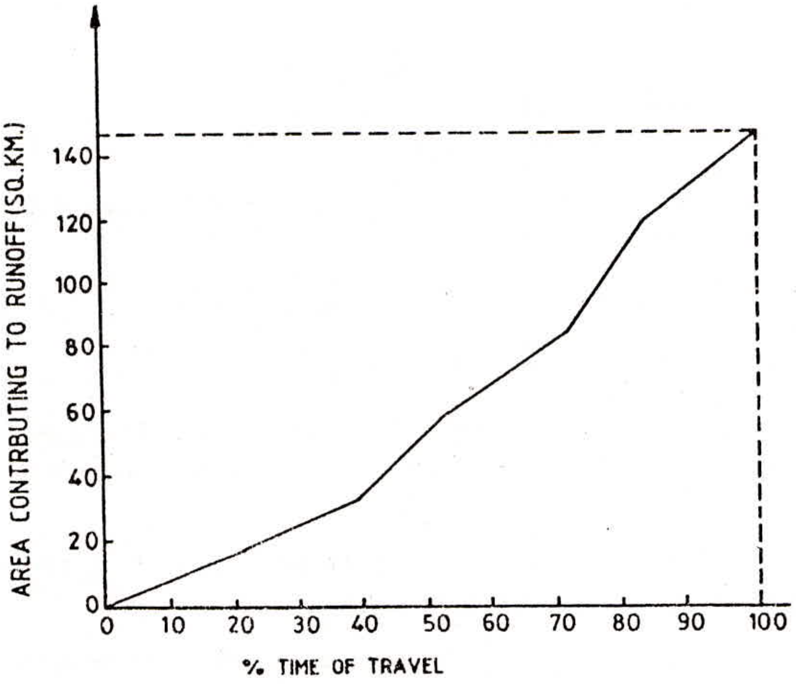

FIG. 4. A TYPICAL PLOT BETWEEN AREA CONTRIBUTING TO RUNOFF AND % TIME OF TRAVEL

A unit hydrograph of desired duration (D) may be derived using the following equation :

$$U_i = \frac{1}{n}(0.5u_{i-n}+u_{i-n}+u_{i-n+1}\cdot\ \cdot\ \cdot\ \cdot\ +u_{i-1}+0.5u_i) \qquad (4)$$

where;

U_i ⇒ ith ordinate of unit hydrograph of duration D-hour and at computational interval Δt hours
n ⇒ no. of computational intervals in duration D hrs = $D/\Delta t$
u_i ⇒ ith ordinate of the IUH

3.5 Use of Geomorphological Characteristics

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:

$$q_p = 1.31\ R_L^{0.43}\,V/L_\Omega \qquad (5)$$

$$t_p = 0.44\,(L_\Omega/V)\,(R_B/R_A)^{0.55}\,(R_L)^{-0.38} \qquad (6)$$

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.

On multiplying eq. (5) and (6) we get a non-dimensional term $q_p \times t_p$ as under.

$$q_{pg} \times t_{pg} = 0.5764\ (R_B/R_A)^{0.55}\,(R_L)^{0.05} \qquad (7)$$

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.

3.6 Development of Relationship Between the Intensity of the Excess Rainfall and the Velocity

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. However, for ungauged catchments the peak discharge is not known and so this criteria for estimation of velocity cannot be applied. In such a situation the velocity may be estimated using the relationship developed between the velocity and the excess rainfall. Two approaches for developing this relationship are presented here under.

APPROACH I:

This approach may be utilized when the geometric properties of the gauging section is known and the Manning's roughness coefficient can be assumed with an adequate degree of accuracy.

The steps involved in this approach are as below.

(i) Compute cross sectional area (A), Wetted Perimeter (P)and hydraulic radius (R) on the basis of X-sectional details corresponding to different depths.

(ii) Assume the frictional slope to be equal to the bed slope of the channel.

(iii) Choose an appropriate value of Manning's roughness coefficient (n) from the values given in literature (Chow 1964) for different surface conditions of the channel.

(iv) Compute the discharge (Q) using the Manning's formulae corresponding to each depth.

(v) Plot depth v/s discharge and depth v/s area curves.

(vi) Compute the equilibrium discharge (Q_e) corresponding to an excess rainfall intensity (i in mm/hr) using the relation :

$$Q_e = 0.2778 \; i \; A_c \tag{8}$$

where ;

$A_c \Rightarrow$ catchment area in Sq. Kms..

(vii) Compute the depth corresponding to the equilibrium discharge (Q_e) using the depth v/s discharge curve.

(viii) Compute the area corresponding to the depth computed at step (vii) using the depth v/s area curve.

(ix) Compute the velocity V by dividing the discharge (Q_e) by the area computed at step (viii).

(x) Repeat steps (vi) to (ix) to find velocity with respect to different intensities (e.g., 1, 2, 3 mm/hr. etc.) of rainfall excess.

(xi) Develop the relationship between velocity and rainfall excess intensity obtained at step (x) in the form : $v = a\, i^b$, using method of least square.

APPROACH II:

This approach is based on the assumption that the value of the Manning's roughness coefficient is not available but the velocities corresponding to discharges passing through the gauging section at different depths of water flow are known from the observations. The steps involved in this approach are given below.

(i) For different depths of flow the discharge and the corresponding velocities are known by observation.

(ii) Let these velocities and discharges be the equilibrium velocities V_e and the corresponding equilibrium discharges Q_e

(iii) For these Q_e find the corresponding intensities i of excess rainfall from the expression:

$$i = Q_e / (0.2778\ A_c) \tag{9}$$

(iv) From the pairs of such V_e and i develop the relationship between the equilibrium velocity and the excess rainfall intensity in the form : $v = a\ i^b$, using method of least square.

It is to be noted here that this approach though requires the information of discharges and velocities at the gauging site does not necessarily mean that it can be applied for the gauged catchments only. For the ungauged catchments too, this information may be easily obtained by gauging the stream intermittently for all ranges of depth of flow. This type of information may be gathered without incurring much cost and effort.

3.7 Derivation of Unit Hydrograph Using the New "GIUH Based Clark Model" Approach

A new approach has been developed at the National Institute of Hydrology (NIH, 1993) for the estimation of the parameters of the Clark model through use of geomorphological characteristics. The step-by-step explanation of the procedure for simulating a flood event using the proposed approach is given here under:

(a) Excess rainfall hyetograph is computed either by uniform loss rate procedure or by SCS curve number method (Soil Conservation Service, 1971) or by any other suitable method.

(b) For a given storm the estimate of the peak velocity V using the highest rainfall excess is made by using the relationship between equilibrium velocity and intensity of rainfall excess (as explained above).

(c) compute the time of concentration (T_c) using the equation:

$$T_c = 0.2778\ \frac{L}{V} \tag{10}$$

where L ⇒ the length of the main channel

(d) Obtain the time-area diagram for the catchment corresponding to the time of concentration computed in step(c) with the help of non-dimensionalised plot between cumulative isochronal area and the time of travel.

(e) Compute the peak discharge (q_{pg}) of GIUH given by Eq.(5).

(f) Using Newton-Raphson's iterative procedure compute the value of the storage coefficient R such that the peak of the IUH by Clark model is equal to q_{pg} (within tolerable limits) obtained in step(e).

(g) Compute the instantaneous unit hydrograph (IUH) using the GIUH based Clark Model with the help of final values of storage coefficient (R) obtained in step (f) above, time of concentration (T_c) and the time-area diagram.

(h) Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour.

(i) Convolute the rainfall excess hyetograph with the unit hydrograph obtained in step (h) to obtain the computed direct surface runoff hydrograph.

3.8 Computation of Direct Surface Runoff Using Derived Unit Hydrograph

The direct surface runoff for a storm event whose excess rainfall values are known at D-hour interval are computed using the convolution based on the D-hour unit hydrograph. The convoluted hydrograph ordinates are given as:

$$Q(t) = \Delta t \sum_{i}^{n} [\, U(D, t-(i-1)) \,] \, I_i \qquad (11)$$

where,

U(D,t) ⇒ ordinate of D hour unit hydrograph at time t

I_i ⇒ rainfall intensity at ith interval (i.e., at time = $\Delta t \times i$)

n ⇒ no. of rainfall blocks

Δt ⇒ computational time interval

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