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Rainfall-Runoff Modelling using a GIUH based Conceptual Model

by
Chandramohan T.

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Hard Rock Regional Centre
National Institute of Hydrology
Belgaum-590 001 (Karnataka)

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Chandramohan T.
Scientist 'C'
Hard Rock Regional Centre
National Institute of Hydrology
Belgaum – 590 001 (Karnataka)

1.0 Introduction

The understanding of rainfall-runoff process and the time distribution of runoff are the basic components of water resources planning and design. Mathematical modelling is extensively used to simulate the rainfall-runoff process. Whenever catchments are gauged, event based models can be developed, which may be calibrated and validated for the historical flood events. The linearity principle of unit hydrograph theory put forward by Sherman in 1932 has been widely applied for this purpose for small and medium sized catchments. But the application of this technique requires historical rainfall-runoff records. Unfortunately, small catchments are large in number and most of them are ungauged. Therefore, it would not be possible to calibrate and validate these event-based models in the absence of flow data for ungauged catchments.

Streamflow simulation from ungauged catchments has long been recognised as a subject of scientific investigations. In this regard, the derivation of regional and synthetic unit hydrograph was a great achievement to estimate the unit hydrograph ordinates or the unit hydrograph parameters. The procedure involved in regional unit hydrograph analysis requires evaluation of representative unit hydrograph parameters and pertinent physical characteristics for the gauged catchments in a hydrometeorologically homogeneous region. Then multiple linear regression analysis is applied, considering one of the unit hydrograph parameters at a time as dependent variable and various catchment characteristics as independent variables. Thereafter, the unit hydrograph for an ungauged catchment in the hydrometeorologically homogeneous region can be derived using the physical characteristics of the ungauged catchment. But such relations do not seem to be scientifically sound, since the regionalisation of parameters is a tedious task. Hydrological behaviour of many nearby catchments have to be ascertained before being confident about the values of the parameters.

The other approach, which may be utilised for developing the unit hydrograph for ungauged catchments, utilises geomorphological characteristics. This approach has many advantages over the regionalisation approach as it avoids the requirement of data and computations in the neighbouring gauged catchments in the region. Geomorphologic techniques have recently been advanced for hydrograph synthesis, adding a new dimension to hydrologic simulations. Linking of geomorphological parameters with the hydrological characteristics of the basin can provide a simple way to understand the hydrologic behaviour of different catchments, particularly the ungauged ones. Many investigators have tried to relate the IUH parameters to the catchment geomorphology and thus to obtain the geomorphological instantaneous unit hydrograph (GIUH). The concept of GIUH was first introduced by Rodriguez-Iturbe and Valdes (1979) in their pioneering studies on the geomorphologic structure of hydrologic response.

Hydrological response of a basin is dependent on its geology, soil characteristics, topography, vegetation and climate. The transformation of the rainfall into runoff is dependent on the surface of a basin and is reflected in the indices that are described by geomorphology of the basin such as its linear, aerial and relief aspects. So the hydrological response of a basin is greatly influenced by its geomorphological characteristics. The development of relationship between geomorphological characteristics and the hydrological variables serves as a useful tool to determine the hydrological response of the basin. It attains greater importance particularly in case of ungauged basins, where lack of data poses problems in optimal planning of water resources development activities.

2.0 Geomorphological Parameters

Nature shapes river catchments in an orderly and organised manner. Any river catchment reflects the interdependence of geology, soil characteristics, vegetation, topography, and climate. The channel network and the overland flow region in a river basin satisfy Horton's empirical geomorphological laws when ordered according to the Strahler ordering scheme.

The quantitative study about channel network was originated by Horton in 1945. He developed a system for ordering stream networks and derived laws relating the number, length, and catchment area associated with streams of different order and suggested several empirical laws regarding stream numbers, stream lengths, and stream areas for a catchment.

The quantitative expressions of Horton's laws are:
(i) law of stream numbers, $N_w/N_{w+1} = R_B$
(ii) law of stream lengths, $L_w/L_{w-1} = R_L$
(iii) law of stream areas, $A_w/A_{w-1} = R_A$
where N_w is the number of streams of order w, L_w is the mean length of stream of order w, and A_w is the mean area of the catchment of order w. R_B, R_L, and R_A represent the bifurcation ratio, the length ratio, and the area ratio whose values in nature are normally between 3 and 5 for R_B, 1.5 and 3.5 for R_L, and 3 and 6 for R_A (Smart, 1972).

Strahler (1957) slightly revised Horton's classification scheme such that the ordering scheme, unlike Horton's purely topological classification, refers to interconnection and not the lengths, shapes, or orientation of the links comprising a network. Based on this representation, Strahler classified streams according to the following procedure;

- channels that originates at a source are defined as first order streams
- when two streams of order w join, a stream of order (w+1) results
- when two streams of different order join, the channel segment immediately d/s is taken to be the continuation of the higher order stream
- the order of the basin is the highest sream order

Recently, many attempts have been made to relate the response of a catchment to its morphologic or topologic aspects, using various hypothesis to model both the advection and attenuation effects of a river network. The geomorphological theory of the unit hydrograph was originated by Rodriguez-Iturbe and Valdes (1979), who rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for the geomorphological structure of a fluvial basin.

The basic idea of GIUH is that the distribution of arrival times at the basin outlet of a unit instantaneous impulse injected throughout a channel network is affected both by the underlying natural order in the morphology of the catchment and the hydraulic characteristics of the flow along the channels. In the approach proposed by Rodriguez-Iturbe and Valdes (1979), the underlying natural order in the morphology is represented by the Horton ratios which in turn are based on a classification of the channel network of the catchment according to Strahler's ordering scheme. But the holding time of a drop of water within a stream of a given order is represented by means of an exponential law which is, however, a conceptualisation of true flow dynamics. As a consequence of this last hypothesis, the average holding time of a drop within a stream of a given order is proportional to the average length of all the streams of that order, and the proportionality factor is the flow velocity, which is considered uniform throughout the drainage basin.

In this approach, two formulae have been proposed for the peak characteristics of GIUH. But these formulae are not adequate to describe the shape of the instantaneous unit hydrograph fully.

A new approach, in which the conceptual modeling of IUH is combined with the geomorphologic instantaneous unit hydrograph approach, has been developed at the National Institute of Hydrology. This has enabled to determine the complete shape of the IUH by using the formulae given for the peak characteristics of the GIUH. This methodology may be applied for simulation of the flood hydrographs and evaluation of design floods especially for small to medium sized ungauged catchments. Using this method, estimation of parameters of the conceptual model of IUH is not to be carried out through the tedious regionalisation process. This approach is formulated by linking the Clark's model parameters with the peak characteristics of the GIUH.

3.0 Literature Review

Simulation of transformation of rainfall into runoff has been an active area of research throughout the evolution of the science of hydrology. The simplest among all the methodologies is the estimation of an empirical constant, runoff coefficient, which is used to estimate runoff from rainfall. Large number of conceptual models have been put forward by many researchers where the various interrelated hydrological processes are conceptualised. More sophisticated procedures have also been evolved which are based on the physical concepts of the process in which the rainfall-runoff process is modelled.

The parameters of the types of models mentioned above, are to be calibrated based on the available rainfall-runoff data of a particular basin. But, for ungauged catchments, these parameters need to be determined from the regional relationships correlating the model parameters with physically measurable catchment characteristics. Rainfall-runoff relationships for ungauged catchments have been developed along two complimentary lines; (i) empirical relations have been developed to relate some individual runoff hydrograph characteristics to watershed characteristics, and (ii) procedures have been developed to synthesise the entire hydrograph from watershed characteristics.

In order to develop unit hydrograph parameters for an ungauged catchment, concept of regional and synthetic hydrograph was put forward by early researchers, by relating to the physical characteristics of the catchment. During the evolution of this methodology, it was observed that the shape of unit hydrograph is somewhat unconventional and does not match with the general concept of a smooth unit hydrograph shape. This along with the considerable number of parameters to define the shape of the hydrograph causes practical problems in relating unit hydrograph characteristics with catchment characteristics. Therefore, efforts have been made to define the unit hydrograph with least possible number of parameters. Also, derivation of synthetic unit hydrograph with the help of geomorphological characteristics involves considerable personal judgment.

The concept of Instantaneous Unit Hydrograph (IUH) suggested by Nash (1957) helped in determining the time distribution process of the excess runoff through a simple two parameter model. Thus, IUH is a purely theoretical concept and represents the unit hydrograph obtained when the unit excess rainfall occurs instantaneously. As the rainfall duration term is eliminated, the IUH indicates storage characteristics of a catchment and it is unique for a catchment.

Many conceptual models are available for the derivation of IUH such as Nash model (1957), Clark model (1945), Zoch model (1934, 1936), Dooge model (1973), models suggested by Laurenson (1964) and Diskin (1972), etc.

For the derivation of unit hydrograph or IUH by any of the above techniques, rainfall-runoff data at short intervals are required for a few representative storm events, for the purpose of calibration and validation. The lack of runoff records especially in small and medium catchments forced the researchers to define hydrological processes of a basin in terms of geomorphological and climatological characteristics of the basin.

The quantitative analysis of drainage network has gone through dramatic advances since the findings of Shreve (1966) which led way for a theoretical foundation of Horton's well known empirical laws and provided a new perspective for many other problems in fluvial geomorphology. Based on these, Rodriguez-Iturbe et al. (1979) introduced the concept of Geomorphological Instantaneous Unit Hydrograph (GIUH) as a step towards linking quantitative geomorphological parameters to stream flow response. Several investigators have worked towards developing an IUH from the geomorphology of catchments as derived from readily available topographic maps. A majority of the past studies have used conceptual and synthetic unit hydrograph models.

Rodriguez-Iturbe and Valdes (1979) and Valdes et al. (1979) introduced the concept of the GIUH by linking the IUH peak discharge (q_p) and time to peak (t_p) with geomorphologic parameters of the catchment and a dynamic parameter (velocity). The approach coupled the empirical laws of geomorphology with the principles of linear hydrologic systems. They proposed a simple functional dependence of q_p and t_p with velocity v as q_p=i.v and t_p=k/v, respectively. By relating the parameters i and k with the geomorphological parameters, they presented general equations for estimation of q_p and t_p .

In the approach given by Rodriguez-Iturbe and Valdes (1979), the geomorphologic structure of the catchment plays an explicit role. More specifically, the probabilistic description of the movement of runoff through the drainage network of the catchment is made through its transition probability matrix. They expressed the initial state probability of one drop of rainfall in terms of geomorphologic parameters as well as the transition matrix. The final probability density function of droplets leaving the highest order stream into the trapping state is the GIUH. Using this approach, the main characteristics of GIUH, its peak q_p, and its time to peak t_p are expressed as functions of R_B, R_L, R_A, the velocity v, and the scale parameter L_w.

In India, design discharges for very small and medium catchments were being calculated using empirical formulae viz. Dicken's, Ryve's, Inglis, etc. Later on, the Central Water Commission adopted unit hydrograph approach for the estimation of design flood peak of desired frequency. For this purpose, the country has been divided into 7 major zones which are further sub-divided into 26 hydrometeorologically homogeneous sub-zones. The CWC has developed regional formulae for different sub-zones for the derivation of synthetic unit hydrograph, relating unit hydrograph characteristics to physiographic features.

4.0 Methodology

4.1 Evaluation of Geomorphological Characteristics

For stream order, Strahler's ordering system, is followed. When logarithm of the number of streams is plotted against order it shows a linear relationship. By adding lengths of each stream of an order, it is possible to get the total stream lengths of each order. The total stream length divided by the number of stream segments (N_w) of that order gives the mean stream length L_w for that order. The plot of logarithm of mean stream length as a function of order yields a set of points lying essentially along a straight line. Similarly, the plot of logarithm of mean stream area (Aw) vs. stream order gives a straight line.

Bifurcation, length and area ratios are calculated as the slope of the best fit lines through the plotted points given by the Horton's laws of stream numbers, average lengths and average areas respectively.

4.2 Computation of Excess Rainfall

In a catchment, surface runoff occurs only, after the abstractions such as interception, evapotranspiration, depression storage, and infiltration have taken place. The rainfall amount, which produces surface runoff is termed as rainfall excess. For any rainfall-runoff modelling, the initial step is to estimate rainfall excess by separating the hydrological abstractions from the rainfall hyetograph. Although a number of methods are available for the separation of abstractions, the phi-index method is the simplest and most commonly used. SCS curve number method can also be used for the estimation of rainfall excess, especially for ungauged catchments.

When the phi-index method is used, observed direct surface runoff is used for the estimation of excess rainfall hyetograph. In the cases of ungauged catchments, the phi-index can be estimated by analysing the rainfall-runoff records of flood events of neighbouring catchments having similar hydro-meteorological characteristics.

4.3 Preparation of Time-Area Diagram

The time-area diagram is one of the important inputs for running the GIUH based Clark model. It provides the shape of IUH without considering the storage effects of the catchment.

Time of travel (t) through a stream is considered proportional to $L/S^{0.5}$

or $t = kL/S^{0.5}$ ---------(1)

where, t is the time of travel
L is the length of the stream
S is the slope of the stream
k is the proportionality constant

An initial estimate of time of concentration is obtained by the Kirpich's empirical formula which is given as;

$T_c = 0.0195\, L^{0.77}\, S^{-0.385}$ ---------(2)

where, T_c is the time of concentration in min.
L is the main stream length in meters
S is the mean slope of the main stream in m/m

Substituting the values of L and S in the equation (2) yields the value of time of concentration for the catchment. This value of T_c may be substituted in the equation (1) to get the value of k.

Knowing the value of constant of proportionality k, the equation (1) can be used to calculate time of travel between any two points in the catchment. Starting from the basin outlet, the time of travel can be calculated for various points over the catchment.

All the values of time of travel for different points are marked on the map at their respective locations. Curves of specified time of concentration called isochrones can be drawn through these points by making use of linear interpolation and consideration of elevation contour pattern and stream layout.

[Y1]

4.4 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 through a single reservoir in the form of time-area diagram, which is constructed from the isochronal map. For the derivation of IUH, the Clark model uses two parameters, time of concentration in hours (T_c), which is the base length of the time area diagram, and storage coefficient in hour (R), of a single linear reservoir in addition to the time area diagram.

The governing equation of IUH, using this model, is given as;

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

where, u_i is the ith ordinate of the IUH

C and (1-C) are the routing coefficients, $C = \Delta t / (R+0.5 \Delta t)$

Δt is the computational interval in hours

I_i is the ith ordinate of time area diagram

R is the storage coefficient

A unit hydrograph of desired duration (D) can be derived using the following equation;

$$U_i = (1/n) \{ 0.5\, u_{i-n} + u_{i-n} + u_{i-n+1} + \text{-----------}\ u_{i-1} + 0.5\, u_i) \quad \text{---------(4)}$$

where, U_i is the ith ordinate of unit hydrograph of duration D hour at a computational interval Δt hours

n is the number of computational intervals in duration D hours ($D/\Delta t$)

u_i is the ith ordinate of the IUH

4.5 Use of Geomorphological Characteristics

Rodriguez-Iturbe and Valdes (1979) introduced the concept of geomorphologic instantaneous unit hydrograph (GIUH). Their expression yields full analytical, but complicated expressions for the IUH. They suggested that it is adequate to assume a triangular IUH and to specify only 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 analytical solutions for a wide range of parameters with that of geomorphologic characteristics and flow velocities. These expressions are as follows:

$$q_p = 1.31\, R_L^{0.49}\, V/L_\Omega \quad \text{---------(5)}$$

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

where, L_Ω is the length of the highest order stream in km.

V is the expected peak velocity in m/sec.

q_p is the peak flow in units of inverse hours

t_p is the time to peak in hours

R_B is the bifurcation ratio

R_L is the length ratio

R_A is the area ratio

By multiplying q_p and t_p, we get a dimensionless term,

$$q_p{}^* t_p = 0.5764\, (\, R_B / R_A\,)^{0.55}\, (R_L\,)^{0.05} \quad \text{---------(7)}$$

This term is not dependent upon the velocity and thereby on the storm characteristics. It is a function of only catchment characteristics.

4.6 Development of Relationship between the Intensity of the Excess Rainfall and the Velocity

For the dynamic parameter velocity, Rodriguez et al. (1979) 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 the GIUH, this can be taken as the velocity at the peak discharge for a given rainfall-runoff event in a basin. However, for ungauged catchments, the peak discharge is not known and so this criteria cannot be applied. In such situations, the velocity may be estimated using the relationship developed between the velocity and excess rainfall. Two approaches are available for developing such a relationship, as given below.

Approach 1:

This approach may be utilised when the geometric properties of the gauging section is known and the Manning's roughness coefficient can be assumed with adequate degree of accuracy. The procedure involved in this approach is as below;

(a) Compute cross sectional area, wetted perimeter, and hydraulic radius on the basis of cross sectional details corresponding to different depths.
(b) Assume the frictional slope to be equal to the bed slope of the channel.
(c) Choose an appropriate value of Manning's roughness coefficient for the surface condition of the channel.
(d) Compute the discharge Q using the Manning's equation, corresponding to each depth.
(e) Plot depth v/s discharge and depth v/s area of cross section curves.
(f) Compute the equilibrium discharge (Q_e) corresponding to an excess rainfall intensity i (mm/hr) using the relation, $Q_e = 0.2778\ i\ A$ ---------(8)
where A is the catchment area in sq. km.
(g) Compute the depth corresponding to the equilibrium discharge Q_e using the depth v/s discharge curve.
(h) Compute the area corresponding to the depth computed at step 'g' using the depth v/s area curve.
(i) Compute the velocity V by dividing the discharge Q_e by the area computed at step 'h'.
(j) Repeat steps 'f' to 'i' to find velocity with respect to different intensities of rainfall excess.

(k) Develop the relationship between velocity and rainfall excess intensity in the form, $V = ai^b$ using the method of least squares.

Approach 2:

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 procedure for this approach is given below;

(a) For different depths of flow, the discharge and the corresponding velocities are known by the observations.
(b) Let these velocities and discharges be the equilibrium velocities V_e and the corresponding equilibrium discharges Q_e.
(c) For these Q_e find the corresponding intensities i of excess rainfall from the expression,
$i = Q_e / 0.2778\ A$ ---------(9)
(d) From the pairs of such V_e and i, develop the relationship between the equilibrium velocity and the excess rainfall intensity in the form, $V = ai^b$, using the method of least squares.

4.7 Derivation of Unit Hydrograph using the GIUH Based Clark Model Approach

A new approach has been developed at National Institute of Hydrology (NIH, 1993) for the estimation of the parameters of the Clark model through the use of geomorphological characteristics. The step by step procedure to be followed to derive unit hydrograph for a specific duration using this approach is given below.

(a) Excess hyetograph is computed either by uniform loss rate procedure, by SCS curve number method, 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 velocity and intensity of rainfall (as explained in the previous section).

(c) Compute the time of concentration T_c using the equation;

$$T_c = 0.2778\ L / V \qquad \text{---------(10)}$$

(d) Compute the peak discharge (Q_{pg}) of IUH using the equation (5)

(e) Assume two trial values of the storage coefficient of GIUH based Clark model as R_1 and R_2. Compute the ordinates of two instantaneous unit hydrographs by Clark model using the time of concentration T_c obtained from equation (10) and two storage coefficients with the help of equation (3). Compute the IUH ordinates at a very small time interval say 0.1 or 0.05 hrs so that a better estimate of peak value may be obtained.

(f) Find out the peak discharges Q_{pc1}, Q_{pc2} of the IUH obtained by Clark model for the two storage coefficient R_1 and R_2.

(g) Find out the value of objective function (FCN), using the relation

$$FCN1 = (Q_{pg} - Q_{pc1})^2 \qquad \text{---------(11)}$$

$$FCN2 = (Q_{pg} - Q_{pc2})^2 \qquad \text{---------(12)}$$

(h) Compute the first numerical derivative FPN of the objective function FCN with respect to parameter R as,

$$FPN = (FCN1 - FCN2) / (R_1 - R_2) \qquad \text{---------(13)}$$

(i) Compute the next trial value of R using the following governing equations of Newton-Raphson method:

$$\Delta R = FCN1/FPN \qquad \text{---------(14)}$$

and $RNEW = R_1 + \Delta R$ ---------(15)

(j) For the next trial, consider $R_1 = R_2$ and $R_2 = RNEW$ and repeat steps (e) to (i) till any of the following criteria of convergence is achieved.

(i) $FCN2 = 0.000001$

(ii) no. of trials exceeds 200

(iii) $ABS(\Delta R) / R_1 = 0.001$

(k) The final value of storage coefficient (R_2) obtained above is the required value of the parameter R corresponding to the value of time of concentration for the Clark model.

(l) Compute the instantaneous unit hydrograph (IUH) using equation (3) with the help of final value of storage coefficient, time of concentration and time-area diagram.

(m) Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour, as given by equation (4).

4.8 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:

$$Q(t) = \Delta t \sum_{1}^{n} [U(D,t-(i-1)\,\Delta t)] * I_i \qquad \text{---------(16)}$$

Where,

U(D,t) is the ordinate of D hour UH at time t

I_i is the rainfall intensity at ith interval (ie. at time = $\Delta t * i$)

n is the no. of rainfall blocks

Δt is the computational time interval

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