CS(AR) 3/98-99

DEVELOPMENT OF GEOMORPHOLOGICAL INSTANTANEOUS UNIT HYDROGRAPH FOR MYNTDU-LESKA BASIN

NATIONAL INSTITUTE OF HYDROLOGY
JALVIGYAN BHAWAN
ROORKEE - 247 667
1998-99

PREFACE

Estimation and forecasting of flood are the basic necessities for design, maintenance and operation of irrigation and flood control structures. Many hydrologic methods are developed for this purpose. Unit hydrograph approach is one such method that is simple and reasonably accurate. Since intermittent storms are very common in nature, a large number of different duration unit hydrographs are required to estimate the discharge from the basin for a varying storm pattern. An instantaneous unit hydrograph for a basin is used to avoid the development of large number of unit hydrographs of different duration. IUH of a basin is derived using rainfall and corresponding runoff data. However, in India most of the watersheds are ungauged or having inadequate data. In such cases, a methodology, which does not require large amount of observed rainfall runoff data, may be adopted.

The channel network and geomorphologic features are closely related to the retention and discharge characteristics of a basin. Hence the geomorphologic parameters can be used to derive the IUH. In this report an attempt has been made to develop a computer model for geomorphologic instantaneous unit hydrograph for estimation of flood hydrograph resulting from varying intensity, intermittent storms. The model has been applied to the rainfall runoff data of Myntdu-Leska basin of Meghalaya.

This report is a part of the work programme of the North Eastern Regional Centre and has been carried out by Shri Niranjan Panigrahy, Scientist of the Institute.

(S. M. SETH)
DIRECTOR

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Instantaneous unit hydrograph (IUH) serves as a versatile , ' tool for the estimation of flood hydrograph of a basin due to complex storms. Since the conventional methods of development of IUH such as Nash and Clarke method require adequate rainfall and runoff data, which are not very common for the watersheds in India, an approach capable of deriving IUH from geomorphological features has been used.

According to the theory of GIUH (Gupta *et al.*, 1980) rainfall that occurs over a basin is assumed to be composed of infinite number of non-interacting drops of uniform size. After spending some time in one state (channel or overland region) the drops make transitions from one state to the other to reach the basin outlet. Therefore the time distribution of one drop chosen at random from the basin defines the IUH of the basin.

In this study a GIUH model is developed using the generalised theory. Assuming one parameter exponential time distribution for the movement of drops in every state the functional relationship is developed. A general-purpose software is developed for the model. The model is capable of directly estimating the DRH from the net effective hyetograph using the geomorphologic parameters of a basin of order less than or equal to 17.

The rainfall-runoff data of Myntdu-Leska basin of Meghalaya are used in this study for calibration and validation of the model. The average hyetographs of two storm events of this basin are used to estimate the DRH. The comparison of estimated to actual hydrograph indicates that the response of the GIUH model gives a higher and delayed peak discharge. However, the total runoff from the basin matches with the actual values.

1.0 INTRODUCTION

The hydrologic response of a watershed to different input patterns (storms) has been of prime interest for researchers since very long. Once the response is established functionally, estimation of runoff can be optimized and further design of water resource systems/ projects can be accomplished. Since the transformation of rainfall into runoff is a complex phenomenon, hydrological modelling inevitably requires simplification or abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of simple structure. Models, formal or intellectual on the one hand or material on the other, are thus a central necessity of scientific procedure (Rosenbleuth and Wiener, 1945).

Hydrologic models represent the hydrologic cycle in various and appropriate ways. By using the models, natural phenomena can be understood or explained and under some conditions predictions can be made in a deterministic or probabilistic sense. With the increase in use of digital mini and micro computers, many models have been developed ranging from simple black box type empirical models to very sophisticated physically based distributed models. While the empirical models are very much site specific, the sophisticated models on the other hand require enormous physical data. In developing countries most of the watersheds are ungauged and the requirement of various types of physical data can not be met for a complete physically based modelling. Hence, a methodology in between these extreme types of modelling may be applied to estimate the runoff from rainfall. Unit Hydrograph (UH) Method is one such technique, which assumes a linearity of the transform function, is computationally attractive and often reasonably accurate (Huggins and Burney, 1982).

Application of the unit hydrograph method is based on the assumptions that (a) rainfall is spatially uniform over the entire watershed during the specified time period,

(b) the rainfall rate is constant, (c) the time base of the hydrograph of direct runoff is constant and (d) the hydrograph reflects all combined physical characteristics of the watershed. These assumptions are reasonable for isolated and small duration storms. However, varying intensity and intermittent storms are more common in nature, which restricts the use of a unit hydrograph of specific duration for the estimation of flood hydrograph due to a complex storm. Hence, the unit hydrograph with zero duration i.e., the instantaneous unit hydrograph (IUH) would serve the purpose for such a situation.

Attempts have been made for derivation of IUH for a watershed from sets of rainfall runoff data. Some of these are Nash model (Nash, 1957), Clark model (Clark, 1945) etc. However, the parameters estimated for the IUH using one set of data vary largely from those estimated from other set of data. Hence the consistency, basic requirement of a model, is largely diminished. Moreover, the procedure becomes an exercise in curve fitting with limited physical significance.

The channel network and geomorphological characteristics of a watershed are highly related with its retention and drainage. Significant work has been done in this direction to develop IUH from these parameters. Since the Geomorphological Instantaneous Unit Hydrograph (GIUH) approach is a general theory and can be applied to any watershed, once the model is developed it can be used for innumerable watersheds without any difficulty.

Keeping these things in view this study has been undertaken with the following objectives.

1. To develop a general purpose computer model for geomorphological instantaneous unit hydrograph.
2. To examine the applicability of the developed model for Myntdu-Leska Basin of Meghalaya.

2.0 REVIEW OF LITERATURE

The quantitative analysis of channel networks began with the classical work of Horton (1945). He classified the streams with their orders and established the fundamental laws of geomorphology. Strahler (1957) revised the Horton's scheme of ordering referring to only the interconnections, and not the lengths, shapes or orientation of the links comprising of a network. Shereve (1966) led the way for a theoretical foundation of Horton's empirical laws and provided new perspectives for many other problems in fluvial geomorphology. The statistical properties of stream lengths were analysed and a review on channel networks was made by Smart (1968, 1972).

The probabilistic approach of geomorphological instantaneous unit hydrograph (GIUH) was pioneered by Rodreguez-Iturbe and Valdes (1979) by assumption of a semi-markovian process for the time distribution. According to their theory (R-V theory), the instantaneous unit hydrograph (IUH) of a basin was interpreted as the probability distribution function (pdf) of the travel time that a drop of water landing anywhere in the watershed takes to reach the outlet. The time of travel in streams of given order was assumed to follow an exponential distribution. It was also assumed that a triangular IUH would reasonably specify the peak and time to peak. However, 'peak velocity of flow', a parameter in R-V GIUH was difficult to estimate.

Gupta *et al.* (1980) generalised the R-V theory of GIUH by employing a kinetic theoretic framework for obtaining an explicit mathematical representation of the GIUH at the basin outlet. They developed two examples, leading to explicit formulae for the IUH, which were analogous to solutions that would result if the basin were represented in terms of linear reservoirs and channels, respectively, in series and in parallel. They estimated the unknown parameter of the exponential distribution, assumed as time distribution function for travel of a drop in channels and overland region, through specifying the basin mean lag time independently. Their theory provided good agreement for the basins of larger areas but underestimated the peak flow for a smaller basin that was later explained by a quasi-linear approximation.

Rodreguez-Iturbe *et al.* (1982a) eliminated the mean velocity parameter by introducing climatic dependance in terms of kinematic wave parameters, intensity of rainfall and basic basin geomorphological parameters and termed it as geomorphocilmatic instantaneous unit hydrograph (GCIUH). Since GCIUH depends on the input it departs from the linear assumption of the traditional theory. Rodreguez-Iturbe *et al.* (1982b) evaluated the Nash model in relation to the geomorphoclimatic theory.

Cordova and Rodreguez-Iturbe (1983) developed a simple methodology for the estimation of flood probabilities, using geomorphoclimatic information. This methodology avoided the coupling of the frequencies in intensity and duration of rainfall with a peak discharge of a certain return period.

Other workers (Kirkby, 1976; Mesa and Mifflin, 1986; Naden, 1992) have proposed different formulations of GIUH based on the width function (WF) of the basin coupled with various routing procedures. In these cases, the hydraulic component is characterised by two parameters which represent the celerity and longitudinal diffusivity. These parameters can be determined from the geomorphologic characteristics.

Kirshen and Bras (1983) analysed the effect of linear channel on the GIUH. They derived the response of individual channels by solving the continuity and momentum equations for the boundary conditions defined by the IUH. Both the effects of upstream and lateral inflow to the channels were taken into account in the derivation of the basin's IUH. It was concluded that the adopted methodology was more accurate.

Gupta and Waymire (1983) reviewed the available methodologies and came with the fact that the incorporation of network geometry in terms of the Strahler ordered channels was not appropriate. They formulated an alternative analytical approach that required the use of the path number classification for the purpose.

Gupta and Mesa (1988) discussed the progress related to the need for a comprehensive quantitative theory of channel networks in three dimensions reflecting constraints of space filling and available potential energy as well as climatic hydrologic and geologic controls which are in dynamic equilibrium with channel network forms. They also identified the open problems in the direction.

Al-Turbak (1995) presented a geomorphoclimatic model with a physically based infiltration component. The model used the previous equations to calculate the peak discharge and time to peak which were then incorporated into an infiltration model for calculating the ponding time and effective rainfall intensity and duration. The model was found to predict the peak discharges reasonably well for the events for which detailed and accurate data were available.

Snell and Sivapalan (1994) examined three approaches by which geomorphology can be introduced through the probabilities and lengths of the pathways available within a network: (1) Using the Horton order ratios to derive analytical expressions for these pathways parameters, (2) Extracting these probabilities and lengths directly from Strahler ordered network without using Horton ordered ratios, and (3) using contributing area-flow distance function extracted directly from the digital elevation model without the assumptions of Strahler stream ordering. The geomorphological dispersion coefficient derived from the area-distance function expressed the natural dispersion within the catchment.

Franchini and O'Connell(1996) reviewed different formulations of the GIUH and compared the performances of the original GIUH and width function based IUH (WFIUH). Based on a study carried out on four sub-basins they concluded that the velocity parameter lacks physical interpretation unlike the hydraulic parameters of the WFIUH.

3.0 THEORETICAL CONSIDERATIONS

According to the original theory of the GIUH (Rodreguez-Iturbe & Valdes, 1979) and it's generalisation (Gupta *et al.*, 1980), the unit input i.e., unit depth of rainfall is considered to be composed of an infinite number of small, non-interacting drops of uniform size, falling instantaneously over the entire region. The travel time of one drop of water, chosen at random, from the basin to the outlet is the IUH of the basin. The travel of a drop to the outlet is dependent on the geomorphological features of the basin. The geomorphological laws, parameters responsible for the development of the IUH, with the detailed theory is presented as follows.

3.1. Geomorphological Parameters

The basin geomorphology plays an important role in transition of water from overland region to channels (streams) of different order and also from one order of channel to the other orders. The geomophological laws simplify the explanation of these transitions.

3.1.1. Ordering of channel network

The channel network is ordered according to the Strahler's scheme as per the following rules.

1. Channels that originate at a source (those are unbranched at the starting point) are termed as first order channels.
2. When two channels of order 'j' join, a channel of order 'j+1' is created.
3. When two channels of different order join, the resulting channel at the down stream of the junction retains the higher of the orders of the two joining channels.
4. The order of the basin is same as the highest order channel.

The above ordering scheme is explained in Fig. 1.

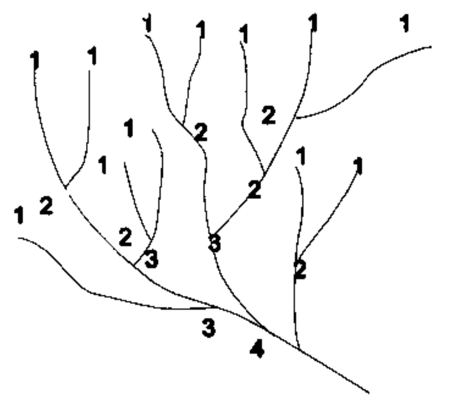

Figure 1 Ordering of stream network using Strahler's scheme

3.1.2. Laws of geomorphology

Let Ω denotes the order of the basin network. If N_i (i =1, 2, 3, ... , Ω) represents the number of streams of order i and L_{ji} (i =1, 2, 3, ... , Ω and j =1, 2, 3, ... , N_i) represents the length of the j^{th} stream of order i then the mean stream length of order i is given by

$$\overline{L}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} L_{ji} \qquad \text{... 1}$$

Using the ordering scheme described above, the Horton's laws of drainage may be expressed as follows. The law of stream numbers is given by

$$\frac{N_{i-1}}{N_i} = R_B \quad i = 1, 2, \ldots, \Omega \qquad \text{... 2}$$

Where, R_B is called as bifurcation ratio, which varies from 3 to 5 for natural basins.

The law of stream lengths is given by

$$\frac{\overline{L_i}}{\overline{L_{i-1}}} = R_L \quad i = 1, 2, \ldots, \Omega \qquad \text{... 3}$$

Where, R_L is the stream length ratio, which ranges from about 1.5 to 3 for natural basins.

Similar to the above laws a law for basin area was proposed by Schumm (Smart, 1972) and is given by

$$\frac{\overline{A_i}}{\overline{A_{i-1}}} = R_A \quad i = 1, 2, \ldots, \Omega \qquad \text{... 4}$$

Where, R_A is the area ratio which ranges from 3 to 6 for most of the basins; $\overline{A_i}$ is the mean area of basins of order i and is given by

$$\overline{A_i} = \frac{1}{N_i} \sum_{j=1}^{N_i} A_{ji} \qquad i = 1, 2, \ldots, \Omega \qquad \ldots 5$$

Where, A_{ji} refers to the area of the overland region that drains into j^{th} stream of order i (not the area of the surface region that drains directly into the j^{th} stream of order i only).

3.2. Derivation of GIUH

Considering a natural basin (B) and assuming that the water contained in the basin is coming as direct runoff i.e., losses due to evaporation, infiltration etc. already taken care of, the continuity equation for B becomes,

$$\frac{d\ S_B(t)}{dt} = -\ Q_B(t) + i_B(t) \qquad t > 0 \qquad \ldots 6$$

Where, t = any instant of time > 0; $S_B(t)$ = volume of water in storage within the basin at instant t; $Q_B(t)$ = outflow from the basin at instant t; and $i_B(t)$ = inflow into the basin i.e., rainfall at time t.

If the basin is dry initially and experiences an instantaneous input volume of i_0 in the form of rainfall, at time 0, and there is no input afterwards then the second term in the RHS of Eq. (6) becomes zero and the rate of change in storage becomes the outflow. Let i_0 consists of a very large number (n) of identical non interacting (or weakly interacting) drops, each having volume of u_0 such that $i_0 = n\ u_0$. Each drop will reach the basin outlet taking some time. If a drop, say i^{th} drop is selected at random from the basin whose holding time in the basin is T_B^i, $1 \leq i \leq n$, then it will contribute to the storage of the basin upto the instant, $t \leq T_B^i$. In other words, only those particles will contribute to the storage $S_B(t)$ whose holding times in the basin exceed t. Mathematically it can be given by

$$S_B(t)=\frac{i_0}{n}\sum_{i=1}^{n} I_{(t,\infty)}\ T_B^i \qquad \ldots 7$$

Where, $I_{(t,\infty)}(T_B^i) = 1$ if $T_B^i > t$ and 0 otherwise. Since n is a very large number and holding times of the drops are independent of each other, using the laws of large numbers, RHS of Eq. (7) can be given by

$$\frac{i_0}{n}\sum_{i=1}^{n} I_{(t,\infty)}\ \left(T_B^i\right) = i_0 E\left[I_{(t,\infty)}(T_B^i)\right] = i_0 P(T_B > t) \qquad \ldots 8$$

Where, $E[\ ]$ denotes the mathematical expectation and $P(T_B^i > t)$ denotes the probability of exceedance of T_B^i from t.

Substituting Eq. (8) in Eq. (7) and differentiating with respect to t,

$$\frac{dS_B(t)}{dt} = -\,i_0\ f_B(t) \qquad \ldots 9$$

Where, $f_B(t)$ denotes the probability density function of T_B. If i_0 is considered to be unity and input term in Eq. (6) is zero after the instantaneous rainfall then comparison of Eq. (6) and Eq. (9) gives that $f_B(t)$ is the discharge at the outlet, $Q_B(t)$, $t > 0$. Since the input is considered to be unity and instantaneous, the IUH, denoted by $h(t)$, is same as $Q_B(t)$. Hence it follows that

$$h(t) = f_B(t) \qquad \ldots 10$$

The derivation of the pdf of a drop reaching the outlet is tackled by defining a set of terms and rules as follows.

1. State is the order of the stream in which the drop is located at time t, denoted by c_i, $1 \le i \le \Omega$. When the drop is still in overland phase, the sate is the order of the stream to which the land drains directly, denoted by, r_i, $1 \le i \le \Omega$. A drop may begin at any state, but all drops eventually terminate in the highest numbered state $\Omega + 1$.
2. Transition is a change of state.

3. The only transition possible out of state r_i are those of the form $r_i \rightarrow c_i$, $1 \leq i \leq \Omega$.

4. The only transition possible out of state c_i are those of the form $c_i \rightarrow c_j$, $j > i$, $i = 1, 2, 3 \ldots \Omega$.

5. The state $c_{\Omega+1}$ is defined as the trapping state from which no transitions are possible.

The above rules define a set of limited number of paths through which a drop may travel to reach the outlet. For a 4[th] order basin (Fig. 1) the path space, i.e., set of paths can be derived as follows.

$$S = \{ s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8 \} \qquad \ldots 11$$

With the paths represented by as follows.

Path s_1: $r_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3 \rightarrow c_4 \rightarrow c_5$
Path s_2: $r_1 \rightarrow c_1 \rightarrow c_3 \rightarrow c_4 \rightarrow c_5$
Path s_3: $r_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_4 \rightarrow c_5$
Path s_4: $r_1 \rightarrow c_1 \rightarrow c_4 \rightarrow c_5$
Path s_5: $r_2 \rightarrow c_2 \rightarrow c_3 \rightarrow c_4 \rightarrow c_5$
Path s_6: $r_2 \rightarrow c_2 \rightarrow c_4 \rightarrow c_5$
Path s_7: $r_3 \rightarrow c_3 \rightarrow c_4 \rightarrow c_5$
Path s_8: $r_4 \rightarrow c_4 \rightarrow c_5$

The rules mentioned above, hence, only specify the spatial evolution of a drop through a geomorphic network of channels and surface regions. It can be very well proved that the path space for an n^{th} order basin would contain a finite and specific number of paths, i.e, 2^{n-1}.

During the travel of a drop along any one of the above paths it spends a certain amount of time in each of the states that compose the path. The time that a drop spends in state x (r_i or c_i), T_x is regarded as a random variable which can have an arbitrary probability density function and can be different from one state to the other. However, it is assumed that T_x and T_y are independent for $x \neq y$.

Defining π_i as the ratio of the area r_i to the total area of the basin and $p_{ci,cj}$ as the ratio of the channels of order i falling into channels of order j to the total number of channels of order i, the probability of a drop taking a path $s \in S$, of the form $s = <x_1, x_2, ..., x_n>$, where $x_i \in \{r_1, r_2, ..., r_\Omega, c_1, c_2, ..., c_\Omega\}$ is given by

$$p(s) = \pi_{x_1} \; p_{x_1,x_2} \; .... \; p_{x_k,l,k} \qquad ... 12$$

Denoting T_s as the total time taken by the drop to travel through the path s, it can be given by

$$T_s = T_{x_1} + T_{x_2} + ... + T_{x_k} \qquad ... 13$$

Since T_B is the random time which the particle spends in the basin can be given by

$$T_B = \sum_{s \in S} T_s \quad I_s \qquad ... 14$$

Where, $I_s = 1$ if the particle follows the path s else it is zero.

Since all the paths, $s \in S$ are distinct, from the basic rules defined above, using Eq. (14) the probability of T_B to be less than any instant t can be written as follows.

$$P(T_B < t) = \sum_{s \in S} P(T_s < t) p(s) = \sum_{s \in S} F_{x_1} * F_{x_2} * \; ... \; F_{x_k} p(s) \qquad ... 15$$
$$s = < x_1, x_2, ..., x_k >$$

Where, F_{xk} is the cumulative distribution function of T_{xk} and the asterisks denote the convolution operation. Differentiating Eq. (15) with respect to t on both the sides,

$$\frac{dP(T_B < t)}{dt} = h(t) = \sum_{s \in S} f_{x_1} * f_{x_2} * ... * f_{x_k} \qquad ... 16$$
$$s = < x_1, x_2, ..., x_k >$$

Let $i(\tau)$, $\tau > 0$, be the rainfall input at time 'τ' then for a small time interval $\Delta\tau$ (>0) the number of particles being injected is $i(\tau) \; \Delta\tau$ out of which the proportion of particles arriving at the outlet at time $t > \tau$ will be $h(t-\tau) \; i(\tau) \; \Delta\tau$. Since the total flow at time t is composed of the contribution from all the particles that were injected between times 0 and t, the ordinate of the hydrograph at time t is represented as,

$$Q_B(t) = \int_0^t h(t - \tau)\, i(\tau)\, d\tau \qquad \ldots 17$$

Eq. (17) gives the linear convolution transformation between input and the output.

Assuming the pdf f_{xi} is exponential with some parameter λ_{xi}, the term within the summation of the RHS of Eq. (16) becomes the k-fold convolution of independent but nonidentically distributed exponential random variables. And can be expressed in the form

$$\sum_{s \in S} f_{x_1} * f_{x_2} * \ldots f_{x_k} = \sum_{j=1}^{k} C_{jk} \; \exp\left\{-\lambda_{x_j} t\right\} \qquad \ldots 18$$

Where, C_{jk} are given by

$$C_{jk} = \frac{\lambda_{x_1} \cdot \lambda_{x_2} \cdot \ldots \lambda_{x_k}}{(\lambda_{x_1} - \lambda_{x_j}) \cdot (\lambda_{x_2} - \lambda_{x_j}) \cdot \ldots (\lambda_{x_{j-1}} - \lambda_{x_j}) \cdot (\lambda_{x_{j+1}} - \lambda_{x_j}) \cdot \ldots (\lambda_{x_k} - \lambda_{x_j})} \qquad \ldots 19$$

Hence the iuh with an exponential time distribution is given by

$$h(t) = \sum_{s \in S} \sum_{j=1}^{k} C_{jk} \; \exp\left\{-\lambda_{x_j} t\right\} \cdot p(s) \qquad s = \langle x_1 \ldots x_k \rangle \qquad \ldots 20$$

3.3. Estimation of parameters

The parameters used in Eq. (20) can be estimated from the basin geomorphology and hydrograph data. The path probability $p(s)$, for each path, can be expressed in terms of π_r and $p_{ci,cj}$ which in turn can be estimated from geomorphology as follows (Rodreguez-Iturbe and Valdes, 1979).

$$\pi_{r_1} = \frac{N_1 \overline{A_1}}{A_\Omega}$$

$$\pi_{r_i} = \frac{N_i}{A_\Omega}\left[\overline{A_i} - \sum_{j=1}^{i-1} \overline{A_j} \cdot \frac{N_j \cdot p_{ji}}{N_i}\right] \qquad i = 2, 3, \ldots, \Omega \qquad \ldots 21$$

$$p_{c_i, c_j} = \left\{ \frac{(N_i - 2N_{i-1})\, E[j, \Omega]}{\sum_{k=j}^{\Omega} E[k, \Omega]\; N_i} \right\} + 2 \cdot \frac{N_{i+1}}{N_i} \cdot \delta_{j+1, i} \qquad 1 \le j < i \le \Omega \qquad \ldots 22$$

Where, $\delta_{j+1, i} = 1$ if j = i+1 and 0 otherwise; $E[i, \Omega]$ denotes the mean number of channels of order i given by (Smart, 1972)

$$E[j, \Omega] = N_i \prod_{j=2}^{i} \left[\frac{N_{j-1} - 1}{2\, N_j - 1} \right] \qquad \ldots 23$$

Eqs. (21 and 22) are approximate estimate of probability of a drop falling in an overland region of order i and probability of a drop making transition from channels of order i to channels of order j respectively, which however can be estimated from basin geomorphology as follows.

$$\pi_{r_i} = \frac{\text{Area of the basin drining directly into channel of order } i}{A_\Omega} \qquad \ldots 24$$

And

$$p_{c_i, c_j} = \frac{\text{No. of channels of order } i \text{ draining into channels of order } j}{\text{Total no. of channels of order } i} \qquad \ldots 25$$

The computation of area contributing directly into a channel of order 'i' is explained in Fig. 2.

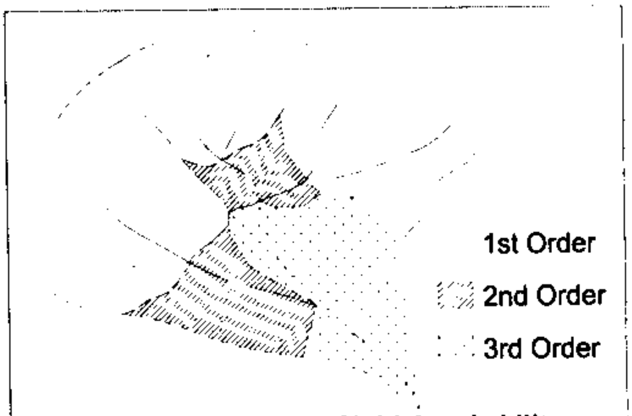

Figure 2 Estimation of initial probability

The mean holding time for channels of order i, $(1/\lambda_{ci})$, and overland regions of order i, $(1/\lambda_{ri})$, are assumed to be proportional to some characteristic length and given by as follows (Gupta *et al.*, 1980)

$$\frac{1}{\lambda_{c_i}} = \gamma \ \overline{L_i}^{1/3} \qquad 1 \leq i \leq \Omega \qquad \text{... 26}$$

$$\frac{1}{\lambda_{r_i}} = \gamma \left[\frac{\pi_{r_i} \ A_\Omega}{2 \ N_i \ \overline{L_i}} \right]^{1/3} \qquad 1 \leq i \leq \Omega \qquad \text{... 27}$$

The mean holding time for regions and channels ($1/\lambda_{ri}$ and $1/\lambda_{ci}$) are dependent on a proportionality factor γ which can be estimated from the mean holding time of the basin as follows.

The mean holding time of the basin can be expressed as the distance of centre of gravity (c.g.) of the hydrograph from the c.g. of the hyetograph and is given by,

$$K_B = \frac{\int_0^\infty t \ Q_B(t) \ dt}{\int_0^\infty Q_B(t) dt} - \frac{\int_0^{t'} t \ I(t) \ dt}{\int_0^{t'} I(t) dt} \qquad \text{... 28}$$

Where, $Q_B(t)$ and $I(t)$ are the discharge and intensity at time t and t' is the duration of rainfall.

The mean holding time of the IUH can be estimated as the first moment of $h(t)$ given by

$$K_B = \frac{\int_0^\infty t \ h(t) \ dt}{\int_0^\infty h(t) dt} = \frac{\int_0^\infty t \ h(t) \ dt}{1} = \int_0^\infty t \ h(t) \ dt \qquad \text{... 29}$$

Since $Q_B(t)$ is a linear transformation of the IUH, $h(t)$, the mean holding time estimated from both of these should be same. Substituting Eq. (20) in Eq.(29) and integrating yields,

$$K_B = \sum_{s \in S} p(s) \cdot \sum_{j=1}^{k} \frac{1}{\lambda_{x_j}} \qquad s = \langle x_1, x_2, \ldots, x_k \rangle. \qquad \text{... 30}$$

Substitution of Eqs. (26 and 27) in Eq. (30) result the RHS comprising of only unknown γ. Hence, when the K_B of a basin is determined from a set of hyetograph-hydrograph data, γ can be estimated using Eq. (30).

3.4. Development of Software for GIUH

The final form of the GIUH equation (Eq. 20) consist of a series exponential functions based on parameters C_{jk}, λ_{ci} and λ_{ri} which are in turn dependent on γ. Hence it can be programmed systematically to arrive at the final equation after estimation of the parameters. The approach used in this study to develop the general form of GIUH is given as follows

3.4.1. Estimation of parameters

The geomorphological parameters of the basin are read from keyboard and/ or a file. These include name of the basin, total area of the basin (km^2), order of the basin, number and length (km) of each order stream and no. of streams of one order falling into streams of higher order. Once the data are fed from the keyboard, these can be stored in a file named with the basin name (BASINNAME.INP; where, BASINNAME represents the first eight or less characters of the basin name).

After reading the basic parameters, π_i and p_{ij} are calculated using Eqs. (24 and 25) and a crosscheck is made for the data, using the following equations.

$$\sum_{i=1}^{\Omega} \pi_i = 1 \qquad \text{... 31}$$

$$\sum_{j=i+1}^{\Omega} p_{ij} = 1 \qquad 1 \le i < \Omega \qquad \text{... 32}$$

If the data are not correct then the process exits and the data set has to be reentered. A line starting with semicolon represents a comment thereby some provision has been made to include the comments inside the file such that the data are not mixed up.

If a set of hyetograph and corresponding hydrograph data are available, then the mean holding time of the basin, K_B is computed using Eq. (28). Since the time, rainfall intensity and discharge are in discrete form a numerical approximation of the equation, as follows, is used.

$$K_B = \frac{\sum_{j=2}^{mq} Q_j \cdot tcq_j}{\sum_{j=2}^{mq} Q_j} - \frac{\sum_{j=2}^{mi} I_j \cdot tci_j}{\sum_{j=2}^{mi} I_j} \quad \text{... 33}$$

Where, Q_j and I_j are the area of the hydrograph and hyetograph for the j-1[th] and j[th] time intervals; tcq_j and tci_j are the distance of centre of gravity of Q_j and I_j from time axis. These are given by

$$Q_j = 0.5 \cdot (q_j + q_{j-1}) \cdot (t_j - t_{j-1})$$
$$I_j = i_j \cdot (t_j - t_{j-1})$$
$$tcq_j = t_{j-1} + (t_j - t_{j-1}) \cdot \frac{(q_{j-1} + 2q_j)}{3(q_{j-1} + q_j)} \quad \text{(assuming trapizoidal strip)} \quad \text{... 34}$$
$$tci_j = t_{j-1} + \frac{(t_j - t_{j-1})}{2} \quad \text{(assuming rectangular strip)}$$

Where, q_j, I_j and t_j are discharge, intensity and time at j^{th} discrete level respectively; mq and mi number of discrete data available for discharge and intensity respectively.

If however, the hyetograph and corresponding hydrograph data are not available, or to input some average value of mean holding time, then an average value of K_B can also be given directly. The value of γ is determined using Eq. (30).

3.4.2. Determination of coefficients

The values of λ_{ri} and λ_{ci} are calculated using Eqs. (26 and 27) and the estimated value of γ.

A recursive algorithm is used to define and store all the possible paths for the stream network into a two dimensional array of integer. The serial no. of the path is represented by the first dimension and the second dimension contains the actual path (i.e., the order of streams which the drop would make transition to reach the outlet following the said path The paths can be determined up to a 17th order basin (for which the number of paths would be 65535!). Since the 16bit unsigned integer value can take up to a maximum value of 65535 only it is a limiting factor. But assigning a long integer (32bit-integer) to number of paths this problem can be solved. However, most of the natural basins/ sub basins are of under 17th order hence the 16bit unsigned integer value has been used for development of this software.

The path array is used further for calculation of *p(s)* values from the values of P_{ij} and π_i using Eq. (12) and then C_{ij} values are calculated using Eq. (19). C_{ij} again refers to a two dimensional array of real number with the fist dimension representing the path number and the second representing the coefficient number in the path. The values of C_{ij} are further cross-checked to examine the error in their estimation using the following equation.

$$\sum_{i=1}^{k} C_{si} = 0 \qquad s \in S, s = < x_1, x_2, \ldots, x_k > \qquad \ldots 35$$

Since the order of the basin, Ω, on which number of π_i, p_{ij}, $p(s)$, λ_{ci}, λ_{ri}, C_{ij}, path values depend, is not known before execution of the program, dynamic memory allocation is used for all the single and two dimensional arrays which are freed once the desired computations are over. Since calculation of these coefficients, during the process, are made in multiple phases there are chances of rounding off errors. When the erroneous values are used in exponential terms of the final equation, the final error is magnified exponentially. To minimise such rounding off errors, double precession is used for all the coefficients.

3.4.3. Estimation of IUH and convolution

The ordinate of the IUH at any instant t is determined using Eq. (20) and the parameters and coefficients estimated/ calculated as described in the earlier section. The computation of ordinates of a direct runoff hydrograph (DRH) however requires the evaluation of the convolution integral given by Eq. (17).

A numerical approximation of Eq. (17) of the following form is used to evaluate it using the discrete data of rainfall intensity.

$$Q_B(t) = \sum_{i=1}^{N} 0.5 \cdot (h_{t-i\cdot\Delta t} + h_{t-(i-1)\cdot\Delta t}) \cdot I_{i\cdot\Delta t} \cdot \Delta t \qquad \dots 36$$

Where, h_t is the ordinate of the IUH at time t calculated using Eq. (20); Δt given by t'/N is a small interval of time; I_t is the intensity of rainfall at time t (obtained from the hyetograph data); t' is a value of the time given by maximum of t and duration of the storm; and N is an integer can be fixed as per the requirement of accuracy (it is fixed as 100 in this study which gives a reasonable accuracy).

A unit hydrograph of duration D can be obtained very easily from Eq. (35) by fixing the storm duration to D hours and intensity of storm to $1/D$.

3.4.4. Conversion of units

The ordinates of the DRH obtained from Eq. (35) are having the dimensions of (T^{-1}) and units per hour (as the K_B value is expressed in hours) these are to be suitably converted to cumec by multiplying a factor which is given by

$$\frac{A_\Omega \times 10^6}{3600} \times 10^{-3} = \frac{A_\Omega}{3.6}$$

10^6 is multiplied to convert the area A_Ω (in km^2) into m^2; 10^{-3} is multiplied to convert the input (in mm) to metres and 3600 is divided to convert the hours into seconds.

4.0 STUDY AREA

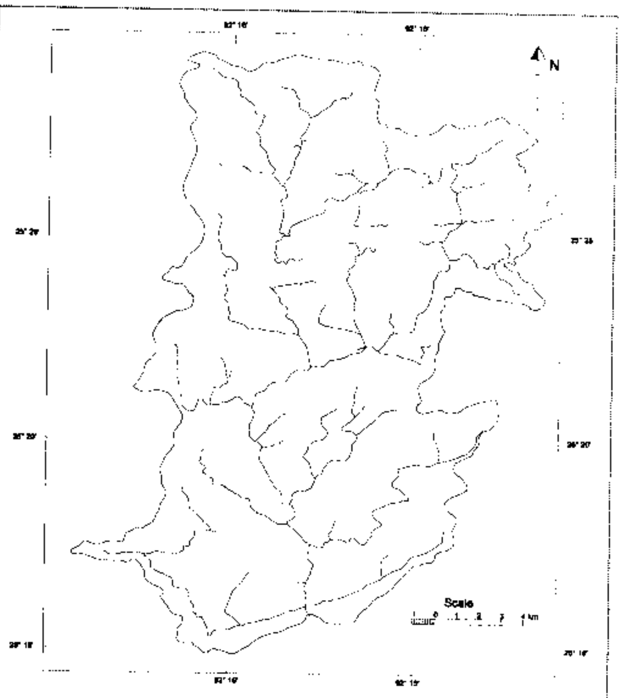

Figure 3. Location of the study area with stream network

The Myntdu river basin is located in Jaintia hills District of Meghalaya, in the northeastern part of India, in the southern slope of the state adjoining Bangladesh. Its geographic location extends from 92°15' to 92°30' E longitude and 25°10' to 25°17' N latitude (Fig.3). The area is narrow and steep, lying between central upland fall of the hills of Meghalaya. The catchment area is about 340 sq km and elevation range varies from about 1372m to 595m. The Myntdu river in the upper reaches originates from the place Mih Myntdu at an elevation of 1372 m and flows towards south for a distance of about 10 km with a steep gradient upto an elevation of about 1220 m. From this point river takes a sharp bend towards east and flows for a distance of about 11 km through a quite wide and flat valley full of cultivation and thickly populated villages. In the next 27 km the river gradually drops by about 595m and flows mostly through narrow valleys towards south west for the first 16 km while during the next 11 km it flows towards south upto an elevation of 595 m near Leska where two tributaries of Myntdu namely Umshakaniang from the west and Lamu from the east meet the main river.

4.1. Climate

The climate is moderate being sub-tropical with medium to sparse vegetation. Summer temperature varies from 24°C to 32°C and in winter temperature ranges between 3°C to 12°C. Sometimes during winter frost occurs in high hills located in the catchment, but there is no instance of snowfall.

The main rain season in this area is May to October. There is also some precipitation during pre-monsoon and post monsoon periods. The annual rainfall in the catchment varies from the 3537 mm to 13710 mm. The lack of forest cover in the catchment with steep slopes gives instantaneous runoff, allowing little time for ground water storage.

4.2. Water Resources

The river Myntdu is endowed with vast water resources potential for irrigation and power generation. The river has surplus water during rainy season. The yield is variable within wide limits from season to season. The monthly average yield during the lean season of about four months, from November to February is 92 Mm^3 and 1951 Mm^3 during rest of the year. There is also appreciable variation in the annual yield from year to year. At Leska, a hydel project has been proposed by Meghalaya State Electricity Board and still it is at design and investigation stage.

4.3. Vegetation

The sub tropical humid climate with very heavy rainfall helps the nature to keep the hills covered with green vegetation. The variation in elevation and rainfall pattern gives it a vivid type of flora and fauna, many of this are not to be seen in any other parts of the country. This area is characterised by jhoom cultivation, which involves the destruction of forest cover, for putting in seeds for crops. Orchards of orange are very common in this area. The principal crop is paddy. The area is very leanly populated. The barren land covers the maximum part (76.63 %). Wherever there is depression between the high lands, thick jungles of mixed forest grow due to good soil by the outwash of the slopes.

4.4. Meteorological Stations

Daily rainfall records have been maintained at three different rain gauge stations namely Pdengshkap, Bataw and Jarain since 1976. Further, rainfall data of Jowai station are available with the Indian Meteorological department for substantial period and five years data have already been supplied. Apart from these rainfall records of Cherapunjee (approximately 50 km. from Myntdu) is available for about 100 years. Hourly rainfall records near dam site for five years are available and supplied. The rainfall data of the catchment is available from three rain gauge stations *viz*. Jowai, Jarain and Pdengshkap which fall within the catchment and a raingauge station at Bataw, which falls just outside the boundary of the catchment

Gauge and Discharge data at Leska dam site are available from 1977. Another discharge station at Pesadwar about 20 km distance of Leska Weir was established in 1980. Central Water Commission is also maintaining a discharge site since 1970 at Kharkhana 18 down stream of dam site. Three hourly gauge data along with W.L is available only for 1985-1986 at Leska discharge site.

5.0 ANALYSIS OF RESULTS

A computer program for GIUH model is developed following the procedures discussed in Art. 3 and is applied for the study area (Myntdu-Leska basin) the results obtained from the model are presented below.

5.1. Geomorphological Parameters of the Study Area

To estimate the geomorphological parameters of the study area the catchment is delineated from 1:50,000 scale toposheets of Survey of India. The basin with its stream network and contours are then digitised for further use. The stream network is ordered using Strahler's ordering procedure. From the digitised map the basic linear and areal parameters like basin perimeter, length of streams, basin length, basin area etc. are measured. Other parameters are estimated using standard procedure. The geomorphological parameters thus obtained are presented in **Tables 1 to 3**. Some additional parameters, which are required for the GIUH model, are also estimated and presented in **Tables 4 and 5**.

Table 1. Linear aspect of Myntdu basin

S.No.	Parameters	Value
1.	Length of main channel, L	51.778 km
2.	Length upto centroid, L_c	16.155 km
3.	Total length of channel, L_t	994.332 km
4.	Mean Length of overland flow L_o	0.1709 km
5.	Basin perimeter, P	113.583 km
6.	Watershed eccentricity,	0.2324 km
7.	Stream Length ratio, R_l	2.1232
8.	Wandering ratio, R_w	1.9897
9.	Fineness ratio, R_f	0.4559
10.	Division ratio, R_d	4.4015
11.	Bifurcation ratio, R_b	3.6648
12.	Length of Basin/ Valley Length, L_v	26.023 km
13.	Drainage Density, D	2.9264 km/ sq km

Table 2. Areal aspect of Myntdu river basin

Sl. No.	Parameters	Value
1.	Drainage Area, A	339.778 sq km
2.	Drainage Density, D	2.9264 km/sq km
3.	Constant of channel maintenance, C	0.342 sq km/ km
4.	Channel segment frequency, F	4.241 per sq km
5.	Circularity Ratio, R_c	0.3310
6.	Elongation Ratio, R_e	0.7990
7.	Watershed Shape Factor, R_s	2.7780
8.	Unity shape factor, R_u	1.4118
9.	Form factor, R_f	0.1267
10.	Compactness ratio, R_k	1.7382
11.	Area ratio, R_a	4.6112

Table 3. Relief aspects of Myntdu river basin

Sl. No.	Parameters	Value
1.	Basin Relief, H	0.7770 km
2.	Relief Ratio, R_h	0.0299
3.	Relative relief, R_{hp}	0.6840 %
4.	Ruggedness number, R_n	2.2761
5.	Average slope of watershed, S_a	0.0588

Table 4. Measurement of drainage network

Stream order	No of Streams	Stream length	Average length	Area	Average area	Area draining directly
		(km)	(km/ each)	(km^2)	(km^2/ each)	(km^2)
1	1148	609.985	0.5313	196.7	0.1714	196.7399
2	233	180.259	0.7736	184.9 40	0.7936	61.2875
3	45	100.328	2.2295	190.8 18	4.2408	32.7702
4	12	59.758	4.9798	216.4 36	18.0406	31.7755
5	2	28.767	14.3835	173.8 87	86.9276	10.8273
6	1	15.235	15.2350	339.7 55	339.7760	6.3752

76

Table 5. Streams falling into different orders

	No. of streams falling into different higher orders					
Stream order	2	3	4	5	6	Total
1	709	189	128	68	54	1148
2		152	43	22	16	233
3			30	11	4	45
4				7	5	12
5					2	2
6						1

The initial and transitional probabilities are extracted from the information given in **Tables** 4 and 5 and are presented below in **Table 6**.

Table 6. Initial and transitional probability matrices

		p_{ij}					
Stream order	π_i	2	3	4	5	6	Total
1	0.5790	0.6176	0.1646	0.1115	0.0593	0.0470	1
2	0.1804		0.6524	0.1845	0.0944	0.0687	1
3	0.0964			0.6667	0.2444	0.0889	1
4	0.0935				0.5833	0.4167	1
5	0.0319					1.0000	1
6	0.0187						-
Total	1.0000						

5.2. Estimation of IUH

The above geomorphological along with the average hyteograhph (rainfall data of two stations *viz.* Nukkum and Jowai are averaged using weights obtained by monthly average of isohyetes) are used for the estimation of paramters and calibration of the IUH.

Since the K_B values obtained from the available data vary from one set to the other an average value of K_B (= 2.7434), estimated from four events, are used to estimate the parameter γ. The value of γ thus obtained is 0.3783. Since the order of the basin is 6 there are 32 number of possible paths for the travel of a drop. Using the initial and transitional probabilities for each transition, the probability of each path is calculated. **Table 7** represents all the 32 paths and their probilities.

Table 7. Description f the path space with probabilities

Path N.	Path descriptin	Prbability
1	R1→ c1→c2→c3→c4→c5→c6→Ω	0.0907
2	R1→ c1→c2→c3→c4→c6→Ω	0.0648
3	R1→c1→c2→c3→c5→c6→Ω	0.0570
4	R1→c1→c2→c3→c6→Ω	0.0207
5	R1→c1→c2→c4→c5→c6→Ω	0.0385
6	R1→c1→c2→c4→c6→Ω	0.0275
7	R1→c1→c2→c5→c6→Ω	0.0338
8	R1→c1→c2→c6→Ω	0.0246
9	R1→c1→c3→c4→c5→c6→Ω	0.0371
10	R1→c1→c3→c4→c6→Ω	0.0265
11	R1→c1→c3→c5→c6→Ω	0.0233
12	R1→c1→c3→c6→Ω	0.0085
13	R1→c1→c4→c5→c6→Ω	0.0377
14	R1→c1→c4→c6→Ω	0.0269
15	R1→c1→c5→c6→Ω	0.0343
16	R1→c1→c6→Ω	0.0272
17	R2→c2→c3→c4→c5→c6→Ω	0.0458
18	R2→c2→c3→c4→c6→Ω	0.0327
19	R2→c2→c3→c5→c6→Ω	0.0288
20	R2→c2→c3→c6→Ω	0.0105
21	R2→c2→c4→c5→c6→Ω	0.0194
22	R2→c2→c4→c6→Ω	0.0139
23	R2→c2→c5→c6→Ω	0.0170
24	R2→c2→c6→Ω	0.0124
25	R3→c3→c4→c5→c6→Ω	0.0375
26	R3→c3→c4→c6→Ω	0.0268
27	R3→c3→c5→c6→Ω	0.0236
28	R3→c3→c6→Ω	0.0086
29	R4→c4→c5→c6→Ω	0.0546
30	R4→c4→c6→Ω	0.0390
31	R5→c5→c6→Ω	0.0319
32	R6→c6→Ω	0.0188
	Total	1.0000

Using the average value of γ, the parameters λ_{ri} and λ_{ci} are calculated (**Table 8**) using Eq. 26 and 27 then coefficients (C_{ij}) for the final GIUH function are calculated. The path-wise C_{ij} values are presented in **Table 9**.

Table 8. Exponential parameters of the GIUH*

Order	λ_{ri}	λ_{ci}
1	4.8559	3.2633
2	4.7713	2.8792
3	4.8355	2.0232
4	4.1105	1.5478
5	4.6123	1.0868
6	4.4522	1.0662

*K_B = 2.7434; γ = 0.3783

Table 9. Coefficients of the response function (Eq. 20)

Path No.	C_{ij} Values for the path (as per Table 6)							ΣC_{ij}
1	0.393	-26.603	58.880	-129.230	207.597	-1264.031	1152.995	0.000
2	-1.363	53.276	-97.102	111.344	-88.048	21.894		0.000
3	-0.840	29.486	-50.648	39.697	-376.450	358.755		0.000
4	2.912	-59.049	83.527	-34.203	6.812			0.000
5	-0.550	16.306	-24.910	48.784	-585.026	545.397		0.000
6	1.908	-32.653	41.080	-20.691	10.356			0.000
7	1.176	-18.073	21.427	-174.231	169.701			0.000
8	-4.077	36.192	-35.337	3.222				0.000
9	-0.270	3.549	-38.419	95.997	-786.887	726.028		0.000
10	0.936	-7.108	33.101	-40.715	13.786			0.000
11	0.577	-3.934	11.801	-234.349	225.904			0.000
12	-1.999	7.878	-10.168	4.290				0.000
13	0.378	-2.175	22.559	-364.192	343.430			0.000
14	-1.310	4.356	-9.568	6.521				0.000
15	-0.807	2.411	-108.463	106.859				0.000
16	2.799	-4.828	2.029					0.000
17	-0.218	7.114	-49.738	110.047	-847.384	780.178		0.000
18	0.739	-11.733	42.854	-46.674	14.815			0.000
19	0.454	-6.120	15.278	-252.366	242.753			0.000
20	-1.538	10.093	-13.164	4.610				0.000
21	0.296	-3.010	25.860	-392.191	369.045			0.000

22	-1.003	4.964	-10.968	7.008				0.000
23	-0.616	2.589	-116.801	114.829				0.000
24	2.089	-4.270	2.180					0.000
25	0.134	-14.643	50.566	-525.456	489.400			0.000
26	-0.463	12.617	-21.446	9.293				0.000
27	-0.285	4.498	-156.490	152.277				0.000
28	0.984	-3.876	2.892					0.000
29	-0.313	12.959	-256.301	243.655				0.000
30	0.870	-5.496	4.627					0.000
31	0.428	-73.458	73.031					0.000
32	-1.402	1.402						0.000

It is observed from **Table 9** that the sum of the coefficients for each path is zero ensuring the response to be zero at $t = 0$.

Substituting C_{ij} in Eq. (20) the ordinates of the IUH with respect to time are obtained. The response function for unit input (i.e, 1 mm of rainfall) is presented in **Fig. 4**. From the figure it cam be observed that the peak is attained after about 2 hours of start of rainfall (t_p = *1.9h*). The peak is observed to be 0.2941 sec^{-1} which, wiien multiplied by the factor (= 339.7758/ 3.6 = 94.38217), is found to be 27.7578 cumec. In other words a peak discharge of 27.7578 cumec would occur after 1.9 hours of instantaneous rainfall of 1 mm throughout the basin.

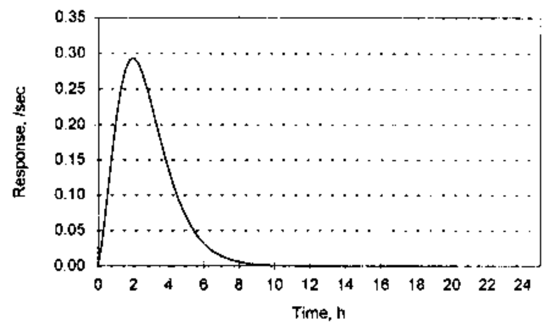

Figure 4. Geomorphological Instantaneous Unit Hydrograph for Myntdu-Leska Basin

5.3. Computation of Unit Hydrographs from IUH

Unit hydrographs with 1, 2, 3 and 4 hours duration of rainfall are computed by evaluating the convolution integral and are presented in **Fig. 5**. It is observed from the figure that the t_p values for 1, 2, 3 and 4-hour storms are 2.5, 3, 4 and 4.5 and respectively with Q_p values 27.0031, 25.1926, 22.507 and 20.0477 respectively. Hence the time to peak increases with the increase in storm duration, however the peak discharge decreases giving a prolonged flood.

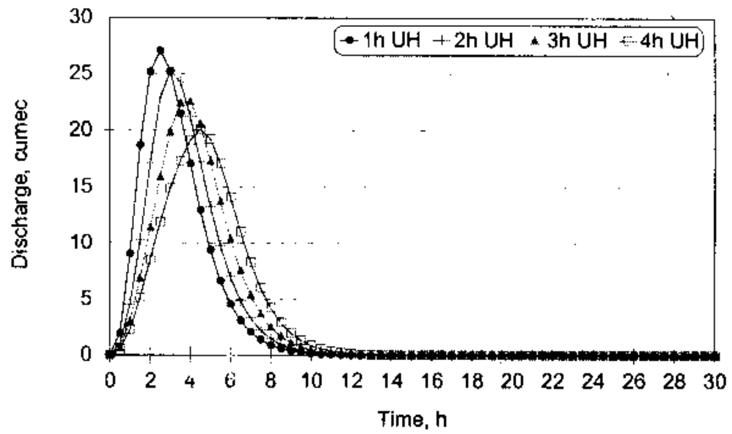

Figure 5. Unit Hydrographs of Different Storm Duration

5.4. Computation of Hydrograph from Hyetograph

Two approximate hyetographs for the study area are obtained by taking the average intensity of rainfall at two raingauge stations in the basin. Since other raingauge stations are having non-recording type raingauges their data could not be used for the hyetograph-hydrograph analysis. The hyetographs are then used as input to the GIUH model and the response of the model for both the cases are obtained. The response of the model is then compared with the actual hydrographs recorded at the gauging site. The comparison for bot the cases are shown in **Figs. 6** and **7**. It is observed from both the cases that the GIUH model gives a higher and delayed peak discharge for the basin compared to the actual hydrograph data. This may be a result of assumption of an average mean holding time (assumed to be

2.7434 hours in this analysis) which is too less compared to the actual. Also the weights assigned for averaging of rainfall intensity may be disproportional, making the intensity too high compared to the actual, resulting a higher peak discharge. However the area under both the curves (response of GIUH and actual hydrograph) are fairly equal. This signifies the correctness of the model.

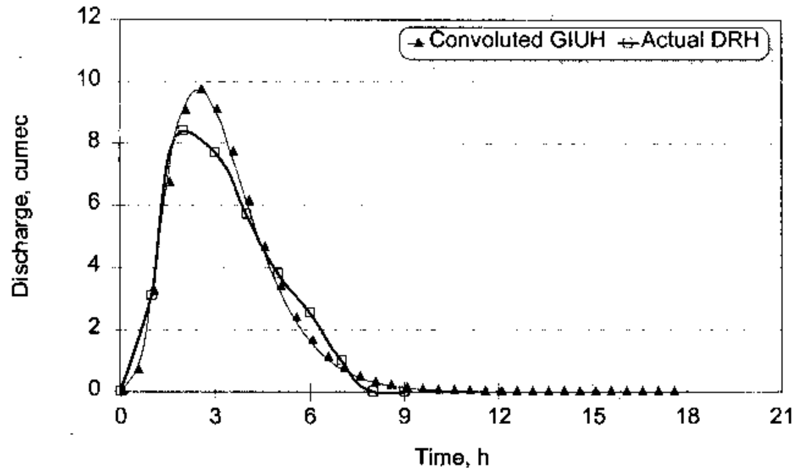

Figure 6 Comparison of DRH for the Storm on 26.08.96

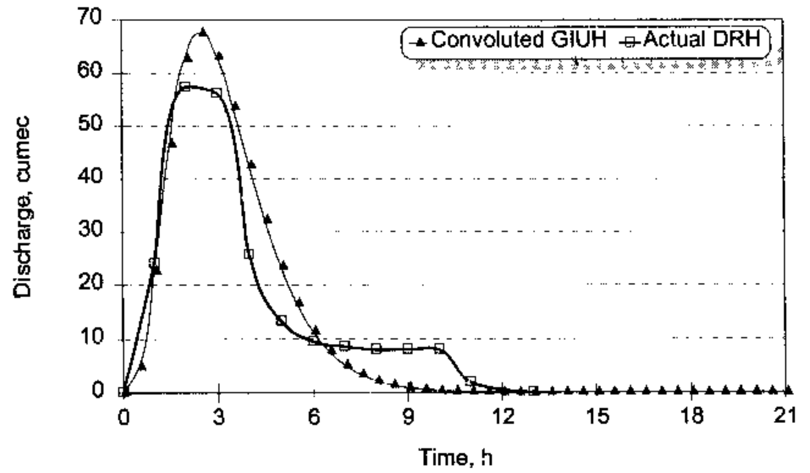

Figure 7 Comparison of DRH for the Storm on 03.09.96

6.0 CONCLUDING REMARKS

IUH serves as a very good tool for the estimation of flood hydrograph of a basin. Of the techniques available for development of IHU, Nash and Clarke model are most common in use. However, the use of these models is limited to a certain set of data, and lack physical significance as the complexity of the basin increase. In view of this a model capable of deriving IUH from geomorphological features has gained considerable attention.

The theory of GIUH starts with the assumption that rainfall that occurs over a basin is composed of infinite number of non-interacting drops of uniform size. The drops spend some time in one state and then make transitions from one state to the other to reach the basin outlet. Hence the time distribution of one drop chosen at random from the basin defines the IUH of the basin. The time spent by a drop in a state is dependent on the distance it travels in that state and the functional relationship of time and distance. In most of the cases it is assumed to be one parameter exponential distribution. The basic structure of the GIUH, given by Rordiguez-Iturbe and Valdes (1979) contains a parameter 'peak velocity of flow', which is difficult to estimate. However, the parameter of the GIUH from a generalised theory (Gupta *et al.*, 1980) can be estimated from the direct runoff hydrograph and hyetograph data.

In this study a GIUH model is developed using the generalised theory. General-purpose software is developed for the model, which is capable of estimating the DRH from the net effective hyetograph. The software can be used for any basin of order less than or equal to 17. The sample input and output of the model are given in **Appendices 1** and **2**.

Myntdu-Leska basin of Meghalaya is taken as the study area. The average hyetographs of two storm events of the study area are used to estimate the DRH. The comparison of estimated to actual hydrograph indicates that the response of the GIUH model gives a higher and delayed peak discharge. This, however, may be due to incorrect estimation of parameters. Since sufficient number of rainfall-runoff events are not available the parameter is estimated from four events only and the validation is made with two events. The total runoff from the basin matches with the actual values.

When applied to a basin with sufficient number of rainfall-runoff data the model would give better results.

REFERENCES

Al-Turbak, A. S. (1996) Geomorphoclimatic peak discharge model with a physically based infiltration component. J. Hydrol., 177: 1-12.

Clark, C. O. (1945) Storage and the unit hydrographs. Trans. of ASCE, 110.

Cordova, J. R. and Rodreguez-Iturbe, I. (1983) Geomorphoclimatic estimation of extreme flow probabilities. J. Hydrol., 65: 159-173.

Franchini, M. and O'Connell, P. E.(1996) An analysis of the dynamic component of the geomorphologic instantaneous unit hydrograph. J. Hydrol., 175: 407-428.

Gupta, V. K. and Mesa, O. J. (1988) Runoff generation and hydrologic response via channel network geomorphology - recent progress and open problems. J. Hydrol., 102: 3-28.

Gupta, V. K. and Waymire, E. (1983) On the formulation of an analytical approach to hydrologic response and similarity at basin scale. J. Hydrol., 65: 95-123.

Gupta, V. K., Waymire, E. and Wang, C. T. (1980), Representation of an instantaneous unit hydrograph from geomorphology. Water Resour. Res., 16(5): 855-862.

Horton, R. E. (1945) Erosional development streams and their drainage basins: Hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Am., 56: 275-370.

Huggins, L. F. and Burney, J. R. (1982) Surface runoff storage and routing. In: Haan, C. T., Johnson, H. P. and Brakensiek, D. L. (ed.), Hydrologic modelling of small watersheds. ASAE monograph No. 5. Pp 201-203.

Kirkby, M. J. (1976) Tests of the random network model and its application to basin hydrology. Earth Surface Processes, 1: 197-212.

Kirshen, D. M. and Bras, R. L. (1983) The linear channel and its effect on the Geomorphologic IUH. J. Hydrol. 65: 175-208.

Mesa, O. J. and Mifflin, E. R. (1986) On the relative role of hillslope and network geometry in hyrologic response. In: Gupta, V., Rodriguez-Iturbe, I. and Wood, E. (Ed.) Scale Problems in Hydrology. D. Reidel. Dordrecht, pp 1-7.

Naden, P. S. (1992) Spatial variability in flood estimation: the exploitation of channel network structure. J. Hydrol. Sci., 37(1-2): 53-71.

Nash, J. E. (1957) The form of the instantaneous unit hydrograph. IASH Publ., 42: 114-118.

Rodreguez-Iturbe, I. and Valdes, J. B. (1979) The geomorphologic structure of hydrologic response. Water Resour. Res., 15(6): 1435-1444.

Rodreguez-Iturbe, I and Gonzalez-Sanabria, M. (1982a) A geomorphoclimatic theory of the instantaneous unit hydrograph. Water Resour. Res., 18(4): 877-886.

Rodreguez-Iturbe I., Gonzalez-Sanabria, M. and Caamano (1982b) On the climatic dependance of the IUH: A rainfall runoff ,odel of the Nash model and the geomorphoclimatic theory. Water Resour. Res., 18(4): 887-903.

Rosenblueth, A. and Wiener, N (1945) Role of models in science. Phil. Sci., 7(4): 316-321

Shereve, R. L. (1966) Statistical laws of stream number. J. Geol., 74: 17-37.

Smart, J. S. (1968) Statistical properties of stream lengths. Water Resour. Res., 4(10): 1001-1021.

Smart, J. S. (1972) Channel networks. Advances in Hyrdosci., 8: 305-346.

Snell, J. D. and Sivapalan, M. (1994) On geomorphological dispersion in natural catchments and the geomorphological unit hydrograph. Water Resour. Res., 30(7): 2311-2323.

Strahler, A. N. (1957) Watershed geomorphology. Trans. Am. Geophys. Union, 38(6): 913-920.

Input data

File name: MYNTDU.INP

```
;Basin name
      myntdu
;Basin order
      6
;Basin area
      339.7758
;No. of 1 order streams
      1148
;Length of 1 order streams
      609.9850
;Area draining directly to 1 order streams
      196.7399
;No. of 1 order streams falling into 2 order streams
      709
;No. of 1 order streams falling into 3 order streams
      189
;No. of 1 order streams falling into 4 order streams
      128
;No. of 1 order streams falling into 5 order streams
      68
;No. of 1 order streams falling into 6 order streams
      54
;No. of 2 order streams
      233
;Length of 2 order streams
      180.2590
;Area draining directly to 2 order streams
      61.2875
;No. of 2 order streams falling into 3 order streams
      152
;No. of 2 order streams falling into 4 order streams
      43
;No. of 2 order streams falling into 5 order streams
      22
;No. of 2 order streams falling into 6 order streams
      16
;No. of 3 order streams
      45
;Length of 3 order streams
      100.3280
;Area draining directly to 3 order streams
      32.7702
;No. of 3 order streams falling into 4 order streams
      30
;No. of 3 order streams falling into 5 order streams
      11
;No. of 3 order streams falling into 6 order streams
      4
```

```
;No. of 4 order streams
      12
;Length of 4 order streams
      59.7580
;Area draining directly to 4 order streams
      31.7755
;No. of 4 order streams falling into 5 order streams
      7
;No. of 4 order streams falling into 6 order streams
      5
;No. of 5 order streams
      2
;Length of 5 order streams
      28.7670
;Area draining directly to 5 order streams
      10.8273
;No. of 5 order streams falling into 6 order streams
      2
;No. of 6 order streams
      1
;Length of 6 order streams
      15.2350
;Area draining directly to 6 order streams
      6.3752
```

Program Output

File name: MYNTDU.PAR

Initial state matrix:

Order	Probability
1	0.5790
2	0.1804
3	0.0964
4	0.0935
5	0.0319
6	0.0188
TOTAL	1.0000

Transitional probability matrix:

	1	2	3	4	5	6	Total
1	0.0000	0.6176	0.1646	0.1115	0.0592	0.0470	1.0000
2	0.0000	0.0000	0.6524	0.1845	0.0944	0.0687	1.0000
3	0.0000	0.0000	0.0000	0.6667	0.2444	0.0889	1.0000
4	0.0000	0.0000	0.0000	0.0000	0.5833	0.4167	1.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000
6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Path probablilities

Path No.	Probability
1	0.0907
2	0.0648
3	0.0570
4	0.0207
. . . .	
. . . .	
29	0.0546
30	0.0390
31	0.0319
32	0.0188
TOTAL	1.0000

Lambda valuses (Kb = 2.7434 and gamma = 0.3783)

n	r	c
1	4.8559	3.2633
2	4.7713	2.8792
3	4.8355	2.0232
4	4.1105	1.5478
5	4.6123	1.0868
6	4.4522	1.0662

```
      Cij values for different paths
1  0.3929 -26.6033  58.8800  -129.2302 207.5971 -1264.0310  1152.9946
0.0000
    1    2    3    4    5    6    7
2  -1.3626  53.2755 -97.1024 111.3440 -88.0484  21.8938   0.0000
    1    2    3    4    6    7
. . . . . . . . . . . .
. . . . . . . . . . . .
32 -1.4019   1.4019   0.0000
    6    7

      Kb from IUH:     2.7420
```

File name: MYNTDU.PTH (All the possible paths for the basin)

```
1      r1==>c1==>c2==>c3==>c4==>c5==>c6==>O       (0.0907)
2      r1==>c1==>c2==>c3==>c4==>c6==>O      (0.0648)
3      r1==>c1==>c2==>c3==>c5==>c6==>O      (0.0570)
4      r1==>c1==>c2==>c3==>c6==>O     (0.0207)
. . . . . . . . . . . .
. . . . . . . . . . . .
28     r3==>c3==>c6==>O   (0.0086)
29     r4==>c4==>c5==>c6==>O   (0.0546)
30     r4==>c4==>c6==>O   (0.0390)
31     r5==>c5==>c6==>O   (0.0319)
32     r6==>c6==>O (0.0188)
       There are 32 possible paths for basin myntdu
```

File name: MYNTDU.IUH (Time vs. ordinates of GIUH)

```
  0.0000         0.0000
  1.0000         0.2061
  2.0000         0.2941
  3.0000         0.2291
  4.0000         0.1358
. . . . . . . . .
. . . . . . . . .
 27.0000         0.0000
 28.0000         0.0000
 29.0000         0.0000
 30.0000         0.0000
```

File name: MYNTDU.01H (Time vs. ordinates of one-hour unit hydrograph)

```
  0.0000         0.0000
  0.5000         1.9196
  1.0000         9.0189
  1.5000        18.6441
. . . . . . . . .
. . . . . . . . .
 17.0000         0.0002
 17.5000         0.0001
 18.0000         0.0001
. . . . . . .
```

DIRECTOR : Dr.S.M.SETH

COORDINATOR : Dr.K.K.S.BHATIA

HEAD : B.C.PATWARY

STUDY GROUP :NIRANJAN PANIGRAHY, Sc 'B'