Runoff estimation from a hilly watershed using geomorphologic instantaneous unit hydrograph

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Abstract: Estimation of direct runoff using Geomorphologic Instantaneous Unit Hydrograph (GIUH) for a fourth-order hilly watershed in Uttarakhand (India) is presented in this study. The kinematic-wave theory was used to analytically and probabilistically determine the travel times for overland-flow and stream-flow in Horton-Strahler stream-ordering system of the watershed using topographic parameters alone (GIUH-I), and in terms of stream-order-law ratios (GIUH-II). The time to peak runoff for the predicted hydrograph was occurring about one half-hour prior (25% error) to that of the observed one for the given data set; however, the hydrograph shapes were comparable. The coefficient of efficiency for models was lower probably due to the shift in the predicted time to peak runoff, while the errors in magnitude of peak runoff and volume were within the acceptable limits. The GIUH-I model gave better prediction of peak and runoff volume. However, on the basis of coefficient of efficiency alone, the GIUH-II was found to be better than GIUH-I. Because these models utilize only topographic and geomorphologic parameters of the watershed and the only measurable field data is the width of watershed-outlet, these models are well applicable to ungauged hilly watersheds.

Keywords: geomorphologic instantaneous unit hydrograph, runoff, hilly watershed, soil conservation

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1 Introduction

Evaluation of the effects of soil conservation and flood control programmes and economic appraisal of watershed resources development and management projects requires accurate methodology for prediction of watershed runoff. The hydrological behavior of a natural watershed is an extremely complex phenomenon due to the vast spatial and temporal variability of physiographic and climatic characteristics, and various complex and interdependent processes involved in the rainfall-runoff transformation. In this context, Sherman (1932) initiated the important theory of Unit Hydrograph (UH), which may be defined as a direct runoff hydrograph, resulting from one unit of rainfall-excess uniformly distributed spatially over the watershed for the entire duration of its occurrence. If the duration of rainfall excess is assumed to be infinitesimally small, the UH so developed is called an instantaneous unit hydrograph (Chow, 1964). Due to the scarcity of hydrologic and physiographic data, conceptual models are generally used to simulate the rainfall-runoff transformation process (Nash, 1957; Dooge, 1959).

In order to develop the rainfall-runoff models for ungauged watersheds, the hydrologists used empirical relationships to determine the parameters of the conceptual models. However, these empirical relationships are not universal and therefore require extensive analysis of watershed experimental data. The introduction of the geomorphologic instantaneous unit hydrograph (GIUH) by Rodriguez-Iturbe and Valdes...
As an advantage over that, these GIUH-based Clark and Nash models were gauged data numerically by Gupta et al. (1976) and Stephenson (1979) for which Wooding (1965) presented the instantaneous unit hydrograph of the basin. They derived the equations for the peak and time to peak of an IUH in terms of Horton’s order ratios. This concept was further generalized by Gupta, Waymire and Wang (1980) for developing two examples leading to explicit formulae for the IUH which were analogous to the solutions resulting from the basin represented in terms of linear reservoirs and channels in series and in parallel.

Lighthill and Whitham (1955) introduced the kinematic-wave theory and utilized it in describing flood movement in long rivers. They proved that the velocity of the main part of a natural flood wave approximates that of a kinematic wave. The major assumption in kinematic-wave theory is that the friction slope is approximated by the bed slope of the channel; also, the back-water effect is neglected as in case of channels with steep bed slopes. Wooding (1965) numerically calculated the predicted form of stream hydrograph using the kinematic wave theory for flow over a catchment and along the stream, assuming that the rainfall is of constant intensity and of finite duration. Miller (1984) summarized several criteria for determining when the kinematic wave approximation is applicable, but there is no single, universal criterion upon which to base this decision. As an advantage over the unit hydrograph method, the kinematic-wave model of the rainfall-runoff process is a solution of the physical equations governing the surface flow, but the solution is only for one-dimensional flow, whereas the actual watershed surface flow is two-dimensional as the water follows the topography of the land surface. Overton and Meadows (1976) and Stephenson and Meadows (1986) presented detailed information on the application of kinematic-wave models for the rainfall-runoff process.

Lee and Yen (1997) derived the GIUH using kinematic wave theory based on the travel times for overland and channel flows in a stream ordering sub-basin system for Keelung river catchment in Taiwan. Yen and Lee (1997) also developed the GIUH by computing the travel times in terms of Horton’s stream-law-ratios. Based on different concepts, Sahoo et al. (2006) and Kumar et al. (2007) derived the GIUH from geomorphologic characteristics of a catchment and related it to the parameters of the Clark IUH model as well as the Nash IUH model for deriving its complete shape. These GIUH-based Clark and Nash models were applied for simulation of the direct surface run-off (DSRO) hydrographs for ten rainfall-runoff events of Indian watersheds. The performances of the models in simulating the DSRO hydrographs are compared with other models with reasonable accuracy. Application of these models to the ungauged watersheds is limited by the presence of dynamic velocity factor, or the product of peak runoff and time to peak, which requires gauged data of rainfall and stream flow.

Because of non-availability of sufficient rainfall and stream flow records, particularly for hilly watersheds of India, the GIUH approach is suitable to hydrologic response of such watersheds to predict direct runoff. Therefore, this study was undertaken in a fourth-order Chaukhutia watershed of Ramganga river located in the Indian central Himalayan region with steep overland and stream slopes to derive GIUH based on kinematic-wave theory using topographical and geomorphologic parameters as suggested by Lee and Yen (1997) and Yen and Lee (1997), respectively, without using the dynamic velocity parameter. The primary objective of this study was to assess the applicability of these approaches and to derive the GIUH models for hilly watersheds, for which stream flow data are not available.

2 Materials and methods

2.1 Theory

When a unit depth of effective rainfall, consisting of a large number of independent, non-interacting raindrops, occurs uniformly and instantaneously onto a watershed, it is assumed to follow different flow-paths towards the outlet of the watershed to produce the instantaneous unit hydrograph. Each raindrop falling on the overland region moves successively from a lower to a higher order
channel until it reaches the watershed outlet. A watershed may be divided into several interconnected sub-watersheds according to path types from one state (overland plane) to another state (stream channel) until the water drops reach watershed outlet. For a watershed of order \( k \), the number of possible paths will be \( 2^{k-1} \).

Using the probabilistic approach, the probability of a drop of rainfall excess following the path \( W (x_{oi} \rightarrow x_i \rightarrow x_j \rightarrow \cdots x_k) \) can be expressed as,

\[
P(W) = P_{oi}P_{x_i} \cdots P_{x_j} \cdots P_{x_k}
\]

(1)

Where: \( P_{oi} \) is the initial state probability of rain drop moving from \( i^{th} \) order overland region to the \( j^{th} \) order channel and is equal to the total \( i^{th} \) order overland area to the total watershed area; \( P_{x_i} \) is the transitional probability of raindrop moving from \( i^{th} \) order overland region to \( i^{th} \) order channel (equal to unity); and \( P_{x_j} \) is the transitional probability of rain drop moving from \( i^{th} \) order channel to \( j^{th} \) order channel, which can be computed as:

\[
P_{x_{ij}} = \frac{N_{ij}}{N_i}
\]

(2)

Where: \( N_{ij} \) is the number of \( i^{th} \) order channels contributing flow to \( j^{th} \) order channels; \( N_i \) is the number of \( i^{th} \) order channels. The transitional and initial state probabilities of Chaukhutia watershed are given in Table 1.

### Table 1: Transitional and initial-state probabilities for the Chaukhutia watershed

<table>
<thead>
<tr>
<th>Stream order</th>
<th>Number of streams draining to order</th>
<th>Transition probability, ( P_{wei} )</th>
<th>Initial state probability, ( P_{om} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>1</td>
<td>134 96 27 11</td>
<td>0.72 0.20 0.08 0.673</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>31 28 3</td>
<td>1 0.90 0.10 0.169</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7 7</td>
<td>1 1 1 1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1 1 1 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.089</td>
<td></td>
</tr>
</tbody>
</table>

Based on the probabilistic travel times for overland and stream flows, Lee and Yen (1997) gave the ordinates of GIUH for the watershed, \( u(t) \) at time \( t \) as:

\[
u(t) = \sum_{w \in W} \left[ f_{x_i} (t) * f_{x_j} (t) * f_{x_k} (t) * \cdots f_{x_k} (t) \right]_w P(w)
\]

(3)

Where: \( f_{x_i} (t) \) is the travel time probability density function for overland flow; \( * \) denotes the convolution integral; and \( f_{x_j} (t) \) is the probability density function for the channel flow component.

Gupta, Waymire and Wang. (1980) conceptualized the hydrologic behavior of a watershed as a combination of linear reservoirs and linear channels in series and/or in parallel. Here, the GIUH is computed from Eq. (3) using the probability density function (PDF) for overland and channel flow components, \( f_w \) as:

\[
f_w = \frac{1}{T_w} \exp \left[ -\frac{t}{T_w} \right]
\]

(4)

Where: \( T_w \) is the mean travel time for the state \( r \), for both the overland flow and channel flow components in a particular path.

The application of this approach depends on the determination of travel times for overland and stream flows in a catchment. The GIUH-I and GIUH-II models were developed by computing the travel times using topographic parameters and Horton’s stream order laws, respectively, as described in the following sub-sections.

#### 2.1.1 GIUH model of Lee and Yen (1997) (GIUH-I)

The travel-times \( (T_{oi}) \) for overland and stream flows were estimated using only the topographic parameters of the watershed to give GIUH-I. Using the kinematic-wave approach with the continuity and simplified momentum equations, the travel time for \( i^{th} \) order overland plane is given by Wooding (1965) as:

\[
T_{x_i} = \left[ \frac{n_i L_{oi}}{S_{oi} 0.5 q_{li} 0.667} \right]^{0.6}
\]

(5)

Where: \( T_{x_i} \) is the travel time for \( i^{th} \) order overland plane; \( n_i \) is the Manning’s roughness coefficient for over-land flow; \( L_{oi} \) is the mean length for \( i^{th} \) order over-land flow; \( S_{oi} \) is the mean slope of the over-land plane; and \( q_{li} \) is the lateral flow rate or the intensity of effective rainfall for application part. The value of \( n_i \) for hilly watershed dominated by grasses, dense forest and agricultural land was taken as 0.40 (Suresh, 1993).

The first order channel conveys only the lateral discharge contributed by two first-order overland planes. Therefore, neglecting the rain falling directly onto the channel, the travel time for the first-order channel \( (i=1) \) is given as (Lee and Yen, 1997):

\[
T_{c1} = \frac{B_1}{2q_{i1} L_{c1}} \left( \frac{2q_{n1} L_{oi} L_{c1}}{B_1 S_{c1}^{0.6}} \right)^{0.60}
\]

(6)

Where: \( B_1 \), \( L_{c1} \) and \( S_{c1} \) are the width, mean length, and
slope of the first order channel; \( L_{oi} \) is the mean length of overland flow for first order channel; and \( n_{e} \) is Manning’s channel roughness coefficient, which is taken as 0.03 for mountain stream with rocky beds and river with variable sections and some vegetation along the banks (Chow, 1964). The expression for the depth of flow at the entrance of the stream of order \( i \) is:

\[
h_{col} = \left[ \frac{q_{e}n_{e}(N_{i}A_{i} - AP_{mol})}{N_{i}B_{i}S_{i}^{0.5}} \right]^{-0.60}
\]

(7)

Where: \( A_{i} \), \( B_{i} \), and \( S_{ci} \) are the means of the \( i \)th order drainage area, channel width and channel slope, respectively; and \( A \) is the total watershed area.

Similarly, for \( t > T_{ui} \), the channel flow at equilibrium will be the sum of flow from upstream sub-catchment and the flow from two \( i \)th order overland planes. Therefore, the travel time for the \( m \)th order channel (\( i > 1 \)) is:

\[
T_{ui} = \frac{B_{i}}{2q_{e}L_{ci}} \left[ \left( h_{col}^{1.667} + \frac{2q_{e}n_{e}L_{ci}L_{oi}}{B_{i}S_{ci}^{0.5}} \right)^{0.60} - h_{col} \right]
\]

(8)

Where: \( L_{ci} \) is the mean length of the \( i \)th order channel.

Generally, the width of the channel increases as the order of the channel increases. Therefore, a linear variation of channel width is assumed (for field conditions) and the width at the watershed outlet is measured to proportionately estimate the channel widths for other stream orders. The travel times were computed using Eqs. (5) through (8) to generate the probability density function given by Eq. (4), and consequently GIUH-II model was developed using Eq. (3).

2.1.2 GIUH model of Yen and Lee (1997) (GIUH-II)

The travel-time for overland and stream flows was also estimated in terms of Horton’s stream-order-laws to get GIUH-II. The travel time for \( i \)th order overland plane in terms of Horton’s stream-order-law ratios based on geomorphologic parameters is given as (Yen and Lee, 1997):

\[
T_{x,i} = \left[ \frac{n_{e}AP_{col} \sum_{k=1}^{i-1} R_{x}^{-k}}{2a^{1/2}S_{x}^{0.5}L(q_{e})} \right]^{1/2}(h_{col}^{1.667} + R_{x}^{1-k} R_{x}^{1-q} R_{x}^{1-k/2})^{-0.60}
\]

(9)

Where: \( R_{b} \), \( R_{L} \), \( R_{A} \) and \( R_{S} \) are the bifurcation ratio, stream-length ratio, stream-area ratio and stream-slope ratio, respectively; \( S_{h} \) is the slope of the highest order channel; \( a \) and \( b \) are the coefficient and exponent as 5.463 and 1.083, respectively; and \( L \) is the sum of the mean lengths of the streams of different orders.

Similarly, depth of flow in \( i \)th order stream due to upstream reaches, \( h_{col} \), and travel time for \( i \)th order stream flow, \( T_{ui} \), are given as:

\[
h_{col} = \left[ q_{e}A_{i}(R_{b}^{i-1} R_{A} - P_{mol}) \sum_{k=1}^{i} R_{l}^{i-k} \right]^{-0.60}
\]

(10)

\[
T_{ui} = \left[ \frac{B_{i}L_{i}^{1/2} R_{b}^{i-k} \sum_{k=1}^{i} R_{l}^{i-k}}{q_{e}AP_{mol} \sum_{k=1}^{i} R_{l}^{i-k}} \right]^{0.60} - h_{col}
\]

(11)

Where: \( B_{i} \) is the width at the watershed outlet.

The travel times were computed using Eqs. (9) through (11) to generate the probability density function given by Eq. (4), and consequently GIUH-II model was developed using Eq. (3).

2.1.3 Computation of direct runoff hydrograph

The ordinates of direct runoff hydrograph (DRH) for the watershed were obtained by convoluting the effective rainfall hyetograph with the derived GIUH. The ordinates of DRH, \( Q(t) \), at time \( t \), may be given as:

\[
Q(t) = \sum_{i=1}^{m} I(t)u[t - (i-1)D]
\]

(12)

Where: \( (t) \) is the effective rainfall value of \( i \)th part when total duration of effective rainfall is divided into \( m \) equal parts of duration \( D \).

2.2 Performance evaluation measures

The models were tested to determine the validity of the GIUH concept, and used to generate DRH by operating an element of the effective rainfall hyetograph using Eq. (12). The performance of the developed GIUH models was evaluated by visual observation of the shape of predicted and observed DRH with respect to the peak rate, time to peak, time-base of DRH and the overall shape of the DRH for different storm events. Eight
isolated storm-events of one hour duration for the watershed were used for validation of the developed GIUH models, by comparing the DRH obtainable from the GIUH models and the corresponding observed DRH. A quantitative evaluation was also made between the predicted and observed DRH for the given storm events, on the basis of flowing criteria.

To assess the goodness of fit between observed and predicted DRH, the Coefficient of Efficiency ($CE$) as suggested by Nash and Sutcliffe (1970) is used:

$$CE = 1 - \frac{\sum_{i=1}^{N} [Q_o(t) - Q(t)]^2}{\sum_{i=1}^{N} [Q_o(t) - \bar{Q}(t)]^2}$$

Where: $Q_o(t)$ and $Q(t)$ are the ordinates of observed and predicted DRHs, respectively at time $t$; and $N$ is the total number of time intervals.

The relative error in peak ($REP$) gives the relative error for the deviation in peaks of observed and predicted flows to the observed peak runoff rate, and is computed as:

$$REP = \frac{Q_o - Q_p}{Q_o}$$

Where: $Q_o$ and $Q_p$ are the observed and predicted peak rates of direct runoff.

The error in volume ($E_v$) denotes the relative error in total direct runoff volume for predicted and observed hydrographs, and is computed as:

$$E_v = \frac{V_o - V}{V_o}$$

Where: $V_o$ and $V$ are the observed and predicted volumes of direct runoff, respectively.

### 2.3 Study area and data collection

The Chaukhutia watershed contributes to the North-Eastern part of the Ramganga river in the Chamoli district of Uttarakhand (India). The watershed lies between 29°46'15"N to 30°06'N latitude and 79°12'15"E and 79°31'E longitude. Total area of the watershed is 452.25 km$^2$, with highest and lowest elevations of 3114 m and 929 m above mean sea level, respectively. The mean slope of the longest flow channel was 7.3%. Based on 20 years of meteorological data, the average annual rainfall in the watershed varies from 1,084 mm to 1,679 mm with an overall average of 1,384 mm. The width of watershed outlet was 60 m.

The hydrological data were obtained from the Forest Department (Soil Conservation Division), Ranikhet, Uttarakhand. In the Chaukhutia watershed, the recording type rain gauges are located at Chaukhutia and Gairsain, while non-recording rain gauges are located at Mahalchauri station (Figure 1) and at Binta, Bhirpani and Bungidhar stations of the nearby Gagas watershed, situated east of the Chaukhutia watershed. The runoff data were recorded at the outlet of the Chaukhutia watershed. The rating curves using the velocity area method were developed annually, and runoff hydrographs were computed with the help of stage hydrograph. The rainfall hyetographs were developed using rainfall mass curves for selected storm events, and corresponding direct runoff hydrographs were developed by subtracting the base flow from the total runoff hydrograph using Chow’s method (Chow, 1964). The rainfall and corresponding runoff data for eight isolated storm events from 1978 to 1985 were used in the analysis.

A topographic map of Chaukhutia watershed drawn on 1:50,000 scale (with 50 m contour interval) was used to manually determine the geomorphologic parameters,
viz. stream number, stream length, stream slope, stream drainage area, etc. Based on Horton’s laws, the bifurcation ratio, stream length ratio, stream area ratio and stream slope ratio were determined using existing formulae based on the method of least-squares to the plot of logarithm of stream parameter on stream order (Chow, 1964) as given in Table 2. The relationship between mean overland slope \((S_{oi})\) and corresponding channel slope \((S_{ci})\) was related as follows (Lee and Yen, 1997):

\[
S_{oi} = a S_{ci}^b
\]

Where: the values of coefficient \(a\) and exponent \(b\) were taken as 5.463 and 1.083, respectively.

### Table 2  Geomorphologic parameters of Chaukhutia watershed

<table>
<thead>
<tr>
<th>Stream order, (i)</th>
<th>Total number of streams, (N_i)</th>
<th>Total length of streams, (L_i/\text{km})</th>
<th>Total drainage area of streams, (A_i/\text{km}^2)</th>
<th>Mean stream length, (L_i/\text{km})</th>
<th>Mean stream area, (A_i/\text{km}^2)</th>
<th>Mean stream slope, (S_{ci})</th>
<th>Mean overland slope, (S_{oi})</th>
<th>Bifurcation ratio, (R_B)</th>
<th>Stream length ratio, (R_L)</th>
<th>Stream area ratio, (R_A)</th>
<th>Stream slope ratio, (R_S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>134</td>
<td>189.342</td>
<td>304.314</td>
<td>1.413</td>
<td>2.271</td>
<td>0.1911</td>
<td>0.910</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>82.181</td>
<td>380.804</td>
<td>2.651</td>
<td>12.284</td>
<td>0.1234</td>
<td>0.567</td>
<td>5.040</td>
<td>2.471</td>
<td>5.738</td>
<td>0.448</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>50.435</td>
<td>421.239</td>
<td>7.205</td>
<td>60.177</td>
<td>0.0414</td>
<td>0.174</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>20.653</td>
<td>452.3</td>
<td>20.653</td>
<td>452.3</td>
<td>0.0189</td>
<td>0.074</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3 Results and discussion

The ordinates of geomorphologic instantaneous unit hydrographs based on topographic parameters alone (GIUH-I) and Horton’s stream-order-laws (GIUH-II) were developed using Eq. (3) with the help of equations (4) to (11), as shown in Figure 2. The difference in hydrograph shapes could be due to the fact that GIUH-I utilizes the topographic parameters alone, while GIUH-II additionally utilizes Horton-Strahler stream-ordering laws in terms of dimensionless ratios such as \(R_B, R_L, R_A,\) and \(R_S\) also. The transitional and initial state probabilities used for travel time estimation are given in Table 2. As evident from Figure 2, both the models predicted the same time to peak of direct runoff (1.5 hours), while GIUH-I predicted higher peak runoff than GIUH-II. The DRH ordinates for eight storm-events were predicted by using Eq. (12), and compared with the observed ones as shown in Figures 3 to 10. Visual comparison between predicted and observed DRH indicates that the time to peak of predicted DRH generally falls about half-an-hour prior to that of the observed ones, whereas the peak runoff rate and the time-base of both DRHs matched reasonably well. Generally, the magnitude of peak runoff and its time of occurrence at watershed outlet depend, apart from other factors, on the roughness coefficients for the overland and channel flows. Keeping other factors unchanged, less surface roughness allows higher peak and less time to peak. In this case also, the reduced time to peak could be due to lower values of Manning’s roughness coefficients for the overland and channel states for all the stream orders. A sensitivity analysis (not done in this study) may provide better understanding of the effect of surface roughness on peak runoff and its temporal occurrence. The only measurable data in field condition was the width of watershed outlet.
Figure 3  Comparison between observed and predicted DRH for the storm event of August 18, 1978

Figure 4  Comparison between observed and predicted DRH for the storm event of July 21, 1979

Figure 5  Comparison between observed and predicted DRH for the storm event of August 31, 1980

Figure 6  Comparison between observed and predicted DRH for the storm event of August 2, 1981
Figure 7  Comparison between observed and predicted DRH for the storm event of July 23, 1982

Figure 8  Comparison between observed and predicted DRH for the storm event of August 21, 1983

Figure 9  Comparison between observed and predicted DRH for the storm event of August 18, 1984

Figure 10  Comparison between observed and predicted DRH for storm event of August 10, 1985
The quantitative evaluation was carried out by determining the performance indicators using Equations (13) through (15) as given in Table 3, and indicated that the coefficient of efficiency for GIUH-I was consistently lower than that of GIUH-II, with average values of 0.482 and 0.711, respectively. This could be due to the shift in time to peak of the predicted DRH as a consequence of the inherent property of kinematic-wave in which the rising limb becomes steeper without becoming attenuated; however, the other momentum equation terms become more important and introduce dispersion and attenuation. Also, the celerity of the flood wave by kinematic-wave GIUH models might be more than that of the observed.

<table>
<thead>
<tr>
<th>Storm event</th>
<th>Coefficient of efficiency</th>
<th>Relative error in peak</th>
<th>Error in volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIUH-I</td>
<td>GIUH-II</td>
<td>GIUH-I</td>
<td>GIUH-II</td>
</tr>
<tr>
<td>August 18, 1978</td>
<td>0.457</td>
<td>0.683</td>
<td>0.120</td>
</tr>
<tr>
<td>July 21, 1979</td>
<td>0.482</td>
<td>0.707</td>
<td>0.095</td>
</tr>
<tr>
<td>August 31, 1980</td>
<td>0.569</td>
<td>0.772</td>
<td>0.023</td>
</tr>
<tr>
<td>August 2, 1981</td>
<td>0.402</td>
<td>0.673</td>
<td>0.004</td>
</tr>
<tr>
<td>July 23, 1982</td>
<td>0.526</td>
<td>0.752</td>
<td>0.035</td>
</tr>
<tr>
<td>August 21, 1983</td>
<td>0.431</td>
<td>0.674</td>
<td>0.084</td>
</tr>
<tr>
<td>August 18, 1984</td>
<td>0.527</td>
<td>0.748</td>
<td>0.078</td>
</tr>
<tr>
<td>August 10, 1985</td>
<td>0.459</td>
<td>0.682</td>
<td>0.097</td>
</tr>
<tr>
<td>Average</td>
<td>0.482</td>
<td>0.711</td>
<td>0.067</td>
</tr>
</tbody>
</table>

The peak runoff rates of predicted DRHs were, in general, lower than the observed ones for all the storm events. Also, the DRH peaks predicted by the GIUH-I model were higher than that of the GIUH-II model; the GIUH-I predicted peaks were closer to the observed ones, with the average values of error being 0.067 and 0.122, respectively (Table 3). The error in direct runoff volume varied closely for GIUH-I and GIUH-II models within the acceptable range, with the average values being 0.025 and 0.03, respectively. The volume of direct runoff was predicted almost equally well by both methods, but peak of DRH was predicted more accurately by GIUH-I than GIUH-II.

These results indicate that the kinematic-wave based GIUH models using topographic parameters and Horton’s stream-order-law ratios give reasonably good prediction of peak, total runoff volume, and time-base of DRH for the hilly watershed under study. Because these models utilize only topographic and geomorphologic parameters (obtainable from topographic maps) of the watershed, without using past record of rainfall-runoff data, they can be used for prediction of direct runoff hydrograph for ungauged or partially gauged hilly watersheds. This study further suggests that the GIUH-I gives fair prediction of peak rate and total volume of direct runoff from hilly watersheds.

4 Conclusions

1) The direct runoff from ungauged hilly watersheds could be estimated fairly accurately using kinematic-wave theory based geomorphologic instantaneous unit hydrograph (GIUH) utilizing topographic and/or geomorphologic parameters only (without using rainfall-runoff data) for the hilly watershed of the Ramganga river in Uttarakhand (India).

2) The GIUH-I based on topographic parameters of the watershed gives better prediction of peak rate and volume of direct runoff in hilly watersheds, which provides some guidance for planning and hydrologic design of water-storage, soil conservation and flood control structures in hilly areas. The only measurable data in the field is the width of channel at watershed outlet.

[References]


