Development of geomorphological instantaneous unit hydrograph (GIUH) model for a new un-gauged watershed

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**Abstract**

A geomorphological instantaneous unit hydrograph (GIUH) model was developed for a watershed of Damodar valley corporation, Hazaribagh, using Nash (1959) and Itrube (1982) methods to compute peak discharge \( q_{\text{peak}} \) and time to peak \( t_{\text{peak}} \). The model was calibrated and validated for five storm events, i.e., June 24-25 (1992), October 12-13 (1993), November 2-3 (1993), June 28 (1994) and August 6 (1996) by comparing their ordinates with the ordinates of instantanous unit hydrograph (IUH). The GIUH was tested with absolute prediction errors (APE) of the ordinate of peak discharge. On comparison, it was found that, most of the GIUH models overestimated the runoff at initial stage, while underestimated at the latter stage in comparison to the IUHs, which was mainly due to consideration of constant value of \( \Phi \)-index for computation of effective rainfall. The absolute prediction errors (APE) were computed to be 5.97, 18.09, 23.32, 9.64 and 7.52% of the ordinates of peak discharge for the storm events of June 24-25 (1992), October 12-13 (1993), November 2-3 (1993), June 28 (1994) and August 6 (1996) respectively.

**Keywords**

Direct Runoff, Instantaneous Unit Hydrograph, Nash’ Method, Prediction, Synthetic Instantaneous Unit Hydrograph, Watershed

**How to Cite this Article**


The rainfall - runoff relationship is an important tool for approximation of runoff likely to be generated by the rainfall from the watershed, which may be useful for better planning of water resource system and management of the watershed, as well. Many such models are in use in hydrology (Itrube and Valdes, 1979, Itrube et al., 1982, Singh, 1983, Subramanyan and Kumar, 1990, Bhaskaran et al., 1997). However, they require a long-term database on the rainfall and runoff for the watershed. Due to paucity of runoff data in many catchments such models are useful especially in un-gauged catchments. However, the geomorphological technique to synthesize the unit hydrograph on the basis of morphological characteristics of watershed, added a new dimension to the field of hydrologic simulation (Itrube et al., 1982, Jena and Tiwari, 2006). On this concept, several attempts have been made to relate the parameters of unit hydrograph with the geomorphologic characteristics of the watershed, which in turn to the development of geomorphological instantaneous unit hydrograph (GIUH) for the un-gauged watershed. With aforesaid views, in present study the geomorphological instantaneous unit hydrograph model was developed, using a popular approach in new catchment i.e. Kahuwatri sub-catchment of Damodar Valley Corporation, Hazaribagh, Jharkhand (India).

**Materials and Methods**

The requisite database on rainfall and runoff for five storm events i.e. June 24-25 (1992), October 12-13 (1993), November 2-3 (1993), June 28 (1994) and August 6 (1996) along with topographic map of the watershed were collected from the department of soil and water conservation, located at Damodar Valley Corporation, Hazaribagh (Jharkhand), India. The other input data for development of geomorphological instantaneous unit hydrograph were also borrowed from the available literatures.

**Development of Instantaneous Unit Hydrograph (IUH)**

The Nash model (Nash, 1959) was used to derive the instantaneous unit hydrograph for
different storm events, which consists of determining the Nash model parameters, i.e. shape parameter (n) and scale parameter (K) for given storm events. The depth of direct runoff is computed by using the standard method given by Chow (1964). Finally, the ordinates of storm instantaneous unit hydrograph were computed by using the following formula (Nash, 1959):

\[ u(t) = \frac{1}{K \Gamma(n)} \left( \frac{t}{K} \right)^{n-1} e^{-t/K} \quad \ldots (1) \]

where, \( u(t) \) is the ordinate of IUH (cm h^{-1}) at time \( t \) and symbol \( \Gamma \) is the gamma function. The computed ordinates of instantaneous unit hydrograph (cm h^{-1}) were further converted in the unit of cumec, by multiplying the area of the watershed and a factor 2.78, i.e.

\[ u(t), \text{ cumec} = 2.78 \times A \times u(t), \text{ cm h}^{-1} \quad \ldots (2) \]

in which \( A \) is the area of watershed (sq km).

**Development of Geomorphological Instantaneous Unit Hydrograph (GIUH) Model**

The ordinates of geomorphological instantaneous unit hydrograph (GIUH) were determined by using the equation (1), in which the parameters \( n \) and \( K \) were computed (Itrube et al. 1982) on the basis of geomorphological parameters of the watershed i.e. bifurcation ratio (\( R_b \)), stream length ratio (\( R_l \)), stream area ratio (\( R_s \)) and the peak flow velocity (\( V_{max} \)). The computed ordinates (cm h^{-1}) of GIUH were also modified in the unit of cumec, by multiplying the area of the watershed and a factor 2.78. The geomorphologic parameters of watershed i.e. bifurcation ratio (\( R_b \)), stream length ratio (\( R_l \)) and stream area ratio (\( R_s \)) were evaluated by the method of Itrube et al. (1982) which came to be 3.48, 1.549 and 3.66, respectively. The maximum flow velocity (\( V_{max} \)), peak discharge (\( q_p \)) and time to peak (\( t_p \)) were determined by the following formulae (Sorman, 1995 and Itrube et al. 1982):

\[ V_{max} = \alpha_\Omega^{0.6} \times A_\Omega \times i_c \times 0.4 \quad \text{for} \quad t_c > t_c \quad \ldots (3) \]

\[ V_{max} = \alpha(t_c \times i_c)^{0.75} \times \left( \frac{A_\Omega}{L_\Omega} \right)^{0.75} \quad \text{for} \quad t_c < t_c \quad \ldots (4) \]

in which, \( \alpha_\Omega = \frac{S_\Omega^{0.5}}{\eta \times b_\Omega^{0.75}} \quad \ldots (5) \)

\[ q_p = \left( \frac{1.31}{L_\Omega} \right) \times R_l^{0.43} \times V_{max} \quad \ldots (6) \]

\[ t_p = 0.44 \left( \frac{L_\Omega}{V_{max}} \right) \times \left( \frac{R_b}{R_a} \right)^{0.55} \times R_l^{0.38} \quad \ldots (7) \]

in which, \( t_c \) is the duration of excess rainfall (s); \( i_c \) is the intensity of excess rainfall (ms^{-1}); \( \eta \) is the Manning’s roughness coefficient; \( t_c \) is the time of concentration (minute); \( S_\Omega \) is the slope of main stream (mm^{-1}); \( L_\Omega \) is the length of main stream (km); \( A_\Omega \) is the area of watershed (m^2); \( b_\Omega \) is the breadth of main stream (m) and \( \alpha_\Omega \) is the kinematics wave parameter (m^{1/2} s^{-1}). The Nash parameters i.e. \( n \) and \( K \) for GIUH were computed by using the following formulae (Subramanyan and Kumar, 1990):

Shape parameter (\( n \)) = \( 3.29 \times \left( \frac{R_b}{R_a} \right)^{0.78} \times R_l^{0.07} \quad \ldots (8) \)

Scale parameter (\( K \)) = \( \frac{0.70 (R_a / R_b)^{0.48}}{(R_b / R_l)} \times \frac{L_\Omega}{V_{max}} \quad \ldots (9) \)

these relationships have been tested by Safi Hassan (2004) and were found to be fit for the study watershed. The time of concentration (\( t_c \)) was determined by using the method suggested by Kirpich (1940) which came to be 149.79 minutes for the study watershed. The intensity of effective rainfall (i.e) was computed by dividing the depth of effective rainfall with its duration, which was obtained as 9.083, 9.41, 5.77, 1.44 and 4.83 ms^{-1} for the storm events of June 24 -25 (1992), October 12 -13 (1993), November 2 -3 (1993), June 28 (1994) and August 6 (1996), respectively. The Manning’s roughness coefficient (\( \eta \)) was taken as 0.04 (Chow, 1964) for the existing stream, bearing the features of steep sides slope, covered with trees, bushes and gravels or boulders lying at the bottom. The \( S_\Omega \) was determined by dividing the difference of maximum and minimum elevations of the main stream, with its total length. The computed values of requisite parameters for determining the maximum flow velocity are shown in Table 1 and accordingly the maximum flow velocities for different storm events have been given in Table 2.

**Validation of GIUH**

The validity of derived GIUHs was tested by two ways; first one by comparing the ordinates of GIUHs and the observed unit hydrograph and second one by determining the absolute prediction errors (APE) of their peak discharge ordinates.
The following formula was used for computing the APE percent:

\[
APE = \frac{\sum_{i=1}^{n} (O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100 \quad \ldots (10)
\]

in which, \(O_i\) and \(P_i\) are the observed and predicted ordinates of unit hydrographs, respectively. In this case, the ordinates of IUH were considered as the observed \((O_i)\) and of GIUH as predicted \((P_i)\) ordinates of the unit hydrograph.

RESULTS AND DISCUSSION

Computation of Nash’s Shape (N) and Scale (K) Parameter

The computed values of Nash parameters i.e. \(n\) and \(K\) for storm instantaneous unit hydrograph and geomorphological instantaneous unit hydrograph tells that in case of GIUH, the value of shape parameter \((n)\), which was determined on the basis of geomorphological characteristics of the watershed was found to be 3.26, while for IUH it was 1.12, 2.97, 2.82, 3.39 and 1.02, respectively for the storm events of June 24-25 (1992), October 12-13 (1993), November 2-3 (1993), June 28 (1994) and August 6 (1996). Comparatively, the value of \(n\) for GIUH was higher than the values of \(n\) for IUH which may be due to the effect of geomorphological characteristics of the watershed. The scale parameter \((K)\) which represents the dynamic behavior of rainfall - runoff process in the watershed, was found to be different for different storm events for both the hydrographs. It might be due to variations in the geomorphological characteristics of the watershed and peak flow velocity. Overall, for most of the storm events, the values of \(K\) (1.22, 0.34, 0.85, 0.74 and 1.43) for IUH were found to be less as compared to the GIUH (0.45, 0.29, 0.62, 0.74 and 0.70). On the contrast, it is obvious from Table 2 that the products of \(n\) and \(K\) which represent the lag time of watershed were found to be at par, for both the unit hydrographs, \(i.e. 1.25, 1.01, 2.40, 2.50\) and 1.45 in case of GIUH and 1.47, 0.95, 2.38, 2.48 and 2.28 in case of IUH, respectively for the storm events of June 24 -25 (1992), October 12 -13 (1993), November 2 -3 (1993), June 28 (1994) and August 6 (1996), resulting into the same time to peak of the GIUH and IUH for most of the storms, \(i.e. Oct 12-13 (1993), Nov 2-3(1993) and June 28 (1994).\)

Computation of Ordinates and Development of GIUH Model

The ordinates of IUH and GIUH for different storm events have been computed and Synthetic unit hydrograph was developed with these parameters which are shown in figure 1 for storm events of June 24-25, Oct 12-13 and Nov 2-3 and for storm events of June 28 and Aug 6 depicted in figure 2. It is obvious from the figures that at the initial stage, the GIUH overestimated the runoff while at later stage; they underestimated the runoff for most of the storm events. It may be due to consideration of constant value of \(\Phi\)- index for determining the depth of effective rainfall. The constant \(\Phi\)- index resulted a lower infiltration rate \(i.e. initial loss\) in the beginning; and higher at the latter stage of runoff formation as compared to the actual infiltration rate. Such variations between the runoff of GIUH and SIUH have also been reported by Ashokan (1981), Bhashkaran et al. (1997) and Kumar (1999).

Testing the Validity of GIUH

The validity of GIUHs was evaluated over IUHs on the basis of comparison between their ordinates and absolute prediction error (APE) of \(q_{peak}\). It is observed from Table 3 that in most of the storm events, the ordinates of SIUH and GIUH are close to each other which reveal the validity of developed GIUHs. The computed values of absolute prediction error (APE) at peak discharge were found to be 5.97, 18.09, 23.32, 9.64 and 7.52 for the storm events of June 24 -25 (1992), October 12 -13 (1993), November 2 -3 (1993), June 28 (1994) and August 6 (1996), respectively. Bhaskaran et al. (1997) and Mane and Atre (2010) have also advocated this range of APE with the claim of validity of unit hydrograph.

CONCLUSION

Thus, it may be concluded that, the developed geomorphological instantaneous unit hydrograph (GIUH), based on the geomorphological characteristics of the study watershed \(i.e. Kahuwatri watershed\) located in the Damodar Valley Corporation, Hazaribagh (Jharkhand) is well
Table 1. Requisite parameters for estimation of stream flow velocity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of watershed ($A_\Omega$)</td>
<td>m²</td>
<td>$27.93 \times 10^6$</td>
</tr>
<tr>
<td>Length of main stream ($L_\Omega$)</td>
<td>m</td>
<td>1446.72</td>
</tr>
<tr>
<td>Breadth of main stream ($b_\Omega$)</td>
<td>m</td>
<td>19.00</td>
</tr>
<tr>
<td>Slope of main stream ($S_\Omega$)</td>
<td>m/m</td>
<td>$1.75 \times 10^{-4}$</td>
</tr>
<tr>
<td>Time of concentration ($t_c$)</td>
<td>min</td>
<td>149.77</td>
</tr>
</tbody>
</table>

Table 2. Computed lag time of watershed “n.k” of IUH and GIUH for different storm events

<table>
<thead>
<tr>
<th>Storm event</th>
<th>Vmax (m/s)</th>
<th>Lag time of watershed (n.k)</th>
<th>Time to peak (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IUH</td>
<td>GIUH</td>
<td>IUH</td>
</tr>
<tr>
<td>June 24-25 (1992)</td>
<td>0.78</td>
<td>1.25</td>
<td>1.47</td>
</tr>
<tr>
<td>Oct 12-13 (1993)</td>
<td>1.20</td>
<td>1.01</td>
<td>0.95</td>
</tr>
<tr>
<td>Nov 2-3 (1993)</td>
<td>0.55</td>
<td>2.40</td>
<td>2.38</td>
</tr>
<tr>
<td>Jun 28 (1994)</td>
<td>0.41</td>
<td>2.50</td>
<td>2.48</td>
</tr>
<tr>
<td>Aug 6 (1996)</td>
<td>0.50</td>
<td>1.45</td>
<td>2.28</td>
</tr>
</tbody>
</table>

Table 3. Absolute percentage error (APE) of IUH and GIUH of the ordinates at peak

| S. No. | Storm event       | Peak discharge (cumec) | APE (%) | |
|--------|-------------------|------------------------|---------|
|        | IUH               | GIUH                   |         |
| 1.     | June, 24-25 (1992)| 41.57                  | 44.05   | 5.97     |
| 2.     | Oct, 12-13 (1993)| 57.78                  | 68.23   | 18.09    |
| 4.     | June, 28 (1994)  | 25.93                  | 23.43   | 9.64     |
| 5.     | Aug, 6 (1996)    | 33.37                  | 35.88   | 7.52     |
Fig. 1. SIUH and GIUH for storm events of June 24-25, Oct 12-13 and Nov 2-3

Fig. 2. SIUH and GIUH for storm events of June 28 and Aug 69
suitable for prediction of direct runoff. It can be used as a tool for predicting the runoff, for other watersheds, provided that they fall in the same meteorological region with identical physiographical features. However, for its more veracity, the developed instantaneous unit hydrographs should also be tested for other watersheds.

REFERENCES


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