



DERIVATION OF GEOMORPHOLOGICAL UNIT HYDROGRAPH FROM CATCHMENT BASED GEOMORPHOLOGICAL CHARACTERISTICS USING REMOTE SENSING AND GIS

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Abstract - Geomorphological characteristics of river basin in mountainous areas affect runoff process and formation of flood in these areas. Since, most of the locations in mountainous areas are either ungauged or sufficient data are not available for them; the use of remote sensing and GIS techniques is very important. Studies of geomorphological characteristics of such areas become much more important and significant as the geomorphological characteristics can be useful in understanding the runoff process for the catchment. In this study, the geomorphological characteristics of Devak basin such as Bifurcation Ratio, Length Ratio and Area Ratio are determined using Nash model, for which the values are 4.263, 3.720 and 4.997 respectively, which can be useful in finding out the runoff response for the catchment. Also, results obtained from the present study are compared with results obtained from toposheets, variation in length ratio 3.720 as per DEM and 2.030 as per toposheets is observed. This variation is high comparing to the variation for Bifurcation Ratio which is 4.263 as per DEM and 4.870 as per toposheets, and Area Ratio 4.997 as per DEM and 5.634 as per toposheets.

Keywords - Geomorphology, unit hydrograph, Nash model, geomorphological unit hydrograph, ungauged basin.

I. INTRODUCTION

Hydrological studies in drainage basins and sub basins often suffer setbacks due to lack of various long-term data. Then there is a need to extrapolate the results of few small sub systems to other hydrological similar regions. For most of the cases, the network of hydro-meteorological observations in basin is not available especially for hilly regions. Moreover, the stream network is very complicated with most of the first, second and third order streams flowing on steep slopes. Even many of the major streams remain dry during non-monsoon period and experience flash flood during rainy days. Therefore, geomorphological parameters of the basin may provide an alternative to establish relationship describing the flow process of the network [32].

Every hydrologic design is different because the factors that affect the design vary with location. Thus, it is necessary to make measurements at the design site. Factors such as the following may be important: the size, the slope and the land use of the watershed as well as the water storage and vegetation within the channel. However, the geomorphometric analysis of the catchment will provide information on runoff process in the basin. During past four decades advances made in the geomorphology have furthered our understanding of channel properties, its geometry [19] and hydrology. The coastal areas and hilly areas are sensitive in nature compared to deserts and prone to various hydrological problems viz. floods, cyclones etc. The geomorphological studies are helpful in regionalizing the hydrologic models. Since most of the hilly regions are either ungauged or sufficient data is not available, the study of geomorphologic characteristics of such basins become much more important [3, 15].

Evaluation suggests that many rainfall-runoff models have been developed as the need of estimating the flood is must these days. Due to the incorporation of process knowledge, simple structure, conceptual models are relatively robust and reliable [28] and hence selected for this study.

In India, many catchments in the hilly region are ungauged because of inaccessibility of gauging site, topographic situation of site may not allow to set up gauging station etc. Hence, the conceptual methods for forecasting the floods in ungauged catchments are developing, from which GIUH based Clark model and GIUH based Nash model has been short-listed from the available conceptual methods as only these two methods use the geomorphological characteristics as an input [1, 2]. Followings are the concluding remarks which are summarized as follows:

- a) Out of which the parameters of Nash's model (n and k) are easily calculated then that of storage coefficient R of Clark model for which the procedure is very iterative and laborious.
- b) Hence, Nash model is selected for derivation of Geomorphological Unit Hydrograph (GUH) [20].

II. METHODOLOGY

The regionalization procedure requires some of the important geomorphological characteristics which are to be evaluated from the toposheets. It is extremely difficult for the user to manually derive the geomorphological parameters from toposheets. Thus, it discourages the user from adopting this approach. To overcome this difficulty, now a days geographical information system (GIS) software like ArcMap, ILWIS, ERDAS, GRASS etc. are available for derivation of these characteristics in a very less time and also in a simplified manner. In this study, the geomorphological characteristics of Devak basin have been derived using the GIS package i.e. ArcMap 9.3.

Watershed Stream Delineation Tool (WSDT)

The solution has several approaches depending on the software that we use. Watershed and streams delineation tool is the solution to this problem using ArcGIS 9.3. With just one click this tool uses the capabilities and features of this software in order to achieve a simple process that gives a well-organized output. Without this tool, the user has to apply several steps, call numerous functions and repeat procedures that are going to give the same result but with much more time consumed.

Constructing tools for solving problems depends basically on the software for which they are developed. WSDT (Watershed and Stream Delineation Tool) was built to be used on ArcGIS software. WSDT is a simpler Graphics User Interface in which the processes of Hydrology Modelling are made with one click. The methodology used to obtain sub-watersheds and streams order, from a Digital Elevation Model is divided in nine steps where followed:

- A. Fill the sinks in the DEM;
- B. Apply the flow direction function to the filled DEM;
- C. Apply the flow accumulation function on the flow direction
- D. Apply a threshold condition to the flow direction grid;
- E. Obtain a streams grid from the threshold condition grid;
- F. Obtain the stream links grid.
- G. Obtain watersheds grid from the streams grid;
- H. Vectorize the streams grid;
- I. Vectorize the watersheds grid;

Topology Building in Autodesk 3D Map 2006

The above steps will create one raster and one vector files stream order generated. In this file the stream is in segmented form i.e. the stream is divided at every intersection but Strahler's method of stream ordering does not allow this. Hence, to create a continuous stream till the higher order stream insect the stream, the topology must be built in order to get correct number of streams of each order which can be done in Autodesk Map 3D software. After the topology has been built the file is exported with its attributes to ArcMap and the number of streams, their length and the contributing area is calculated and the Horton's ratio is calculated.

Estimation of Geomorphological Characteristics

Three of Horton's ratios namely bifurcation ratio (R_B), stream-length ratio (R_L) and stream-area ratio (R_A) are unique representative parameters for a given watershed and are fixed values for a given watershed system.

Bifurcation Ratio (R_B)

- For ordering of streams Strahler's method of stream ordering is followed. Through the application of ArcGIS, the number of streams of each order is stored in a table and for each order the total number of streams is computed.
- Bifurcation ratio is defined as the ratio of the stream segment of the given order N_u to the number of stream segment of the next higher order N_{u+1} i.e. $R_B = \frac{N_u}{N_{u+1}}$
- It has been very widely used in the derivation of geomorphologic instantaneous unit hydrograph for various catchments. The value of R_B for different catchments generally varies from 3 to 5.

Length Ratio (R_L)

- Horton (1945) defined length ratio (R_L) as the ration of the mean stream length (\bar{L}_u) of segment of order u , to mean stream length (\bar{L}_{u-1}) of the next lower order $u-1$, i.e. $R_L = \frac{\bar{L}_u}{\bar{L}_{u-1}}$
- The length of the channel of a given order is determined largely by the type of soil covering the drainage basins. Generally more pervious the soil, longer will be the channel length of a given order. The value of R_L for different catchment generally varies from 1.5 to 3.5.

Area Ratio (R_A)

- The area ratio is defined as the ratio of area of streams (A_u) of order u , to the area of streams (A_{u-1}) of order $u-1$, i.e. $R_A = \frac{A_u}{A_{u-1}}$

- Area ratio has been used in the derivation of geomorphologic instantaneous unit hydrograph for various catchments. The value of R_A for different catchment generally varies from 3 to 6.

NASH MODEL

- The Nash model is based on the concept of routing of the instantaneous inflow through a cascade of linear reservoirs with equal storage coefficient. Catchment is assumed to be made up of series of ‘n’ identical linear reservoirs, each having same storage coefficient ‘k’.
- 1st reservoir receives a unit volume, equal to 1 cm of effective rainfall from the catchment, instantaneously. Inflow is routed through the first reservoir to get the outflow hydrograph.
- Output from 1st reservoir is input to 2nd reservoir and so on for nth reservoir. The outflow of nth reservoir is taken as Instantaneous unit hydrograph (IUH) of the catchment.
- Now from the continuity equation,

$$I - Q = \frac{dS}{dt} \text{----- (1)}$$

For linear reservoir,

$$S = kQ$$

$$\therefore \frac{dS}{dt} = k \left(\frac{dQ}{dt} \right) \text{----- (2)}$$

- Now from equation (1) and (2),

$$I - Q = k \left(\frac{dQ}{dt} \right)$$

$$\therefore I = k \left(\frac{dQ}{dt} \right) + Q$$

Where, ‘Q’ and ‘I’ are the functions of time ‘t’.

$$\therefore Q = \frac{1}{k} \left(e^{-\frac{t}{k}} \right) \int \left(e^{\frac{t}{k}} \right) I dt \text{----- (3)}$$

- Now for the 1st reservoir, the input is instantaneous hence, t = 0

$$\therefore \int I dt = \text{instantaneous volume inflow} \\ = 1 \text{ cm of effective rainfall}$$

- So, impulse input for 1st reservoir is,

$$Q_1 = \frac{1}{k} \left(e^{-\frac{t}{k}} \right) \text{----- (4)}$$

- For 2nd reservoir,

$$Q_2 = \frac{1}{k} \left(e^{-\frac{t}{k}} \right) \int e^{-\frac{t}{k}} I dt$$

- The outflow of 1st reservoir becomes the inflow for 2nd reservoir

Hence, $I = Q_1$

$$\therefore I = \frac{1}{k} \left(e^{-\frac{t}{k}} \right)$$

- So,

$$Q_2 = \frac{1}{k} \left(e^{-\frac{t}{k}} \right) \int \left(e^{-\frac{t}{k}} \right) \frac{1}{k} \left(e^{-\frac{t}{k}} \right) dt$$

$$\therefore Q_2 = \left(\frac{1}{k^2} \right) t \left(e^{-\frac{t}{k}} \right)$$

- So, for 3rd reservoir the outflow of 2nd reservoir becomes the inflow of 3rd reservoir.

$I = Q_2$

$$Q_3 = \frac{1}{2} \left(\frac{1}{k^3} \right) t^2 \left(e^{-\frac{t}{k}} \right)$$

- Similarly for nth reservoir,

$$Q_n = \left(\frac{1}{(n-1)!} \right) \left(\frac{1}{k^n} \right) t^{(n-1)} \left(e^{-\frac{t}{k}} \right)$$

- Ordinates of unit hydrograph are given by replacing ‘Q_n’ with U(t).

$$\therefore U(t) = \left(\frac{1}{(n-1)! k^n} \right) t^{(n-1)} \left(e^{-\frac{t}{k}} \right)$$

$$\therefore U(t) = \left(\frac{1}{((n-1)! (k^{n-1}))k} \right) t^{(n-1)} \left(e^{-\frac{t}{k}} \right)$$

$$\therefore U(t) = \left(\frac{1}{k \Gamma(n)} \right) \left(\frac{t}{k} \right)^{n-1} \left(e^{-\frac{t}{k}} \right) \text{----- (5) } (\because \Gamma(n) = (n-1)!)$$

- Unit hydrograph of desired duration ‘D’ can be derived by using the following expression

$$U(D, t) = \frac{1}{D} \left[\left\{ I \left(n, \frac{t}{k} \right) \right\} - \left\{ I \left(n, \frac{t-D}{k} \right) \right\} \right]$$

Where,

$U(D, t)$ = ordinates of D hour UH, hour⁻¹

t = sampling time interval, hour

$I \left(n, \frac{t}{k} \right)$ = incomplete gamma function of the order 'n' at $\left(\frac{t}{k} \right)$.

- The complete shape of the GIUH can be obtained by linking the q_p and t_p of the GIUH with scale parameter 'k' and shape parameter 'n'.
- By equating the 1st derivative of equation (5) w.r.t. 't' to zero, t becomes t_p , thus taking natural logarithm on both sides of equation (5), differentiating w.r.t 't' and by simplification, following equation is derived.

$$\frac{\partial \ln(u(t))}{\partial t} = \left[-\frac{1}{k} + \frac{(n-1)}{t} \right] \text{----- (6)}$$

- Equating equation (6) with zero and also replacing 't' with ' t_p '.

$$\therefore -\frac{1}{k} + \frac{n-1}{t_p} = 0$$

$$\therefore \frac{(n-1)}{t_p} = \frac{1}{k}$$

$$\therefore t_p = k(n-1) \text{----- (7)}$$

- Now substituting the value of t_p in equation (5)

$$q_p = \left(\frac{1}{k \Gamma(n)} \right) \left(\frac{k(n-1)}{k} \right)^{n-1} e^{\left(\frac{-k(n-1)}{k} \right)}$$

$$\therefore q_p = \left(\frac{1}{k \Gamma(n)} \right) (n-1)^{n-1} e^{(1-n)} \text{----- (8)}$$

Combining (7) and (8)

$$q_p t_p = \left[\frac{1}{k \Gamma(n)} (n-1)^{n-1} e^{(1-n)} \right] [k(n-1)]$$

$$q_p t_p = \frac{(n-1)}{\Gamma(n)} (n-1)^{n-1} e^{(1-n)} \text{----- (9)}$$

- Now, Rodriguez, Iturbe and Valdes derived the peak discharge ' q_p ' and time to peak ' t_p ' characteristics of IUH as functions of Horton's order ratios (1945), which are as follows:

$$q_p = 1.31 (R_L^{0.43}) \left(\frac{V}{L_\Omega} \right) \text{----- (10)}$$

$$t_p = 0.44 \left(\frac{L_\Omega}{V} \right) \left(\frac{R_B}{R_A} \right)^{0.55} (R_L^{-0.38}) \text{----- (11)}$$

Where,

q_p = peak discharge, hour⁻¹

t_p = time to peak, hour

L_Ω = length of highest order stream, km

V = dynamic velocity parameter, m/s

R_B = Horton's bifurcation ratio

R_L = Horton's length ratio

R_A = Horton's area ratio

Now, combining equation (10) and (11), we get

$$q_p t_p = 0.5764 \left(\frac{R_B}{R_A} \right)^{0.55} R_L^{0.05} \text{----- (12)}$$

- Equation (12) shows that $(q_p t_p)$ is not dependent on velocity and thereby on the storm characteristics and hence, it is a function of geomorphological characteristics of basin. Now, equating the equation (9) and (12)

$$\frac{n-1}{\Gamma(n)} (n-1)^{n-1} e^{(1-n)} = 0.5764 \left(\frac{R_B}{R_A} \right)^{0.55} R_L^{0.05} \text{----- (13)}$$

- The Nash model parameter 'n' can be obtained using Newton-Rapson method for equation (13). Shape parameter 'k' can be obtained using equation (7) and (11) for given value of velocity 'V'.

$$k(n-1) = 0.44 \left(\frac{L_\Omega}{V} \right) \left(\frac{R_B}{R_A} \right)^{0.55} (R_L^{-0.38})$$

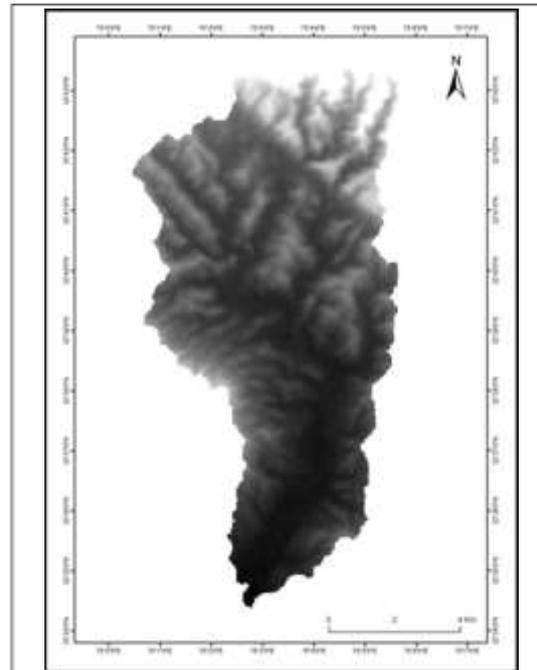


Fig 1 - Image of Devak Basin Obtained using Remote Sensing

$$\therefore k = \frac{0.44}{(n-1)} \left(\frac{L\Omega}{V}\right) \left(\frac{R_B}{R_A}\right)^{0.55} (R_L^{-0.38}) \text{ ----- (14)}$$

After finding out the Horton's ratio using above mentioned methodology, now find the parameters of Nash model i.e. 'n' and 'k'. Solving equation (13) find out the value of 'n'. Using equation (14) find the value of 'k' assuming different values of velocities.

III. STUDY AREA AND DATA COLLECTION

Devak is a small tributary of Ujha river (Ravi river basin) in western Himalayas and the catchment is located between latitude 32° 35' to 32° 45' N and longitude 75° 00' to 75° 10' E. The catchment is on the southern slope of lower Himalayas range in the Western Himalayas. The area of the catchment is 87.57 km², with its elevation varying from 332 m to 824 m at the peak above the mean sea level. No meteorological station is available in the basin for measurement of rainfall and temperature. The nearest meteorological station for the catchment is Jammu, where the average annual rainfall is about 1055 mm and average temperature varies from 4 °C to 40 °C. The temperature at higher altitudes in the northern part of the catchment is expected to be little low. There are two rainy seasons: one from December to March, associated with passage of western disturbance, and the other from mid-June to mid-September, due to south-west monsoon currents. The rainfall in October and November is generally small in amount. The western disturbance occasionally gives very stormy weather. In April and May thunder storms are occasionally observed giving light to moderate showers of rain. The south-west monsoon is predominant feature in this region. For estimating the geomorphological characteristics of Devak basin, an aster image is obtained using remote sensing and converted into grid format for its further use in evaluation (Fig 1). Image is at 20 m resolution and threshold value is taken as 200 for the derivation of geomorphological characteristics.

IV. RESULT & ANALYSIS

The stream network and sub-watershed polygons have been derived using WSDT, hydrology tool of ArcMap and Autodesk Map 3D 2006 collectively (fig 2) and also the obtained results are compared with the results obtained from toposheets for the same catchment.

Tables 1 and 2 show values of numbers of streams, stream length and the contributing area of each stream order in basin respectively.

The values obtained of bifurcation ratio 4.263 and area ratio 4.997 lies within their general range 3 to 5 and 3 to 6 respectively but the value obtained of length ratio 3.720 is exceeding the limit of 1.5 to 3.5.

Stream Order	Number of streams	$R_B = N_u / N_{u+1}$	Mean R_B
1 st	250	5.000	4.263
2 nd	50	5.555	
3 rd	9	4.500	
4 th	2	2.000	
5 th	1		

Stream Order	Number of streams	Total length of stream (km)	Mean length of stream (km)	$R_L = \bar{L}_{u+1} / \bar{L}_u$	Mean R_L	Contributing area (km ²)	Total contributing area (km ²)	Mean contributing area (km ²)	$R_A = \bar{A}_{u+1} / \bar{A}_u$	Mean R_A
1 st	250	99.747	0.398	2.794	3.730	51.002	51.002	0.204	7.049	4.997
2 nd	50	55.754	1.115	2.588		20.926	71.928	1.438	6.209	
3 rd	9	25.974	2.886	0.578		8.460	80.388	8.932	4.593	
4 th	2	3.339	1.669	8.963		1.653	82.041	41.020	2.135	
5 th	1	14.965	14.965			5.53	87.571	87.570		

Table 3 – Comparison of Number of streams, mean length of each order and mean area of each stream order as per DEM and as per toposheets for the same basin

Stream Order	Number of Streams		Mean Length of each order stream (km)		Mean Area of each order stream (km ²)	
	As per DEM	As per toposheet	As per DEM	As per toposheet	As per DEM	As per toposheet
1 st	250	353	0.398	0.590	0.204	0.160
2 nd	50	65	1.11	1.090	1.438	1.170
3 rd	9	16	2.83	2.850	8.932	5.640
4 th	2	2	1.669	5.220	41.021	47.010
5 th	1	1	14.965	9.580	87.57	97.270

Variations in each of the three parameters mentioned in the table 3 are clearly visible. Variation in mean length of 1st, 2nd and 3rd order is very negligible but considerable variation can be seen for 4th and 5th order streams.

Similarly, variations in the contributing area are less for 1st and 2nd order streams but variations increase for 3rd, 4th and 5th order streams. Table – 4 shows comparison of the Horton’s ratio obtained for the Devak basin from present study and results obtained using toposheets for the same catchment. The values obtained of bifurcation ratio 4.263 and area ratio 4.997 lies within their general range 3 to 5 and 3 to 6 respectively but the value obtained of length ratio 3.720 is exceeding the limit of 1.5 to 3.5.

Table 4 - Horton’s Ratio for the Devak Basin

	Bifurcation Ratio (R _B)	Length Ratio (R _L)	Area Ratio (R _A)
As per DEM	4.263	3.720	4.997
As per Toposheets	4.870	2.030	5.634

The parameter “n” of the Nash model comes out to be 3.65. The parameter “k” of the Nash model was estimated from the derived Horton’s dimensionless parameters (i.e. R_B, R_L and R_A) at different velocities of flows. Using the estimated values of the n and k at different velocity of flows, V, the ordinates of Instantaneous Unit Hydrograph (IUH) was computed and 1-hour UHs were derived for various velocities of flow. The 1 h-UH at different velocities are depicted in fig. 3.

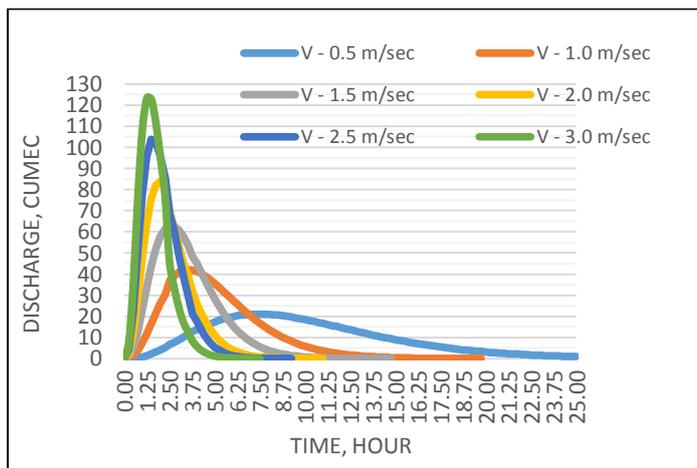


Fig. 3 Geomorphological Unit Hydrograph (GUH) at Different Velocities for Devak Basin

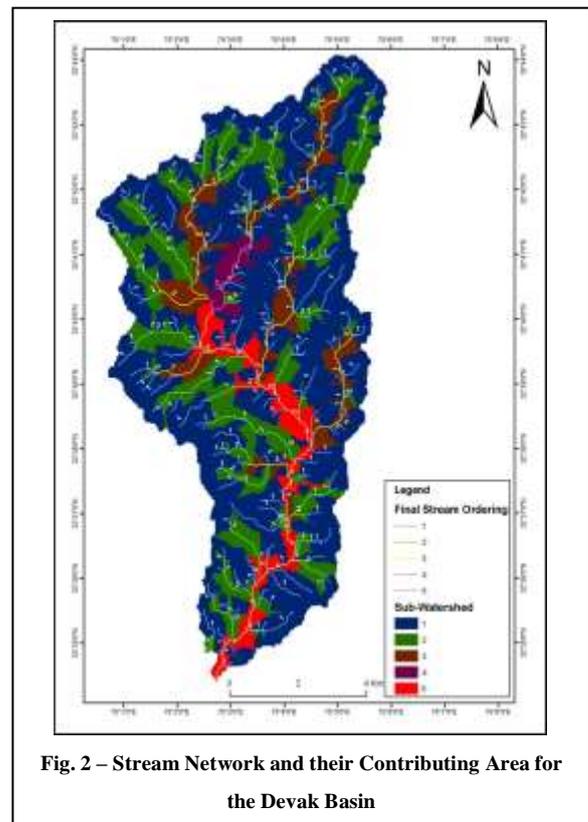


Fig. 2 – Stream Network and their Contributing Area for the Devak Basin

For the Devak Basin, the Unit Hydrographs (UH) are prepared assuming the velocity starting from 0.5 m/sec to 3 m/sec at an interval of 0.5 m/sec. The graph shows the variation in the peak discharge and time to peak as the velocity changes. As the velocity increases, time of concentration decreases and peak discharge increases.

V. CONCLUSIONS

Since most of the hilly regions are ungauged, the study of geomorphological characteristics is one of the methods to study the hydrological response of a basin. The following are the conclusions derived based on the results obtained for the Devak basin.

Various geomorphological parameters such as length of the length of the basin and Horton's ratio have been calculated. The basin is of 5th order covering 87.57 km² areas. The length of the basin obtained is 25.128 km from DEM and that of 27.47 km obtained from toposheets.

The mean length and mean contributing area of each order stream increases as stream order increase.

Results obtained from the present study are compared with results obtained from toposheets, variation in length ratio 3.723 as per DEM and 2.030 as per toposheets is observed. This variation is high comparing to the Bifurcation Ratio which is 4.263 as per DEM and 4.870 as per toposheets and, Area Ratio 4.997 as per DEM and 5.634 as per toposheets.

The GUH based approach becomes more realistic, as parameters like flow velocity, drainage network, contributing area of the different order drains and their lengths are incorporated. It also provides the complete shape of the UH at different values of velocity of flow.

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