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## Development of Geomorphological Instantaneous Unit Hydrograph – A Case Study of Hemavathi Catchment

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**ABSTRACT:** Geomorphological Instantaneous Unit Hydrograph (GIUH) model which proves to be simple and analytical approach is popular because of its direct application for proper assessment of runoff response to an ungauged catchment resulting from a rainfall event. It is an essential for protection of environment issues for sustainable development of life and hydrological response of Hemavathi catchment. It avoids adoption of tedious methods of regionalization of unit hydrograph where in, the historical rainfall – runoff data are required to be analysed. In this study, the GIUH based Nash model has been developed for the estimation of direct surface runoff hydrographs. The GIUH derived from geomorphological characteristics of Hemavathi catchment has been related to the parameters of Nash model for deriving its complete shape in which these shape parameters of the Nash model is found to depend on Horton's ratios of area ratio ( $R_a$ ), bifurcation ratio ( $R_b$ ) and length ratio ( $R_l$ ) of the catchment and thus obtained GIUH is compared with the CWC method of unit hydrograph.

**KEYWORDS:** GIUH, Nash model, CWC method of unit hydrograph

### I. INTRODUCTION

#### I.I. Background of GIUH Based Approach

Rodriguez-Iturbe and Valdes (1979) introduced the GIUH model to assess the direct runoff of catchment and theory of relating the peak discharge and time to peak discharge with geomorphologic characteristics of the catchment and a dynamic velocity parameter. This Pioneer work of Rodriguez-Iturbe and Valdes which explicitly integrates the geomorphologic details and the climatologic characteristics of the basin which is a framework of travel time distribution which is boon for stream flow synthesis in the basin having no or scanty information of flow data. This formulation of GIUH is based on the probability density function (pdf) of the time history of a randomly chosen drop of effective rainfall arrived to the trapping state of a hypothetical basin, treated as a continuous Markovian process, where the state is the order of the stream in which the drop is located at any time and the value of this pdf produces the main characteristics of GIUH.

$$qp = 1.31 R_l^{0.43} V / L \quad (1)$$

$$tp = 0.44 (L / V) (R_b / R_a)^{0.55} \chi R_l^{-0.38} \quad (2)$$

Where,  $qp$  is the peak flow,  $L$  is the length of the highest order stream (km),  $V$  is the dynamic velocity parameter (m/s). Multiplying equations (1) and (2) a non-dimensional term  $qp \chi tp$  is derived as.

$$qp \chi tp = 0.5764 [ R_b / R_a ]^{0.55} \chi R_l^{0.05} \quad (3)$$

The term  $qp \chi tp$  is not dependent on the velocity and there by on the storm characteristics and hence, it is a function of only the geomorphologic characteristics of the basin. The Characteristics velocity for the basin as a whole changes throughout as the storm progress. The dynamic velocity parameter in the formulation of GIUH incorporates the effect

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of climatic variation. Rodrigluez-Iturbe et al. (1979) showed the dynamic velocity parameter of the GIUH can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in the catchment. Valdes et.al. (1979) compared the GIUHs for some real world basin with the IUHs derived from the discharge hydrograph predicted by a physically based rainfall- runoff model of the same basins and found them to be remarkably similar. For few of Indian catchments this GIUH based approach was successfully demonstrated (Kumar et.al. 2002; 2007). In the present study, the Nash based model was tested for the Hemavathi catchment.

## I.II. NASH Model

The Nash model (Nash, 1957) is based on the concept of routing of the instantaneous inflow through a cascade of linear reservoirs with equal storage coefficient. The Nash model can be expressed as follows:

$$u(t) = \frac{1}{k\Gamma n} (t/k)^{n-1} e^{-\frac{t}{k}} \quad (4)$$

Where  $u(t)$  is the ordinates of IUH ( $\text{hour}^{-1}$ ),  $t$  is the sampling time interval (hour),  $n$  and  $k$  are the parameters of the Nash model, in which  $n$  is the number of linear reservoirs, and  $k$  is the storage Coefficient (hour).

The complete shape of the GIUH can be obtained by linking the  $q_p$  and  $t_p$  of the GIUH with scale ( $k$ ) and shape ( $n$ ) parameters of the Nash model. By equating the first derivative with respect to  $t$  of eq (4) to zero,  $t$  becomes the time to peak discharge,  $t_p$ . Thus, taking the natural logarithm of both sides of eq (4), differentiating with respect to  $t$  and by simplification eq. (5) is derived.

$$\frac{\delta}{\delta t} \ln [u(t)] = -\frac{1}{k} + \frac{(n-1)}{t} \quad (5)$$

Equating eq. (5) to zero results in by replacing  $t$  with  $t_p$ ,

$$t = t_p = k(n-1) \quad (6)$$

Simplifying the value of  $t_p$  from equation (6) in equation (4) and simplifying yields

$$q_p = \frac{1}{k\Gamma n} e^{[-(n-1)]} \chi(n-1)^{(n-1)} \quad (7)$$

Combining equations (6) and (7) results:

$$q_p \chi t_p = \frac{(n-1)}{\Gamma n} e^{[-(n-1)]} \chi(n-1)^{(n-1)} \quad (8)$$

Equating equation (8) with equation (3) results in:

$$\frac{(n-1)}{\Gamma n} e^{[-(n-1)]} \chi(n-1)^{(n-1)} = 0.5764 [R_b / R_d]^{0.55} \chi R_i^{0.05} \quad (9)$$

The Nash parameter  $n$ , can be obtained by solving equation (9) using the Newton-Raphson method. The Nash's parameter  $k$  for the given velocity  $V$  is obtained using equation (2) and (6) and the known value of the parameter  $n$  as follows:

$$k = \frac{0.44 L\Omega}{V} [R_b / R_d]^{0.55} \chi R_i^{-0.38} \frac{1}{(n-1)} \quad (10)$$

The derived values of  $n$  and  $k$  are used to determine the complete shape of the Nash based GIUH using equation (4). In this paper GUIH based NASH model Geomorphological parameters have been estimated using GIS, since the use of GIS not only make this task relatively easy but accurate as well with the following objectives. 1) Development of Geomorphological Instantaneous Unit Hydrograph. 2) To validate the model using CWC method of unit hydrograph.

## II. STUDY AREA

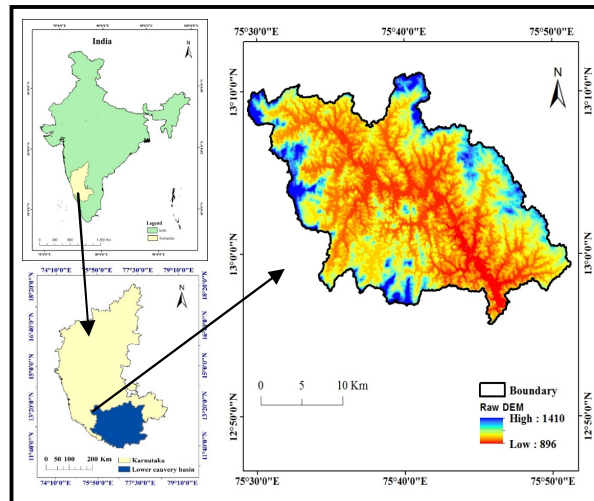
For the present study, the head water catchment of the Hemavathi defined by hydrology tool in ArcGIS 10.3 having outlet point at  $77^\circ 47' 7''$  E and  $12^\circ 57' 3''$  N even though the gauging site is at Sakleshpura to apply Nash Model with river length approximately 52 km having an area of  $589.15 \text{ km}^2$  with perimeter 221.56 km is considered. The study area

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Vol. 8, Issue 3, March 2019



**Fig1. Location Map of Hemavathi catchment**

of Hemavathi catchment which is geographically lies between 12°50' 0" and 13°10' 0" North latitude and 75° 30' 0" and 75° 50' 0" East in south western part of Chickmagalur and Hassan districts as shown in figure 1.

### III. MATERIALS AND METHODOLOGY

To estimate the geomorphological parameter of the study area the catchment is delineated using ASTER Global DEM (Digital elevation model) of 30 m resolution which is downloaded from USGS earth explorer which represents the digital topographical surface using ArcGIS 10.3 software.

#### The study was carried out in two phases:

1. Extraction of drainage networks form the DEM using the flow direction method, which consists of the following steps (O'Callaghan and Mark, 1984).
  - a. Fill sinks: A sink is an uncompleted value lower than the values of its neighbourhood. To ensure proper drainage mapping, these sinks were filled by increasing elevations of sink points to their lowest outflow point.
  - b. Calculate Flow Direction: using the filled DEM produced in the step (a) the flow directions were calculated using the eight-direction flow model, which assigns flow from each grid cell to one of its eight adjacent cells in the direction with the steepest downward slope.
  - c. Calculate Flow Accumulation: Using the output flow direction raster created in step (b) the number of upslope cells flowing to a location was computed.
  - d. Stream Segmentation: After the extraction of drainage networks, a unique value was given for each section of the network associated with a flow direction.
  - e. Define Stream Network: The next step is to determine a critical support area that defines the minimum drainage area that is required to imitate a channel using a threshold value.
  - f. Morphometric Analysis using Strahler's classification method (Strahler, 1964).

Strahler's system of stream analysis is probably the simplest and most used system and hence, was used for this study. According to this method, each finger-tip drainage network is designated as a segment of the first order. At the connection of any two first-order segments, a network of the second order is produced, which extends down to the point where it joins another second order river, where upon a segment of the third order results and so on.

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Vol. 8, Issue 3, March 2019

2. Development of GIUH model: To develop GIUH model the parameters obtained from the morphometric analysis has been used in the present study which was first introduced by Rodriguez-Iturbe and Valdes (1979) and to develop complete hydrograph Nash model is used.

## IV. RESULTS AND DISCUSSIONS

The quantitative morphometric analysis of the drainage basin is considered to be the most satisfactory method because it enables us:

- i. To understand the relationship between different aspects of the drainage pattern of the same drainage basin.
- ii. For comparative evaluation of different drainage basins developed in various geologic and climatic regimes.
- iii. To define certain useful parameters of drainage basins in numerical terms.

Remote sensing and Geographic Information System (GIS) techniques are being efficiently used in recent times as a tool in determining the quantitative description of basin geometry that is morphometric analysis also people have developed unit hydrograph also.

In this output map totally 5 orders are identified. Total number of 1<sup>st</sup> order streams is 316 with length 283.55km, total number of 2<sup>nd</sup> order streams is 72 with length 116.77km, total number of 3<sup>rd</sup> order streams 17 with length in 83.4km, total number of 4<sup>th</sup> order streams 4 with length 31.71km, and the total number of 5<sup>th</sup> order streams 1 having length 27.17 km which is shown in figure 2 also Horton's ratios are found to be Bifurcation ratio ( $R_b$ ) is 3.38, Length ratio ( $R_l$ ) is 1.98 and Stream-area ratio ( $R_a$ ) is 0.465.

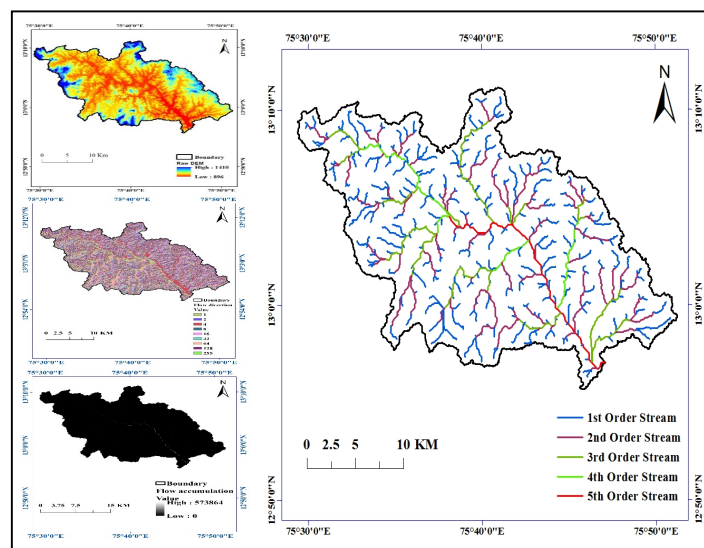


Fig 2. Stream order map of Hemavathi Catchment

The drainage pattern of the basin is predominantly dendritic and semi-dendritic pattern is less pronounced. The types of drainage patterns indicate lack of inhomogeneity in the geological formation and structural control. The quantitative morphometric analysis coupled with limited field studies demonstrate the hydrological nature of the underlying geology, precipitation, exogenic and endogenic forces operating within the basin [15].

### IV.I. Estimation of Geomorphological Instantaneous Unit Hydrograph

The final form of the GIUH is obtained by substituting the value of  $R_a$ ,  $R_b$ ,  $R_l$  and value of  $k$  at different dynamic velocities are tabulated in table 1.

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Vol. 8, Issue 3, March 2019

**Table 1. Value of k at different dynamic velocity**

V (m/s)	n	k	V(m/s)	n	k
0.50	3.9	18.9341	3.00	3.9	3.1556
1.00	3.9	9.467	3.50	3.9	2.7048
1.50	3.9	6.311	4.00	3.9	2.3667
2.00	3.9	4.7335	4.50	3.9	2.1037
2.50	3.9	3.7868	5.00	3.9	1.893

**Table 2. Derivation of Nash based unit hydrograph at dynamic velocity 4 m/s, k = 2.3667 and n = 3.9 is as follows**

t (hr)	t/k	$e^{(-\frac{t}{k})}$	$(t/k)^{2.9}$	u(t) cm/hr	u(t) m <sup>3</sup> /s	t (hr)	t/k	$e^{(-\frac{t}{k})}$	$(t/k)^{2.9}$	u(t) cm/hr	u(t) m <sup>3</sup> /s
0	0	1	0	0	0	14	5.9152	0.0027	173.2675	0.0329	80.2202
1	0.4225	0.6554	0.0822	0.0038	6.2104	15	6.3377	0.0018	211.6462	0.0264	66.3128
2	0.8450	0.4295	0.6137	0.0186	30.3815	16	6.7603	0.0012	255.2077	0.0208	53.8811
3	1.2675	0.2815	1.9888	0.0394	64.5324	17	7.1828	0.0008	304.2620	0.0163	43.1353
4	1.6901	0.1845	4.5806	0.0595	97.4100	18	7.6053	0.0005	359.1171	0.0126	34.0895
5	2.1126	0.1209	8.7490	0.0745	121.9400	19	8.0278	0.0003	420.0793	0.0097	26.6365
6	2.5351	0.0793	14.8451	0.0829	139.6049	20	8.4503	0.0002	487.4531	0.0073	20.6049
7	2.9576	0.0519	23.2129	0.0849	151.9712	21	8.8728	0.0001	561.5414	0.0055	15.7968
8	3.3801	0.0340	34.1906	0.0820	160.2041	22	9.2954	0.0001	642.6457	0.0042	12.0136
9	3.8026	0.0223	48.1115	0.0756	164.3171	23	9.7179	0.0001	731.0659	0.0031	9.0704
10	4.2252	0.0146	65.3049	0.0673	154.1544	24	10.1404	0.0000	827.1008	0.0023	6.8033
11	4.6477	0.0096	86.0963	0.0581	138.7231	25	10.5629	0.0000	931.0475	0.0017	5.0723
12	5.0702	0.0063	110.808	0.0490	116.0654	26	10.9854	0.0000	1043.2023	0.0012	3.7611
13	5.4927	0.0041	139.759	0.0405	99.1028	27	11.4079	0.0000	1163.8600	0.0009	2.7748

We tried to derive Complete Derivation of Nash based unit hydrograph at velocities and by trial and error we got 4 m/s is found to be good, therefore here we described only at 4m/s (Table 2) according to the procedure given by Rodriguez-Iturbe and Valdes (1979) which is already described in I.I and I.II.

### IV.II. Validation of GIUH with CWC Method of Unit Hydrograph

To validate the derived GIUH of study area a comparison is made with UH computed from the procedure adopted by CWC. The CWC method is well accepted by field engineers / hydrologist for the derivation of UH on the ungauged catchment in India for the estimation of hydrograph. In this method a set of equations for UH parameters (viz., peak flow rate, time to peak flow rate and time base of the hydrograph) as a function of slope, length of the longest stream and drainage area were developed for the catchment.

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Vol. 8, Issue 3, March 2019

**Table 3. Calculation of slope**

Segment Length (L <sub>i</sub> , km)	Elevation from outlet (m)	Datum (m)	D <sub>i</sub>	D <sub>i</sub> + D <sub>(i-1)</sub>	L × D <sub>i</sub> + D <sub>(i-1)</sub>	Segment Length (L <sub>i</sub> , km)	Elevation from outlet (m)	Datum (m)	D <sub>i</sub>	D <sub>i</sub> + D <sub>(i-1)</sub>	L × D <sub>i</sub> + D <sub>(i-1)</sub>
0.00	896	896	0	0	0.000	1.643	903	896	7	14	23.002
1.98	896		0	0	0.000	4.66	903		7	14	65.240
3.609	896		0	0	0.000	2.866	904		8	15	42.990
2.372	896		0	0	0.000	1.669	907		11	19	31.711
3.99	896		0	0	0.000	1.955	913		17	28	54.740
1.803	901		5	5	9.015	1.1	913		17	34	37.400
1.915	901		5	10	19.150	2.281	919		23	40	91.240
2.465	902		6	11	27.115	1.104	919		23	46	50.784
1.534	902		6	12	18.408	6.216	972		76	99	615.384
2.24	902		6	12	26.880	2.807	1342		446	522	1465.254
3.221	903		7	13	41.873	-	-		-	-	-

$$\sum L_i \times D_i + D_{(i-1)} = 2620.186$$

$$S = 2620.186 / (51.43)^2 = 0.99 \text{ m/km}$$

The following information is obtained from the map of the Hemavathi catchment using ArcGIS. Catchment area as 589.15km<sup>2</sup>, Length of longest stream as 51.43 km, length of the longest stream nearest to C<sub>g</sub> which is nothing but L<sub>c</sub> as 22.64 km. Calculation of slope and other parameters are tabulated in table 3, further the parameters of CWC procedure of unit hydrograph described in table 4.

**Table 4. Parameters of Unit Hydrograph Using CWC Method for Hemavathi Catchment**

q <sub>p</sub> (m <sup>3</sup> /s/sq.km)	2.043/(T <sub>p</sub> ) <sup>0.872</sup>	0.2825
T <sub>p</sub> (hr)	0.553(L × L <sub>c</sub> √S) <sup>0.405</sup>	9.669
W <sub>50</sub>	2.197/(q <sub>p</sub> ) <sup>1.067</sup>	8.464
W <sub>75</sub>	1.325/(q <sub>p</sub> ) <sup>1.088</sup>	5.242
W <sub>R50</sub>	0.799/(q <sub>p</sub> ) <sup>1.138</sup>	3.367
W <sub>R75</sub>	0.536/(q <sub>p</sub> ) <sup>1.109</sup>	2.275
T <sub>B</sub> (hr)	5.08(T <sub>p</sub> ) <sup>0.733</sup>	26.80
T <sub>m</sub> (hr)	T <sub>p</sub> + t <sub>r</sub> /2	10.168
Q <sub>p</sub> (m <sup>3</sup> /s)	q <sub>p</sub> × A	166.43



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Vol. 8, Issue 3, March 2019

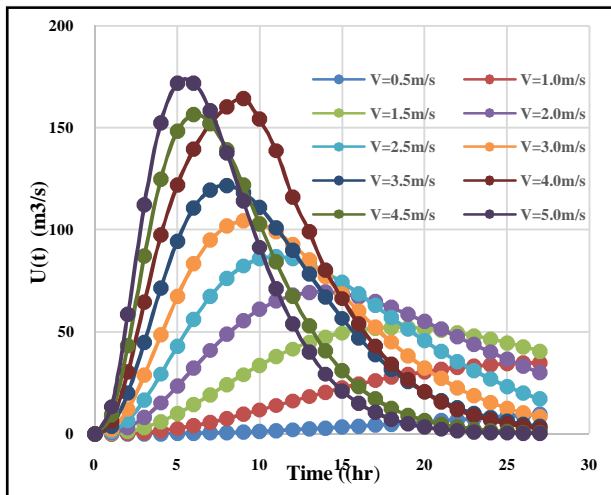


Fig 3. GIUH at different velocities

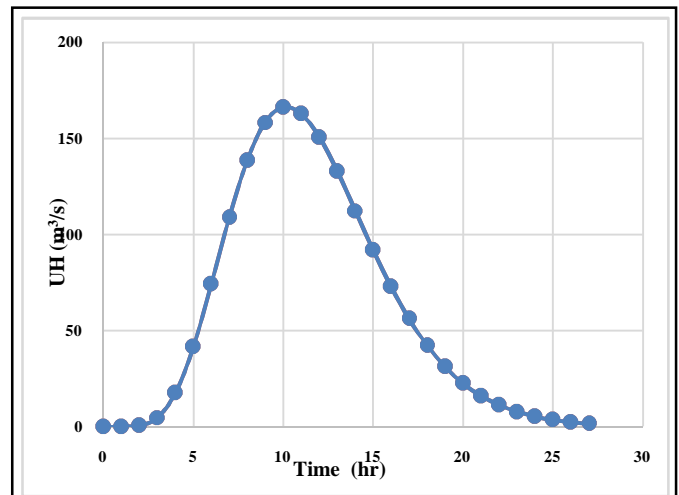


Fig4. CWC method of Unit Hydrograph

Here figure 3 represents unit hydrograph which drawn from the results of geomorphometric analysis with varying dynamic velocities from 0.5m/s to 5m/s further figure 4 represents CWC method of unit hydrograph which is plotted with the help of parameters which is described in above table.

## V. CONCLUSION

We have described here an analytical geomorphological transfer function representing the theoretical distribution of hydraulic lengths in a river basin. This model is based on the assumption that the reduced lengths distributions in order k (Strahler order) are similar and represented by a Gamma law. The analytical geomorphological transfer function results from the convolution of these n Gamma laws (equations 6 and 7) n being the total Strahler order in the river basin. This theoretical result is an analytical function depending on n + 1 geomorphological parameters which are easily available by simply reading a map or analysing digital data (DEM for example). After explaining the approach to obtain this analytical function (equation 7), we have tested our theoretical model for another catchment. It possible to give a fairly accurate description of the morphological structure of the stream network in the river basin.

Table 5. Comparison of Nash Model with CWC method of unit hydrograph

Parameter	Nash Model	CWC Method
n	3.9	-
V (m/s)	4	-
Qp (m <sup>3</sup> /s)	166.43	164.317
Tp (hr)	9	9.66

From the present work Hemavathi catchment is found to be 5<sup>th</sup> order and almost steep terrain. Also, the extracted drainage network of the basin has wide range of application such as installation of the artificial drainage system and laying down the canal system, site identification for rain water harvesting, ground water recharge and waste disposal, etc. However the main theme of the study is to develop a GIUH. To check the accuracy of the GIUH technique the results were compared with CWC procedure of Unit hydrograph, three Horton's ratios of the study areas were coupled with the parameters of Nash's IUH model and the GIUH is derived for different values of dynamic velocity of flow. The results shows that the obtained GIUH with dynamic velocity 4m/s (approx.) for the catchment shows closer

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Vol. 8, Issue 3, March 2019

agreement with CWC approach (table 5). Since, CWC approach is independent of climatic parameter and geomorphologic characteristics other than the slope, drainage area and length of main stream resulting unit hydrograph may have some computational error.

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