Automated Generation of GIUH for Third Order Stream Using ArcGIS

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***Abstract*— A significant advancement in the unit hydrograph method for an ungauged area is the development of the Geomorphological Instantaneous Unit Hydrograph (GIUH). The use of GIS to facilitate the estimation of runoff from watersheds has gained increasing attention in recent years. In this study, the procedure for deriving the GIUH for third order was automated using ArcGIS software. Many parameters and procedures are involved in the runoff computation using GIUH. These involve the determinations of Bifurcation ratio, Length ratio, Area ratio, Travel time parameters, Path probability, GIUH, Unit Hydrograph and Runoff. A tool was developed in Python interface to Arc GIS to generate these parameters so that automatic generation of runoff from an ungauged catchment can be developed. Python is a programming language that lets to do the work more quickly and integrate the systems more effectively. These scripts were added to ArcGIS as a new tool. Eight such tools were developed. Kurumali watershed of Kerala was selected for applying the GIUH tool. Runoff obtained using the GIUH tool was compared with the result obtained manually.**

Keywords—GIUH; ArcGIS; third order; Python

I. INTRODUCTION

A significant advancement in the unit hydrograph method for an ungauged area is the development of the Geomorphological Instantaneous Unit Hydrograph (GIUH). The GIUH approach was developed by Rodriguez-Iturbe and Valdes [1]. They rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for geomorphological structure of a basin. Geomorphology reflects the topographic and geometric properties of the watershed and its drainage channel network. It controls the hydrologic processes –viz., conversion of rainfall to runoff, and the subsequent flow routing through the drainage network [2].

The use of GIS to facilitate the estimation of runoff from watersheds has gained increasing attention in recent years [3]. This is mainly due to the fact that it is often desirable to include the spatial and geomorphologic variation of the watershed in the rainfall/runoff model. The spatially distributed capabilities of GIS facilitate the linkage of watershed data to distributed parameter models. The development of GIUH is being customarily applied using manual procedure, of course using the GIS technology for processing. This procedure is tedious process especially when one wanted to apply it for several times and for several basins. Thus it becomes essential to build a tool for automatic generation of GIUH and thereby avoiding the need for doing repetitive and tiresome work. This tool can be developed within the ArcGIS environment , so that user can find out the runoff from a watershed more efficiently with minimal time and effort. Such generation can be carried out using scripts which can be implemented using popular scripting environments, such as Python, VBScript, JScript, and Perl. In the current study, Python is selected in the current study due to its advantages like elegant syntax and dynamic typing, together with its interpreted nature. Hence the objective of the study can be stated as :

- Automate generation of GIUH parameters from delineated watershed in ArcGIS and hence the automated computation of GIUH for third order watersheds.
- Verification of the model by applying it to actual watershed, viz., Kurumali watershed.

II. LITERATURE REVIEW

Rainfall-runoff relationships are one of the most complex hydrologic phenomena. Predicting runoff in ungauged catchment has various applications like design of drainage infrastructure, flooding defences, runoff forecasting etc. Therefore, the capability of simulating individual storms is important for watershed models to adequately capture hydrologic processes between short intervals [4]. Hence the models like GIUH which can predict the short term variation of flow has gained importance in recent years.

Geomorphologic instantaneous unit Hydrograph (GIUH) is a type of synthetic unit hydrograph which links geo-morphological characteristics of the catchment to its response to rainfall. Geomorphological theory of Instantaneous Unit Hydrograph was developed by Ignacio Rodriguez-Iturbe and

Valdes. They rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for the geomorphological structure of the basin.

Gupta et al. [5] examined the Valdes approach and reformulated, simplified. They linked the hydrologic response of watersheds in terms of the IUH to their geomorphologic parameters, Horton‘s ratios, including area ratio (R_A), bifurcation ratio (R_B) length ratio (R_L), and to a dynamic parameter (V). Two examples were developed which lead to explicit formulae for the IUH.

Sarangi et al. [6] used curve number and geomorphology-based models for surface runoff prediction for ungauged watersheds in Banha watersheds, Jharkhand. This paper discusses the adequacy of a modified exponentially distributed GIUH (ED-GIUH) model in generating direct runoff hydrographs (DRHs). However development of GIUH for a catchment is a tedious process if done manually, and hence restricts its applicability. Its drawback can be avoided if the development of GIUH can be automated by developing a toolbox in GIS environment.

Sarangi et. al [7] developed an interface (built-in macro) within ArcGIS for the estimation of watershed morphological parameters. This was developed using Visual Basic for Applications (VBA) language based on Arc Objects technology developed by (ESRI). The interface can quickly perform a sequence of activities including watershed delineation stream network generation, and estimation of geomorphological parameters. However, no such studies developed an automated tool, for GIUH. Such a development will ease many users who intended to use the GIUH technology for event modelling.

III. METHODOLOGY

A. GIUH

The concept of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) was introduced by Rodriguez-Iturbe and Valdes as a first step in the direction of coupling the hydrologic characteristics of a catchment with the geomorphologic parameters. The GIUH is interpreted as the probability density function of the travel times to the out let of the rain drops, which is randomly and uniformly distributed over the catchment. The travel times on hill slope or along the streams are assumed exponential distributed and the initial and transitional probabilities are calculated based on Horton‘s morphometric parameters. The parameters are area ratio, bifurcation ratio and length ratio.

B. GIUH For a Third Order Basin

1)Horton’s ratios: Horton [8] developed a set of “laws” that are indicators of the geomorphological characteristics of watershed. The Horton ratios can be expressed quantitatively as follows.

a) Bifurcation ratio:

$$R_B = N_i / N_{i+1} \qquad (1)$$

Where Ni and Ni+1 are the number of streams in order *i* and *i+1*. Let Ω represent the highest stream order in the watershed, *i = 1, 2, …, Ω*

b). Length ratio

$$R_L = L_{i+1} / L_i \qquad (2)$$

Where Li is average length of channels of order i.

c) Area ratio

$$R_A = A_{i+1} / A_i \qquad (3)$$

A_i is the mean area of the contributing watershed to streams of order i

2)Transitional state probabilities: The equations for transitional state probabilities of a third order stream is given below[1].

$$P_{12} = \frac{R_B{}^2 + 2R_B - 2}{R_B{}^2 - R_B} \qquad (4)$$

$$P_{13} = \frac{R_B{}^2 - 3R_B + 2}{R_B{}^2 - R_B} \qquad (5)$$

$$P_{23} = 1$$

3)Initial state probabilities: The initial state probability θ_j is equal to the ratio of the area draining directly into streams of order i to the total basin area. It is given by the following expression.

$$\theta_1 = \frac{R_B{}^2}{R_A{}^2} \qquad (6)$$

$$\theta_2 = \frac{R_B}{R_A} - \frac{R_B{}^3 + 2R_B{}^2 - 2R_B}{R_A{}^2(R_B - 1} \qquad (7)$$

$$\theta_3 = 1 - \frac{R_B}{R_A} - \frac{R_B{}^3 - 3R_B{}^2 + 2R_B}{R_A{}^2(2R_B - 1} \qquad (8)$$

3)Path Probabilities: Path probability is defined as the probability of a drop which will travel all possible paths Si to the outlet. Path probability is denoted as Prob(Si).

The total number of possible paths can be calculated using the following formula.

$$N = 2^{\Omega - 1}$$

Where, Ω is the order of the stream.

$$\mathrm{Prob}(s_i) = \theta_j . P_{ij} . P_{jk} . P_{l\Omega} \qquad (9)$$

θ_j is the initial state probabilities and P_{ij} are the transition probabilities

Using the initial and transitional probabilities for each transition, probability of each path is calculated. For a third order stream total number of possible path = 4.

TABLE 1. PATH DESCRIPTION OF EACH PATH: THIRD ORDER

Path Number	***Path description***
1	a1→r1→r2→r3→outlet
2	a1→r1→r3→outlet
3	a2→r2→r3→outlet
4	a3→r3→outlet

a_i - denotes when the rain drop is in hill slope state of order i, and (i=1,2…..Ω)

r_i- denotes when the rain drop is in channel state of order i.

4)Probability Density Function

It is the probability density function of the total path travel time Tsi.

Probability density function is denoted by Prob (Tsi)

The travel times Ts in particular path must be equal to the sum of travel times in the elements of that path.

$$T_{si} = T_{ai} + T_{ri} + T_{ri+1} + ...+ T_{\Omega} \tag{10}$$

T_{ai} is the travel time on the hillslope

T_{ri} is the travel times in each stream segment of order i.

Assuming that these individual times of travel are independent variables such that f_{Ta} is the probability density function of T_{ai} and f_{Tri} is the probability density function of T_{ri}, the probability density function of the sum T_{si}, is a multiple convolution integral of the form :

$$\text{Prob}\ (T_{si}t) = \sum f_{si}(t) \tag{11}$$

$$\text{Prob}\ (T_{si}t) = \sum f_{Tai}(t) * f_{Tri}(t) * f_{Tri+1}(t) * ... * f_{Tr\Omega}\ (t) \tag{12}$$

$f_{Tai}(t)$: Exponential probability density function corresponding to the travel time of a drop in a given hillslope

$f_{Tri}(t)$: Exponential probability density function corresponding to the travel time of a drop in a given channel.

$$f_{Tai}(t) = \alpha\ e^{(-\alpha t)} \tag{13}$$

$$f_{Si} = \sum_{j=1}^{\Omega} \frac{\lambda_i \dots \lambda_\Omega . \exp(-\lambda_j t)}{(\lambda_i - \lambda_j) \dots (\lambda_{j-1} - \lambda_j)(\lambda_{j+1} - \lambda_j) \dots (\lambda_\Omega - \lambda_j)}\ , j \neq i$$

(14)
[9]

The probability density function of travel time of the possible paths, were calculated as a function of the hill slope velocities/stream flow velocities using the following equations.

$$\alpha = \frac{V_o}{L_O} \tag{15}$$

Where, $L_o = \frac{1}{2D}$

L_o – average flow length

D – Drainage density

The value of travel time parameter λ which varies from stream to stream is given by

$$\lambda = \frac{V_s}{L_i} \tag{16}$$

V_s is the stream velocity

Li is the mean length of stream of order i

*5)GIUH: T*he geomorphological instantaneous unit hydrograph can be computed as

$$GIUH(t) = \sum_{s=S} f_{Tai} * f_{Tri} * f_{Tri+1} * \dots prob(S)$$

(17)

[9]

C. Creating Script Tool Within ArcGIS

- A script tool is like any other tool it can be opened and executed from the tool dialog box, within the ArcGIS. Creating a script tool allows us to turn our own Python scripts and functionality into our own geoprocessing tools. Once created, a script tool provides many advantages.
- A script tool that one creates is an integral part of geoprocessing, just like a system tool he can open it from the Search or Catalog window, use it in Model Builder and the Python window, and call it from another script.

A toolbox can be operated from the catalogue window. The output from each tool was saved as a text file.

IV. STUDY AREA

For applying the automated GIUH model, Kurumali watershed from Kerala were selected. It is located in Thrissur district. This watershed drained by the Kurumali river, one of the main tributary of the Karuvannur river. It originates in Chimmony from Poomalai (1116 m from Sea Level) in the Western ghats and flows through the Thrissur District. The Mupli River joins the Chimmony river, forming the Kurumali river at Elikode near Karikulam. The Kurumali watershed with drainage of 394 km^2, delineated with outlet located at $10^o26'30.76''$ N and $76^o16'2.30''$E. Fig. 1 shows the Kurumali watershed.

V. DATA COLLECTION

A. Digital Elevation Model

The Digital Elevation Model (DEM) well define the topography of the area by describing the elevation of any point at a given location and specific spatial resolution as a digital file. SRTM (Shuttle Radar Topography Mission) was used as the basic data for the watershed delineation in ArcGIS. The

DEM was downloaded from the site, http://srtm.csi.cgiar.org/index.asp.

B. Rainfall Data

The model input required for deriving the GIUH is the Rainfall data. The rainfall data for the period 2000-2010 was obtained from the Hydrology Department. Effective rainfall text files were prepared from the rainfall data for a rainfall event, which was needed for computing the runoff using GIUH tool.

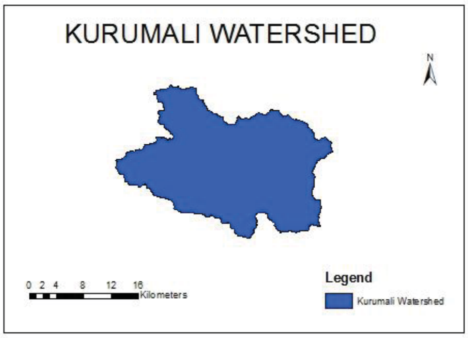

Fig 1. Kurumali watershed

VI. RESULTS AND DISCUSSION

A. Automated Generation of GIUH Parameters Using Python

Many parameters and procedures are involved in the computation of runoff using GIUH. These involve the determinations of Bifurcation ratio, Length ratio, Area ratio, Travel time parameters, Path probability, IUH, Unit hydrograph and Runoff. Using the procedure given for GIUH model, scripts were written for finding the parameters which are described earlier. Then these scripts were added to ArcGIS as a new tool. Eight such tools were developed and put it inside a tool box.

1) Tool for Bifurcation ratio: The tool was developed such that the bifurcation ratio was developed from the stream order feature class. The outputs- Number of streams of each order and Bifurcation ratio-are obtained as a text file.

2) Tool for Length ratio: The tool for length ratio was also developed from the stream order feature class. The outputs from the tool are Total length of streams of each of order, Mean length of streams of each order and Length Ratio.

3) Tool for Area ratio: Area ratio is the ratio of the mean area of watershed contributing to a stream to that of previous lower order stream. Mean area contributing to each watershed is calculated from the bifurcation ratio and length ratio which have been already determined.

4) Tool for Path Probability: For finding out the probability of each path, initial and transitional probabilities have to be calculated. Transitional probabilities are calculated using the bifurcation ratio which have already obtained using bifurcation ratio tool. Initial state probabilities are calculated using bifurcation ratio and area ratio.

5) Tool for Travel Time Parameters: Travel time parameters are required for finding out the probability density function. It is calculated based on overland flow velocity/stream flow velocity. Here also mean length of streams of each order is required for finding the travel time parameters as in the case of length ratio tool.

6) Tool for GIUH: The instantaneous unit hydrograph represents the response of the catchment to an instantaneous rainfall. The GIUH tool was used for finding out the ordinates of instantaneous unit hydrograph for a particular duration. Travel time parameters and path probabilities were used in the IUH determination. Number of hours of simulation was also given as the input.

7) Tool for Unit Hydrograph: The inputs for IUH tool and unit hydrograph tool are same. One additional input required for unit hydrograph is the basin area. The IUH ordinates have the dimension of T^{-1}; hence it is converted into cumecs by multiplying with the area of the watershed with appropriate conversions. Further 1 hour unit hydrograph is obtained by lagging the ordinates by 1 hr GIUH and averaging the coordinates.

8) Tool for Runoff: For finding out the runoff, unit hydrograph ordinates and effective rainfall values are required. Unit hydrograph text file obtained from the previous tool was used as one input. Effective rainfall values were entered into a text file. These two text files were given as the input to runoff tool. The direct runoff hydrograph ordinates for each hour are obtained using the tool.

B. Runoff Estimation for Kurumali Watershed Using GIUH Tool

1) Watershed delineation: Watershed delineation was carried out using the hydrology tool box of the ArcGIS. SRTM digital elevation Model was used for delineating the watershed and has a resolution of 90m. Fig 2. Shows the delineated watershed of Kurumali.

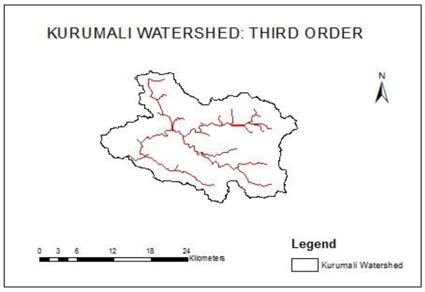

Fig. 2 Delineated watershed of Kurumali river

2) Outputs obtained from the GIUH tool for Kurumali watershed: Stream order feature class of the Kurumali watershed was used as the input to find out the geomorphological parameters of watershed. These parameters were determined by the developed tools. They include the bifurcation ratio, area ratio, length ratio. These are given in

Table 2. Using these parameters initial state probabilities (Table 3), transitional state probabilities (Table 4) path probabilities (Table 5) and Travel time parameters were found out again using the developed tool for that purpose.

TABLE 2. GEOMORPHOLOGICAL PARAMETERS OF KURUMALI WATERSHED

Watershed	***Area (km^2)***	***Stream r***	***Bifurcation Ratio***	***Length Ratio***	***Area Ratio***
Kurumali	394	3	3.82	3.43	7

TABLE 3. INITIAL STATE PROBABILITIES: KURUMALI

Initial probability	***Third order stream***
θ_1	0.449
θ_2	0.337
θ_3	0.214

TABLE 4. TRANSITIONAL STATE PROBABILITIES: KURUMALI

Transitional probability	***Third order stream***
P_{12}	0.742
P_{13}	0.257
P_{23}	1

TABLE 5. PROBABILITY OF EACH PATH FOR THIRD ORDER: KURUMALI

Path Number	***Path description***	***Probability***
1	$a_1 \rightarrow r_1 \rightarrow r_2 \rightarrow r_3 \rightarrow$ outlet	0.333
2	$a_1 \rightarrow r_1 \rightarrow r_3 \rightarrow$ outlet	0.115
3	$a_2 \rightarrow r_2 \rightarrow r_3 \rightarrow$ outlet	0.336
4	$a_3 \rightarrow r_3 \rightarrow$ outlet	0.214

TABLE 6. TRAVEL TIME PARAMETERS: KURUMALI

Parameters	***Third order stream***
α	0.126
λ_1	0.210
λ_2	0.06
λ_3	0.018

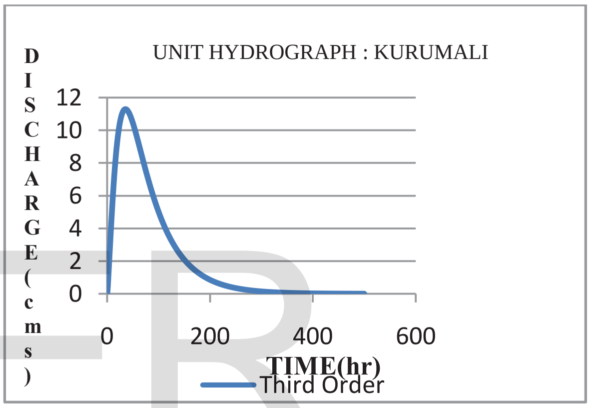

Fig.3 Unit hydrograph: Kurumali

For computing the runoff from the watershed, effective rainfall for each hour was computed. The formula given in the Central Water Commission(1992) was used for finding the effective rainfall. The runoff was generated for Kurumali watershed using the effective rainfall text file and the unit hydrograph ordinates, for duration of more than one month. The amount of base flow was negligible, and hence its value was not considered for the computation of rainfall. The runoff computed and plotted graphically as given in Fig. 4

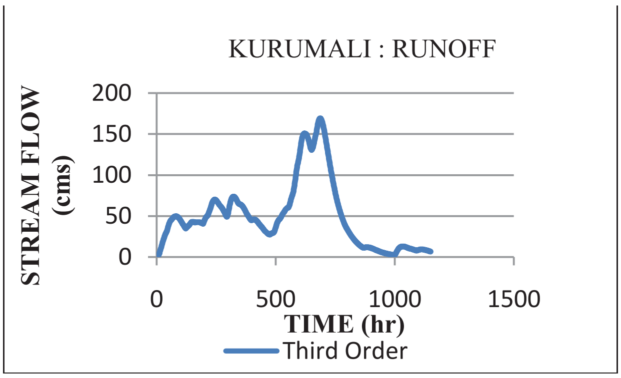

Fig. 4 Kurumali:runoff

C. Manual Computation of GIUH

GIUH were also computed manually to assess the accuracy of the developed tool with the actual GIUH. All the results obtained for the automated and manually computed GIUH were same.

VII. SUMMARY AND CONCLUSION

A. Summary

The main aim of the study is to automate the GIUH process for third order using ArcGIS. For this purpose, a tool box is developed. To assess the accuracy of the model, it was applied to Kurumali watershed. Using the GIUH tool, the runoff hydrograph from watershed is simulated. The results are compared with the manually computed GIUH.

B. Conclusions

Based on the study, the following conclusions were made:

A GIUH tool box is developed within the ArcGIS in order to automate the runoff generation using GIUH. Inside the toolbox, tools are created to find out the bifurcation ratio, length ratio, area ratio, travel time parameters, path probability, IUH, unit hydrograph and the runoff by using Python IDLE for ArcGIS. Hence, automatic generation of GIUH is possible using these tools.

The Runoff hydrograph was computed for Kurumali watershed using GIUH tool. This was compared with manually computed runoff and hence proves the validity of the developed tool.

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