Estimation of Flood Hydrograph using IUH and GIUH Based Clark Models

V.S. Ayana and K.O. Vargheese

Abstract—The basic challenges of hydrology are the quantitative understanding of the processes of runoff generation and prediction of the flood hydrographs. There are several techniques widely applied for the estimation of runoff hydrographs using unit hydrographs and historical rainfall-runoff data. The Clark model is one among them. But this model is questioned for its reliability in ungauged catchments. To overcome such difficulties, the use of Geomorphologic Instantaneous Unit Hydrograph (GIUH) approaches has evolved. In GIUH model, the parameters of the Clark model have been related to the Horton’s ratio, estimated using the geomorphological data with the help of Geographical Information System (GIS). In the present study, flood hydrographs were derived for Karikkadavu basin using IUH and GIUH based Clark model. A comparable performance is observed between the Clark IUH model option of the HEC-HMS package and GIUH-based Clark model, in the estimation of the hydrographs. The results demonstrate that the Clark GIUH models can be successfully used for runoff prediction in ungauged or scantily gauged basins. Also, the application of GIS makes the computation of the geomorphological parameters easy, less time consuming and accurate.

Keywords—Streamflow, Clark Model, GIUH, GIS, HEC-HMS

I. INTRODUCTION

WATER influences every sphere of the environment, supporting the life on earth. Thus its proper utilization and management is very essential. While the human modifications of the environment, including land cover change, irrigation, and flow regulation, occurs on scales, significantly affect seasonal and yearly hydrologic variations. Thus, a thorough knowledge and understanding of the different hydrological phenomena and hydrological cycle as a whole is required for proper utilization and management of available water resources. Hydrological modelling is one efficient way for consistent long term behavioral studies. Hydrological modelling is a mathematical representation of natural processes that influence primarily the energy and water balances of a watershed. The fundamental objective of hydrological modelling is to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner. Thus, in this study, the hydrologic modelling, particularly hydrologic transform modelling is used to study the runoff pattern. In hydrologic transform modelling the effective rainfall is transformed into runoff hydrograph. One of the most important steps towards the construction of the hydrograph is the development of Unit Hydrograph concept.

A Unit Hydrograph (UH) is defined as the hydrograph of direct runoff resulting from unit depth (1 cm) of rainfall excess occurring uniformly over the basin and at a uniform rate for a specified duration (D hours). The special thing about the Unit Hydrograph is that it enables us to derive the hydrograph of design flood, based on which the hydraulic structure is to be designed. And when the unit hydrograph is obtained from an infinitesimally small duration of effective precipitation is called an Instantaneous Unit Hydrograph (IUH). The major advantage of the IUH over the unit hydrograph is that the IUH is independent of the duration of the effective rainfall reducing the number of variables in the hydrograph analysis. As the result, using Instantaneous Unit Hydrographs, for investigation on the rainfall-runoff of a basin, is much suitable than using Unit Hydrographs. Many researchers have made extensive investigation on the derivation of the IUH; among those the Clark conceptual model concept has been widely applied due to its simplicity and efficiency.

The Clark Instantaneous Unit Hydrograph model is based on the concept that IUH can be derived by routing unit excess-rainfall in the form of a time area diagram through a single linear reservoir. For such UH theory, certain amount of historical data is required. As far as Kerala is concerned, most of the watersheds are either ungauged or inadequately gauged. So, these techniques cannot be used directly for the estimation of flood in most of the basins, due to poor stream gauging network. In such situations of nonavailability of data or less data availability, the concept of Geomorphologic Instantaneous Unit Hydrograph (GIUH) have been proposed to estimate floods for ungauged streams by using only the information obtainable from topographic maps or remote sensing. The geographic information systems (GIS) can be used for the task of compiling necessary spatial data and the required hydrologic parameters for modelling the watershed runoff. This approach reduces the excessive topographic data and computational efforts required in full hydrodynamic deterministic routing of watershed runoff.

This paper demonstrates the use of GIS package (HEC HMS) in estimating the flood hydrograph by Clark IUH model. The UH derivation based on geomorphologic approaches is
also included, as the runoff modelling in ungauged catchments are very important.

II. LITERATURE REVIEW

Many researchers have used HEC-HMS in streamflow estimation. Sahoo et al. [2] developed the GIUH based on Clark and Nash model. The derived direct surface runoff hydrograph was then compared with those obtained from conventional Clark IUH model and Nash. For the development of Clark IUH, they used HEC-1 package to optimize the parameters of Clark IUH such as $T_c$ and $R$. The performance was also evaluated using four error functions and concluded that both GIUH and IUH model perform well. Jain et al. [5] derived the flood hydrograph based on Geomorphological Instantaneous Unit Hydrograph (GIUH) approach for an ungauged catchment located in Rajasthan, India. The Clark model parameters for GIUH approach were estimated using the mathematical model developed at the National Institute of Hydrology. It is observed that the design flood is more sensitive to the storm pattern and its time distribution. From the study it is observed that the GIUH and GIS based approach has potential application for the estimation of the design flood particularly for the ungauged catchment. Arash et al. [1] derived geomorphoclimatic instantaneous unit hydrograph (GeIUH) based on Clark model from the geomorphologic characteristics of a watershed. For the comparison of simulated flood hydrographs using the GeIUH-Clark model and the Clark IUH model, option of the Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) package was used. It is observed that the direct surface runoff hydrographs estimated by the GeIUH-Clark model have reasonable conformity with hydrographs estimated by the conventional Clark model using HEC-HMS. Elham et al. [3] has compared different precipitation loss methods available in HEC HMs. Rakesh et al. [6] has been developed a mathematical model, which enables evaluation of the Clark model parameters using geomorphological characteristics of an ungauged basin. Then the model was applied for simulating the direct surface runoff hydrographs. The hydrographs estimated by the GIUH approach have been compared with the observed runoff hydrograph as well with that of computed by Nash model and HEC-1 package.

The GIUH approach has many advantages over the IUH techniques, as they avoid the requirement of rainfall-runoff data and computations for the neighboring gauged watersheds in the region, as well as the updating of the parameters. Another advantage of these approaches is the potential for deriving the geomorphologic parameters using only the information obtainable from topographic maps or remote sensing, possibly linked with geographic information systems (GIS) and digital elevation models (DEM).

III. MATERIALS AND METHODS

A. Description of Models

A brief description of the IUH and GIUH-based Clark model is provided here.

- **Clark IUH Model**

The Clark IUH model is based on the concept that IUH can be derived by routing unit excess-rainfall in the form of a time area diagram through a single linear reservoir. The Clark Method requires three parameters to calculate the IUH: the storage Coefficient ($R$), the time of concentration ($T_c$) and a time area diagram (TAD).

In general, the governing equation of the Clark IUH model can be expressed as Eqn.(1):

$$ u_i = \left(1 - \frac{T_f}{T_c}\right) u_{i-1} + \frac{T_f}{T_c} I_i \quad (1) $$

where $u_i$ is the $i$th ordinate of the IUH; $I_i$ is the $i$th ordinate of the time-area diagram and $\Delta t =$ computational interval in hours. The HEC-HMS package (HEC [4]) uses a synthetic accumulated time-area diagram, given by Eqn.(2):

$$ A_i = \begin{cases} 1.414 T_i^{1.5} & \text{for } (0 < T_i \leq 0.5) \\ 1.414(1-T_i)^{1.5} & \text{for } (0 < T_i < 1) \end{cases} $$

where $A_i$ is the cumulative area as a fraction of total subbasin area, and $T_i$ is the fraction of time of concentration. The ordinates of time-area curve are converted to volume of runoff per unit time for unit effective rainfall, and interpolated to the given time interval. The resulting translation hydrograph is then routed through a linear reservoir to simulate the storage effects of the basin, to synthesize the Clark IUH. The package optimizes the runoff parameters $T_c$ and $R$ by univariate search technique to minimize the square root of the weighted squared difference between the observed and the computed hydrographs, to get the global optimum. To reflect the spatial information effectively, the collected data for the study area were preprocessed using ArcHydro, which can be, then, used as the input data in HEC-GeoHMS to compute the hydrologic parameters.

- **Clark GIUH Model**

The GIUH model structure is coupled with the Clark IUH model to formulate the GIUH based Clark model. The GIUH based Clark model requires the ordinates of the time-area diagram as an input to the model. The step-wise procedure for derivation of the GIUH based Clark model is as follows: (i) The excess rainfall hydrograph is computed using SCS CN method; (ii) The peak velocity $V$ for a given storm using the relationship between peak velocity and intensity of excess-rainfall must be estimated; (iii) Compute the time of concentration using the equation, $0.2778L/V$, where $L$ is the Length of the main channel (km), $V$ is the expected peak velocity (m/s); (iv) Considering this $T_c$ as the largest time of travel, ordinates of cumulative isochronal areas, corresponding to integral multiples of computational time interval, are derived using the non dimensional time-area diagram. This describes the ordinates of the time-area diagram, $I$, at each computational time interval in the domain $[0, T_c]$; (v) Compute the peak discharge ($q_p$) of GIUH given by $q_p = 1.31 R L_{0.43} V/L$, Where $L_{0.43}$ is the length of the highest order stream (km), $V$ is the expected peak velocity (m/s); $R_i$=length ratio;
(vi) Compute the values of storage coefficient ($R$), using a nonlinear optimization procedure, so that peak of the GIUH Clark model matches the peak of the GIUH model. In this technique, two values of $R$ say, $R_1$ and $R_2$ having sufficiently long ranges are assumed and the search for global optimum value of $R$ is carried out in the closed domain ($R_1$, $R_2$) for which the computed peak runoff domain is ($q_{p1}$, $q_{p2}$). The optimization algorithm is as follows: (a) Compute the value of objective function for optimization: $FCN_1 = (q_{p1} - q_{ps1})^2$ and $FCN_2 = (q_{p2} - q_{ps2})^2$ (b) Compute the first numerical derivative of the objective function $FCN$ with respect to parameter $R$ as: $\partial(FCN)/\partial R = -(FCN_1 - FCN_2)/(R_1 - R_2)$; (c) Compute the next trial value of $R$ using the governing equation of Newton-Raphson method: $R_{\text{new}} = R_1 + FCN_1 \times \partial R/\partial(FCN)$; (d) For the next trial consider $R_1 = R_2$ and $R_2 = R_{\text{new}}$ and repeat steps (a) to (d) until the following criteria of convergence are achieved: $FCN_2 \leq 0.000001$ or Number of trials exceeds 200.; (vii) The final value of storage coefficient ($R_2$) obtained as above is the required parameter $R$ corresponding to the value of time of concentration ($T_c$) for the Clark Model. ; (viii) Compute the Instantaneous unit hydrograph (IUH) using the GIUH based Clark Model with the help of final values of storage coefficient ($R$), Time of Concentration ($T_c$) as obtained in step (vii) and time area diagram.

B. Description of Study Area

The area selected for the present study is Karikkadavu basin, which is a subbasin of Kurumali River basin. The Karikkadavu basin has an area of 72 Km$^2$. Fig 1 represents the study area. The main river in this watershed is Mupli river and the outlet is located at 10$^\circ$35’24.22”N and 76$^\circ$16’28.94”E. The landuse data, Soil data, DEM, rainfall data and discharge data for Karikkadavu stream gauge station were collected to meet the objective. The continuous hourly data is available only for July 2010. Therfore the flood hydrograph was derived for a period of 15$^{th}$ July 2010 to 20$^{th}$ July 2010.

![Fig.1: Karikkadavu River Basin](image1)

C. Analysis and Results

- Estimation of Effective rainfall

The effective rainfall was estimated by the distributed SCS Curve Number method using soil cover, land use, and antecedent moisture condition information of the basin. For SCS Curve Number method, each sub-basin requires a value for the Curve Number. Hence SCS curve number grid was generated in HEC GeoHMS to extract the curve number for HRUs. Firstly, the land use and soil map were prepared for the study watershed. All the fields’ necessary in the landuse and soil map was entered. The CN Look Up table was created. Using these land use classes and soil group type, in conjunction with SCS curve numbers, the curve number grid was created. The CN grid generated for the study area was shown in Fig.2. The attribute table of generated CN grid gave the CN value and corresponding area of each hydrologic response unit. Then the effective rainfall ($P_e$) for each HRUs were calculated by Eqn.(3).

$$P_e = (P-0.2S)^2/(P+0.8S)$$

Where, $P$= total precipitation (mm), $I_a$ = initial abstraction (mm), and $S$= potential maximum retention (mm). and $Q_0=0$, for $P< I_a$. The Curve Number (CN) is used to compute $S$ in mm as $S = (25400 - 254CN)/CN$.

- Estimation of Geomorphological Parameters

The boundary of the basin and stream network was mapped using Survey of India toposheets 58B-6, 58B-7 and 58B-11 for extracting the geomorphological parameters of the basin using ArcGIS 9.3. The Geomorphological parameters bifurcation ratio ($R_B$), area ratio ($R_A$) and stream length ratio ($R_L$) were calculated for consecutive order channels using Horton’s laws. $R_B = Nu / Nu+1; R_A = Au / Au-1; R_L = Lu / Lu-1$ where $Nu$=number of stream segments of the given order; $Au+1$=number of stream segments of the next higher order; $Lu+1$=mean stream length of segment of order $u$; $Lu-1$=mean stream segment length of the next lower order $u-1$; $Au$=mean area of basin of order $u$; and $Au-1$ is the mean area of basin of order $u-1$.

![Fig.2: CN Grid for Karikkadavu River Basin](image2)

The Table 1 shows the geomorphology details of the different orders for the study area. The average value of bifurcation ratio $R_B$ was found to be 3.68; stream length ratio $R_L$ as =1.99; and stream area ratio $R_A$ as = 4.64.
Table 1: Geomorphological Details for Karikkadavu Basin

<table>
<thead>
<tr>
<th>Order of the stream</th>
<th>Total number of streams</th>
<th>Total length of streams (km)</th>
<th>Mean Stream Length (km)</th>
<th>Drainage Area (Km²)</th>
<th>Mean stream area (Km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41</td>
<td>31.548</td>
<td>0.769</td>
<td>0.717</td>
<td>0.717</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>18.514</td>
<td>2.057</td>
<td>3.329</td>
<td>3.325</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>10.484</td>
<td>5.242</td>
<td>15.41</td>
<td>15.413</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>3.954</td>
<td>3.954</td>
<td>71.50</td>
<td>71.453</td>
</tr>
</tbody>
</table>

- **Parameter estimation of Models**

The parameters of the Clark IUH model was estimated using HEC-HMS package using an inbuilt optimization scheme. Initially DEM preprocessing was done through Arc Hydro, which can be used as the input data in HEC-GeoHMS to compute the hydrologic parameters. The HMS project created in Geo HMS was then imported to HEC HMS interface. Based on the preprocessed data and computed parameters; HEC-HMS was run and estimates the streamflow. Fig.3 shows the Karikkadavu basin generated using HEC-GeoHMS.

The Clark GIUH parameters were estimated using the Newton-Raphson optimization technique explained earlier. The value of T_c and R obtained by Clark IUH model is 6.1 and 13.4 respectively. And that by GIUH model is 4.9 and 14.1 respectively.

![Fig. 3: Karikkadavu Basin generated using HEC GeoHMS](image)

- **Performance Evaluation and Comparison**

Using the derived Clark parameters and time area diagram ordinates the flood hydrograph was derived using Eqn. (1). The figure 4 shows the flood hydrograph obtained for an event by Clark IUH and GIUH model. It is seen from the graph that the simulated hydrograph follows the same trend of observed flood hydrograph.

To evaluate the performance of the model, the simulated results are compared with available daily discharge data observed at three time intervals (8.30 am, 12.30 pm and 4.30 pm) using two error functions. (i) Efficiency (EFF) and (ii) Root mean square Error (RMSE). The efficiency of the model is computed using Nash-Sutcliffe model efficiency Eqn.(4).

\[
EFF = \frac{\sum_{i=1}^{n} (Q_{oi} - \bar{Q})^2 - \sum_{i=1}^{n} Q_{oi} - \bar{Q}_{oi})^2}{\sum_{i=1}^{n} (Q_{oi} - \bar{Q}_{oi})^2}
\]

The root mean square error is computed by Eqn.(5).

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Q_{oi} - Q_{ci})^2}{n}}
\]

Where Q_{oi} is the \text{i}^{th} ordinate of observed discharge (m³/sec), Q_{ci} is the computed discharge (m³/sec); \( \bar{Q} \) is the average of the ordinates of the observed discharge (m³/s); n is the number of ordinates. The Table 2 shows the values obtained for EFF and RMSE for the selected event.

![Fig. 4: Flood Hydrograph Simulated by Clark Models](image)

As per table 2 the Clark IUH gives the best flood hydrograph estimates, compared to GIUH model, with highest efficiency and lowest root mean square error. This is due to the fact that the IUH model uses the observed rainfall and runoff data, while the GIUH model uses the morphometric parameters for the derivation of unit hydrograph. However, the results demonstrate that the GIUH based Clark models can be successfully used further, for runoff prediction in ungauged or scantily gauged basin.

It is seen from the graph (Fig 4) that the simulated hydrograph follows the same trend of observed flood hydrograph. The small error in peak may be due to the method adopted for finding the ordinates of average unit hydrograph. Or it may be due to the error in data. Therefore, we can conclude that the Nash and Clark approach can be successfully adopted in Karikkadavu basin, for the derivation of flood hydrograph. And for better and accurate results, use short term data, hourly or less than that.
IV. CONCLUSION

The aim of this paper was to derive the flood Hydrograph for a storm event of Karikkadavu river basin using Clark IUH and GIUH model concept with help of GIS software. The link established between the GIUH theory and the classical theories of the Clark model was tested in the Karikkadavu basin situated in Thrissur District of Kerala. The geomorphological data, land use, and soil cover information obtained from topographic maps, in a GIS environment was successfully used and it is found that this formulation is advantageous for this catchment. Also the comparison of the simulated and observed values of runoff hydrograph showed a good match. The results demonstrate that the IUH and GIUH based Clark model can be successfully used further for runoff prediction in Karikkadavu basin.

REFERENCES


