



Identical linear reservoir model of geomorphologic instantaneous unit hydrograph: A review

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ABSTRACT

Planning, design and management of water resources projects require proper estimation of runoff generated from particular catchment, to make the structures stable to dispose off high runoff volume safely. To accomplish this task, hydrologists apply different rainfall-runoff estimation models, which require estimation of different input parameters to be calculated from the data obtained from gauged basins. But for ungauged basins, geomorphological instantaneous unit hydrograph (GIUH) has proved to be an effective tool to predict the hydrologic response as it does not rely on the measured data sets. GIUH is derived from geomorphological characteristics of a basin and is said to be the link between hydrology and basin geomorphology. This paper discusses the systematic progress made by researchers in derivation of GIUH, the limitations emphasized and modifications suggested by different scientists in determination of various parameters of the linear reservoir model of GIUH, and application of linear reservoir model of GIUH to different watersheds.

1. INTRODUCTION

Hydrological modelling of rainfall-runoff covers wide area of research. Many scientists and researchers have worked and proposed many theories and approaches for modelling of rainfall-runoff processes. Rainfall, infiltration, runoff are the basic phenomena, which are important for further modelling the hydrologic response of watershed. In order to obtain data on these processes, proper gauging of basin need to be done. Planning and designing of water resources structures needs estimation of flood magnitude, which is an important exercise dealt by hydrologist. Previous works of scientists indicate that many methods for estimation of design flood magnitude have been put forth. The most common method for designing the structures was the rational method, which considers only peak discharge. However, now-a-days hydrograph method is widely used for designing of the water resource structures wherein changes in runoff magnitude can be studied with respect to time. Another constraint in designing water resources structures is non availability of data sets due to ungauged basins, which affects the research on estimation of runoff. To overcome this constraint, concept to relate the basin

geomorphologic characteristics to hydrologic response was evolved. Further, this concept got advanced and the theory of GIUH was put forth by Rodriguez-Iturbe and Valdes (1979). This theory got wide acceptance and was tried by various researchers throughout the world for ungauged or partially gauged basins.

Planning and designing of water resources structure is done based on the hydrologic response of basin. Sherman (1932) came up with the unit hydrograph (UH) theory. This theory was widely used for gauged basins, but still the constraint of ungauged basins or unavailability of data sets was not overcome. In this quest Snyder (1938) provided solution based on the use of certain geomorphologic characteristics. He proposed the relationship between time to peak (t_p), peak discharge (q_p) and time base (t_b) of UH and derived the constants, C_i (regional constant representing watershed slope and storage) and C_p (a regional constant) from the study of 20 watersheds located in the Appalachian Highlands of USA. He put forth the concept that basin characteristics can be incorporated to get the hydrologic response from a particular basin. Another scientist who suggested that the physical

characteristics of a watershed influence the runoff brought to the valley, and also on the runoff getting through the outlet of watershed and thus the resultant hydrograph was Edson (1951). He showed those influences by the following expression:

$$Q = \frac{[cAy(yt)^{xe^{yt}}]}{\Gamma(x+1)} \quad \dots(1)$$

Where, Q = Discharge in lps at time ' t ', t = the time in days reckoned from the beginning of runoff, c = Constant of proportionality, A = Drainage area in sq miles, x, y = Parameters expressible in terms of peak discharge, Γ = Gamma function.

Thus, Snyder and Edson showed that the basin characteristics are important in hydrologic response of the basin and their studies gave a new direction for researchers to work through. However, unit hydrograph shape largely depends on the rainfall characteristics and to study two different watersheds for their hydrologic response, the effect of rainfall characteristics need to be eliminated. This calls for the concept of instantaneous unit hydrograph.

If the duration of effective rainfall becomes infinitesimally small, the resulting UH is called instantaneous unit hydrograph (IUH). IUH is the limiting case of a UH of zero duration. Thus IUH is a fictitious, conceptual UH which represents the surface runoff from the catchment due to an instantaneous effective rainfall of 1 cm. IUH is designated as $u(t)$ or as $u(0, t)$. It is a single peak hydrograph with a finite base width and its important properties are:

i) $0 \leq u(t) \leq a \text{ positive value, for } t > 0$; ii) $u(t) = 0, \text{ for } t < 0$; iii) $u(t) \rightarrow 0, \text{ as } t \rightarrow \infty$; iv) $\int_0^\infty u(t) dt = \text{unit depth over the catchment}$; v) $\text{time to peak} < \text{time to the centroid of the curve i.e. IUH}$.

The concept of identical linear reservoir model for watershed response to instantaneous unit effective rainfall was put forth by Nash (1957). This model is widely accepted and used by the researchers for their studies. Nash derived an equation for the IUH by assuming that the operation performed by the catchment on the effective rainfall is analogous to routing of flow through series of identical linear reservoirs. The IUH from a basin is represented pictorially as shown in Fig. 1.

He demonstrated method by which the IUH of this form can be derived from a complex flood. Nash gave the equation for IUH as:

$$U(t) = \frac{1}{k\Gamma n} \left(\frac{t}{k}\right)^{n-1} e^{-t/k} \quad \dots(2)$$

Where, $U(t)$ = ordinates of IUH at time t (h^{-1}), n = number of reservoirs, k = storage constant (h), Γn = gamma function of ' n '.

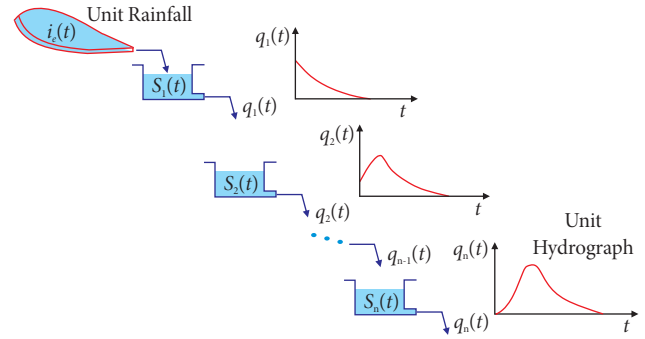


Fig. 1. Pictorial representation of Identical Linear Reservoir Model (Nash model)

The rainfall-runoff data from watershed is needed to determine ' n ' and ' k ' parameters of Nash model. However, scientists tried to explore possibility of determination of ' n ' and ' k ' using geomorphological characteristics of watershed.

This paper attempts to (i) review the work on development and application of GIUH based on Nash model, and (ii) review the work on velocity component in GIUH.

2 Geomorphological Instantaneous Unit Hydrograph (GIUH)

Development of GIUH is a significant contribution in hydrology by the researchers and scientists who made this theory a workable approach to get the hydrologic response of basin. This theory covers many aspects related to basin characteristics. The introduction of the GIUH by Rodriguez-Iturbe and Valdes (1979) renewed the research of ungauged or inadequately gauged watersheds.

Hydrologic response of a catchment to surface runoff was linked to the IUH with the geomorphologic parameters of a basin by Rodriguez-Iturbe and Valdes (1979). Equations of general character were derived which express the IUH as a function of Horton's (1945) numbers R_a, R_b, R_p, L_Ω and velocity of stream flow, V . The area ratio (R_a) can be defined as the ratio of the mean area of basin order u to the mean area of the basin of order $(u-1)$. The bifurcation ratio (R_b) can be defined as the ratio of number of streams of u^{th} order to the number of streams of next higher, $(u+1)^{\text{th}}$ order. The stream length ratio (R_p) can be defined as the ratio of mean length of u^{th} order stream to mean length of $(u-1)^{\text{th}}$ order stream. L_Ω is the length of highest order stream in the watershed. This approach was initiated to define hydrologic similarity of basin based on its hydrologic response.

To analyse GIUH in real world basins, a study was carried out on several basins in Venezuela and Puerto Rico by Valdes *et al.* (1979). The geomorphologic IUH for each basin was compared with the observed IUH of same basins. The effect that the nonlinearities of the rainfall-runoff model

have on the derivation of the IUH was analysed, and further, controlled experiments were carried out in which the IUH was derived under constant velocity conditions. The GIUHs and the ones obtained in the experiments were remarkably similar in all the basins analysed.

Pandit and Atre (2014) found that researchers have mostly applied identical linear reservoir concept for development of GIUH for a basin rather than other GIUH models, like transition probability approach, unequal linear reservoir model, and non linear reservoir model. Therefore, the scope of this paper is restricted to identical linear reservoir model of GIUH.

3 Development of GIUH based on identical linear reservoir model

The validity of the linearity assumption in the rainfall-runoff transformation for smaller basins was studied by Gupta *et al.* (1980), considering the channel network and the overland flow regimes in a river basin satisfying Horton's empirical geomorphologic laws when ordered according to the Strahler ordering scheme. Three basins from Illinois were selected to check the theoretical results with observed direct runoff hydrographs. The theory provided excellent agreement for the two basins with areas of order of 1770 sq km but underestimate the peak flow for the smaller basins with area of 483 sq km.

Rodriguez-Iturbe *et al.* (1982) established a link between climate, geomorphologic structure and hydrologic response of a basin. This link explained the variations observed while estimating IUH from different storms in the same basin. They used geomorphoclimatic theory of IUH to compare with the results obtained through derivation of the IUHs from a series of rainfall-runoff experiments conducted via simulation for one basin and three different climates. It was shown that the uncertainty due to the variability of the IUH with the rainfall input may produce a sizable variance of estimation in the outflow hydrograph when working under the assumed nonlinear framework.

Bhaskar *et al.* (1997) derived GIUH from watershed geomorphological characteristics and then related to parameters of GIUH. They also derived Nash IUH using two approaches. In the first approach (GIUH-I) the rainfall intensity during each time interval was allowed to vary, whereas in second approach (GIUH-II) rainfall intensity was averaged over the entire storm period. This methodology has been applied to Jira River sub catchment in eastern India to simulate floods from 12 storm events. Results from both the GIUH approaches and those obtained by using Nash IUH are comparable with observed events. Results also suggest that GIUH approach can be used for the estimation of floods

from catchments with a reasonable degree of accuracy. Relationships proposed by Bhaskar *et al.* (1997) for parameters of Nash IUH model from the geomorphological characteristics of watershed are given as:

$$\frac{n-1}{\Gamma n} e^{-(n-1)} (n-1)^{n-1} = 0.5764 R_b^{0.55} R_a^{-0.55} R_l^{0.05} \quad \dots(3)$$

$$k = \frac{0.44}{v} L_a R_b^{0.55} R_a^{-0.55} R_l^{0.38} * \frac{1}{(n-1)} \quad \dots(4)$$

Where, n = number of reservoirs, k = storage constant (h), R_a - area ratio, R_b - bifurcation ratio, R_l - length ratio, L_a - length of highest order stream (km), v - mean velocity of stream flow (m s^{-1}).

The theory of the geomorphological unit hydrograph (GUH) was examined by Shamseldin and Nash (1998) and they opined that the inherent assumption that the operation of the drainage network may be modelled by a corresponding network of linear reservoirs restricts the IUH shape in such a way that the effects of the constraints imposed by the geomorphological laws of the channel network, cannot easily be identified. They further concluded that the GUH theory is not testable and must remain only a plausible hypothesis providing an indication of a two-parameter IUH whose shape and scale factors must be related empirically to appropriate catchment characteristics is the absence of effects of constraints by geomorphological laws.

Study of regional analysis was done using the geomorphoclimatic IUH by Hall *et al.* (2001). In this study, the rainfall excess duration was divided into several equal time increments, with separate IUHs generated for each interval. This quasi-linear approach was applied to 105 storm events from nine catchments in the south-west of England, ranging in size from 6 to 420 sq km. They opined that a comparable level of goodness-of-fit can be obtained for catchments covering a range of ratio about 1:75 in area and the modified GIUH approach was, therefore, recommended for further investigation and inter comparison with regression-based regionalization methods.

Sinha *et al.* (2002) developed GIUH for the catchment of river Bino, a tributary of Ramganga River, located in the Himalayan region by determining parameters of Nash IUH from the geomorphological characteristics. The prediction performance of the developed GIUH was evaluated by comparing peak discharge and time to peak. It was observed that the absolute prediction error (APE), absolute percentage error (PE) for all estimated values of peak discharge and time to peak were, in general, well within acceptable limits. It was also found that the extent of the map scale has a significant effect on the prediction performance of the developed model as it affects the values of some of the geomorphological characteristics of the catchment.

Karegowdar *et al.* (2005) analysed GIUH for flat land watershed of Singnodi. They derived Nash parameters using geomorphological characteristics of basin. Their study revealed that the shape parameter 'n' independent of stream flow velocity, indicates that constant effect of each watershed in runoff production is independent of rainfall variations. The scale parameter 'k' is dependent on both, basin geomorphology and stream dynamics.

Sahoo *et al.* (2006) compared direct runoff hydrographs of Ajay River basin at Jamtara in northern India, with direct runoff hydrographs developed using four different models, viz., Clark IUH model option of HEC-1 package, Nash IUH model, GIUH based on Clark model and GIUH based on Nash model. The Clark and Nash model based GIUH gave comparable results with Clark model of HEC-1 and Nash model. Further, they found that map scales of 1:50,000 and 1:250,000 were good for determining geomorphological characteristics using GIS. They concluded that GIS supported GIUH models with 1:50,000 and 1:250,000 map scales can be used for modelling DRH for ungauged watersheds.

The GIUHs for fourth-order hilly sub watershed of the Ramganga River catchment in Uttarakhand were derived using two approaches, geomorphologic parameters (GIUH-I) and stream-order law ratios (GIUH-II) by Kumar and Kumar (2008). The travel times for the overland flow and the stream flow in Horton-Strahler stream-ordering system of the watershed were determined analytically and probabilistically. The statistical analysis showed better overall correlation between predicted and observed direct runoff hydrographs for GIUH-II approach as compared to GIUH-I, where the time to peak was consistently under predicted by half hour for all the storm events. The results in general indicated reasonably good applicability of these approaches to estimate direct runoff from ungauged hilly watersheds.

Rai *et al.* (2009) showed that excess rainfall is an excitation (*i.e.* production function) to the hydrologic system to obtain at the outlet of ungauged basin using GIUH as transfer function. The GUH for ungauged Gomti River basin was derived using geomorphological characteristics and GIUH based transfer function. The GUH derived for Gomti River basin was compared with synthetic unit hydrograph (SUH) derived using CWC procedure. The results revealed that the GUH with dynamic flow velocity of 0.68 m s^{-1} was close to the SUH.

Pandit and Atre (2013) used the relations proposed by Croley (1977) and Bhaskar *et al.* (1997) for determination of 'n' and 'k' parameters of Nash model using basin geomorphology. They found that among the two approaches used to determine 'n' and 'k' parameters, Bhaskar *et al.* (1997) approach was better for the watershed under study as the shape of hydrograph was smooth.

Alemngus and Mathur (2014) tested the applicability of GIUH based Nash model on the upper Mereb-Gash sub-basin in Eritrea (East Africa). Developed GIUH based Nash model UH were compared with the SUH of downstream catchment which showed that the computed peak discharges were higher in case of GIUH. Their study also suggested that derived UHs from GIUH based Nash model for the Debarwa river catchment can be used for computation of direct surface runoffs as there was no significant difference among the UH derived by Sherman method and GIUH based Nash model method.

Khaleghi *et al.* (2014) applied GIUH to simulate the rainfall-runoff process and also to determine the shape and dimensions of outlet runoff hydrographs in a 37.1 km^2 area in the Ammameh catchment, located at northern Iran. The results obtained from the study confirmed the high efficiency of the GIUH and its ability to increase simulation accuracy for runoff and hydrographs and, therefore, recommended for further investigation and inter-comparison with regression-based regionalization methods.

Swain *et al.* (2015) developed GIUH based on Nash IUH by deriving parameters of IUH from geomorphologic characteristics of Koel River basin, India. Using the developed GIUH, GUH was derived and it was compared with SUH derived using Central Water Commission procedure. GIUH proved to be better option for obtaining UH for ungauged basins.

Vargas and Sergio (2015) carried out assessment of the GIUH for four catchments of Itata River basin using GIS. For velocity estimation, the Franchini and O'Connell (1996) approach was used. It was observed by sensitivity analysis that length ratio, which is drainage network parameter, explains the time to peak variations. Further results also showed that bifurcation ratio and area ratios have effect on the calculations of GIUH model. They concluded that GIS technique has good potential in flood modelling, if simple conceptual approaches are used with proper hydrological base and mathematical formulations with few calibration parameters.

Himanshu *et al.* (2015) developed an approach for deriving complete shape of GIUH by linking it to Nash model. To extract the geomorphological features of the basin, ASTER and DEM data were used. Velocity of stream flow for the study was estimated by averaging the stream flow velocity at different depths computed using the Manning's equation. The cross sectional area and wetted perimeter at the outlet of watershed was estimated using MIKE-11 software. Based on this study it was concluded that GIUH technique is applicable for the estimation of direct runoff hydrographs using Nash model.

Richa *et al.* (2016) tried to develop GIUH based Nash model for Kothuwatari watershed having 27.93 sq km area. The model was tested with percentage absolute deviation in peak discharge and coefficient of efficiency (CE). It was found that the model gave quite good agreement with observed direct runoff hydrograph with CE ranging from 0.69 to 0.96. The performance of GIUH based Nash model is quite good for Kothuwatari watershed.

Dynamic Component Velocity in GIUH

The dynamic parameter 'V' of the GIUH was studied by Rodriguez-Iturbe *et al.* (1979) and they observed that the velocity can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. This transforms the time variant IUH throughout the event into a time invariant IUH in each storm occurrence. Drainage basins were defined similar if they had the same IUH when kinematic conditions were kept same.

The spatial distribution of stream flow velocity along the network can be introduced within the context of the GIUH model using a single parameter 'k' that synthesizes the channel slope pattern in the entire network. The major problem in applying the GIUH model in hydrologic practice is the estimation of the time scale of the hydrologic response. In the original model, the kinematic parameter is stream flow velocity as averaged in space and time. This approach used by Agnese *et al.* (1988) was an improvement of the GIUH model because it introduces a spatial distribution of stream flow velocity in the network and, therefore, allows an actual stream flow velocity to be used as the kinematic parameter.

Vander Tak and Bras (1990) incorporated hillslope effects into the gamma GIUH (GGIUH) model by assuming that the hillslope travel distance in an area of a given order is approximated by the inverse of twice the local drainage density and introducing a hill slope velocity term. This study shows that the hill slope has a distinct effect on the shape of GGIUH by introducing a lag in the basin response function.

Al-Wagdany and Rao (1997) investigated the problem of the velocity estimation in the exponential distribution GIUH. During the study, the ED-GIUH model was applied to six watersheds in Indiana, USA. The relationships between the velocity parameter and climatic as well as basin geomorphologic parameters were investigated. The results of the study indicated that the velocity parameter is related to effective rainfall depth, total basin area and cumulative slope; it does not depend on runoff characteristics. Therefore, the ED-GIUH model can be used for estimating discharge hydrographs from ungauged watersheds.

Kumar *et al.* (2004) tried to check the uncertainty introduced by three parameters, R_p , L_n and V in estimation

of the peak discharge of UH. They concluded that uncertainty associated with velocity was highest for GIUH based Nash model (57.7%), whereas for GIUH based Clark model the uncertainty associated with length of highest order stream was 46.6% followed by uncertainty associated with velocity (44.7%). In both the models, R_p contributed less than 10% (8.7% in Clark model and 9.3% in Nash model) to uncertainty in peak flow of UH. Thus, importance of velocity component and length of highest order stream is emphasized.

The scale parameter (k) and shape parameter (n) of Nash model were estimated using geomorphological characteristics and a relationship between rainfall intensity (i) and equilibrium velocity (V_e) developed for small watershed, Tumri in Madhya Pradesh, by observation of discharge and short interval rainfall by Jaiswal *et al.* (2011). They concluded that the Nash model application using geomorphological parameters may provide an easy way for event based rainfall-runoff modelling of ungauged watersheds in the region.

By combining the empirical formulae based on measurable watershed parameters, a new relationship was developed for estimating the dynamic parameter, velocity, in GIUH. Nongthombam *et al.* (2011) applied this model to an ungauged watershed in Barak basin, in India. Applicability of the model was tested by using a standard UH example reported earlier by different investigators. Peak discharge and time to peak value for the selected example were estimated applying the new technique and were compared with earlier results. Model performances showed that the new technique can provide accurate estimate for the dynamic parameter velocity and when used with GIUH approach results in improved prediction for the peak discharge.

Atre *et al.* (2014) while objecting to the use of measured stream flow velocity in GIUH model parameter estimation suggested the rational method for estimation of characteristic peak velocity for GIUH model. Using this velocity, they developed GIUH based on Nash model and compared these with observed DRH of watershed. The results showed that rational method of peak runoff estimation can be satisfactorily used to model GIUH for small watershed.

Kumar (2015) predicted hydrologic response of two fourth-order hilly watershed of Ramganga River basin using GIUH. He used two models to derive GIUH, first is Horton's stream-order model (GIUH-I) and second is Nash's two-parameter gamma distribution based conceptual model (GIUH-II). Stream flow velocity in GIUH-II model was estimated using two approaches one was as a function of effective rainfall intensity (GIUH-II a) and other was on the basis of time of concentration concept (GIUH-II b). This study explained that GIUH-II b model (based on time of

concentration) as compared to other was more applicable for ungauged watershed as it is not depending on the measured velocity of flow corresponding to the peak flow rate at the watershed outlet.

4. CONCLUSIONS

GIUH has proved to be the most appropriate method for estimation of hydrologic response from ungauged basins. Researchers have coupled the GIUH with Nash-identical linear reservoir model to study the hydrologic response of basin, which proved to be good in estimation of runoff from a basin with reasonably good accuracy. GIUH frame work holds good for medium to large watersheds where linearity assumptions are fulfilled. But, in case of small watersheds, this theory needs to be tested where nonlinear rainfall-runoff transformation, sparse stream network and overland flow are encountered. With advent of remote sensing and geographic information system technique, the hydrologists have resorted to these techniques for computation of geomorphological characteristics of watersheds. These techniques have been used very efficiently for development of GIUH model.

Stream flow velocity and length of highest order stream are the main influencing parameters which affect the estimation of runoff in GIUH framework. The relations proposed by Bhaskar *et al.* (1997) for computation of Nash model parameters 'n' and 'k' using geomorphological characteristics of watershed are commonly used. However, these need to be tested, especially for small watersheds, and, if required, modified so as to obtain more accuracy in hydrologic response of small watersheds. In some studies, the dynamic component, stream flow velocity, used in determination of parameter 'k' of Nash model, is measured. However, this needs to be estimated using some indirect method like estimation of time of concentration or estimating peak runoff rate from the watershed. Further studies on determination of velocity of flow from the ungauged catchment can improve the estimation of 'k' parameter of Nash model and thus the performance of GIUH model.

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