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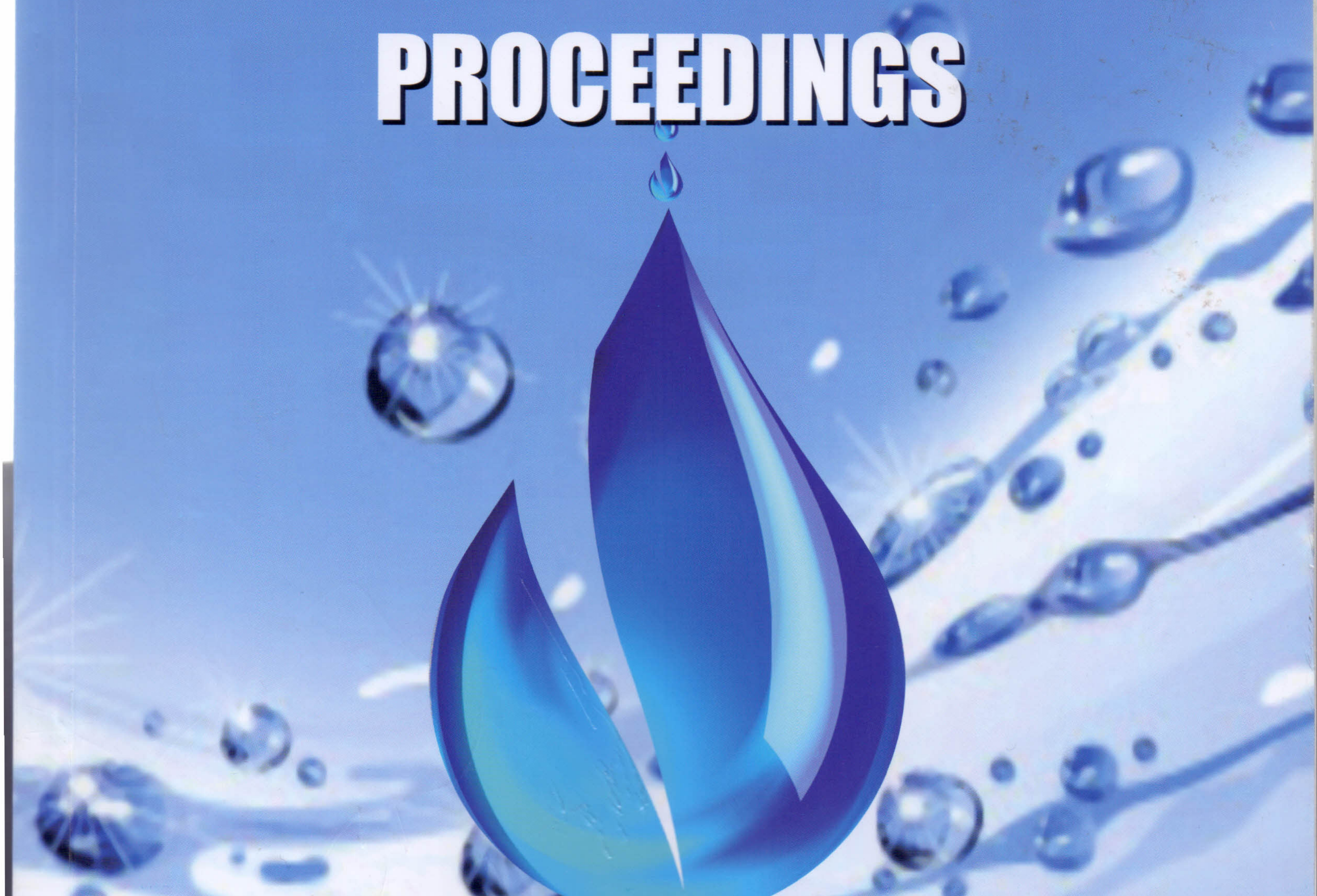
PROCEEDINGS



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Application of the Geomorphologic Instantaneous Unit Hydrograph Concept for Runoff Prediction in an Ungauged Catchment

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Keywords

GIUH, Nash conceptual Model, Ungauged catchments, GIS, DSRO

Synopsis

Reliable prediction of the runoff generation and its routing to the outlets represents one of the most basic, challenging and important aspect of the hydrology, needed for almost all kind of water resources planning and management. Classical techniques for design flood or flow peaks estimation use historical rainfall-runoff data for unit hydrograph development and modeling. Such techniques have been widely applied for the estimation of peak flood hydrograph at the sites of gauged catchment. For ungauged catchments, unit hydrograph may be derived using either regional unit hydrograph approach or alternatively Geomorphological Instantaneous Unit Hydrograph (GIUH) approach. This study was aimed at development of unit hydrograph by relating the geomorphological characteristics of a catchment with the basic characteristics of the catchment IUH through the concept of Geomorphological Instantaneous Unit Hydrograph (GIUH) to address the problem of predictions in ungauged catchments. Nash's instantaneous unit hydrograph (IUH) model (Nash, 1957) based on the concept of 'a cascade of linear reservoirs' in the watershed have been used in the study. The geomorphological characteristics including the Horton's ratios of the catchments were extracted using open source GIS software called ILWIS. The geomorphological characteristics of a catchment were related with the shape and scale parameters of the Nash IUH to derive the complete shape of the GIUH based Nash model. The performances of the calibrated model was evaluated using error functions, namely, coefficient of efficiency, absolute average error, root mean square error, average error in volume and absolute percentage deviation in peak flow rates and the modeled direct surface run-off (DSRO) hydrographs for nine rainfall-runoff events were compared with the observed ones. The DSRO hydrographs are computed with reasonable accuracy by the GIUH based Nash model, which simulate the DSRO hydrographs of the catchment considering the study watershed to be ungauged.

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ABSTRACT:
Reliable prediction of the runoff generation and its routing to the outlets represents one of the most basic, challenging and important aspect of the hydrology, needed for almost all kind of water resources planning and management. Classical techniques for design flood or flow peaks estimation use historical rainfall-runoff data for unit hydrograph development and modelling. Such techniques have been widely applied for the estimation of peak flood hydrograph at the sites of gauged catchment. For ungauged catchments, unit hydrograph may be derived using either regional unit hydrograph approach or alternatively Geomorphological Instantaneous Unit Hydrograph (GIUH) approach. This study was aimed at development of unit hydrograph by relating the geomorphological characteristics of a catchment with the basic characteristics of the catchment IUH through the concept of Geomorphological Instantaneous Unit Hydrograph (GIUH) to address the problem of predictions in ungauged catchments. Nash's instantaneous unit hydrograph (IUH) model (Nash, 1957) based on the concept of 'a cascade of linear reservoirs' in the watershed have been used in the study. The geomorphological characteristics including the Horton's ratios of the catchments were extracted using open source GIS software called ILWIS. The geomorphological characteristics of a catchment were related with the shape and scale parameters of the Nash IUH to derive the complete shape of the GIUH based Nash model. The performances of the calibrated model was evaluated using error functions, namely, coefficient of efficiency, absolute average error, root mean square error, average error in volume and absolute percentage deviation in peak flow rates and the modeled direct surface run-off (DSRO) hydrographs for nine rainfall-runoff events were compared with the observed ones. The DSRO hydrographs are computed with reasonable accuracy by the GIUH based Nash model, which simulate the DSRO hydrographs of the catchment considering the study watershed to be ungauged.

1.0 INTRODUCTION

For planning, development and operation of various water resources schemes estimation of run-off response from ungauged catchments is an important subject of research in the sphere of surface water hydrology. Ungauged catchments are those catchments in which the river discharges have not been measured in the past. Catchments for which available observed discharge time series is inadequate for the calibration are also considered ungauged. Conventional techniques of unit hydrograph derivation require historical rainfall-runoff data. Most of medium and small catchments, however, especially in the developing countries like India, lack the adequate discharge measurements. Hence, indirect inferences through regionalization are sought for such ungauged catchments. In the process of regionalization, the parameters of instantaneous unit hydrograph (IUH) models are related with physiographic and climatologic characteristics for gauged catchments in hydro-meteorologically homogeneous regions. These relationships are then used for runoff estimation for the ungauged catchments of the hydro-meteorologically homogeneous regions. This process of regionalization is a difficult task since it not only requires a good amount of rainfall-runoff data for the gauged catchments, but the hydro-meteorological homogeneity of the region is also difficult to ascertain (Kumar et al., 2007, Jaiswal et al. 2014). Further, with the change of the land-use and climate patterns, the model parameters are required to be updated from time to time. Therefore, geomorphology based approach becomes one of the most popular modelling tools for the computation of runoff hydrographs under these circumstances (Rodriguez-Iturbe and Valdes, 1979; Rodriguez-Iturbe et al., 1982; Yen and Lee, 1997; etc.). Geomorphology of a river basin describes the status of topographic features of the surfaces and streams, and its relationship with hydrology provides the geomorphological control on basin hydrology (Jain and Sinha, 2003). Geomorphology reflects the topographic and geometric properties of the watershed and its drainage

channel network. It controls the hydrologic processes from rainfall to runoff, and the subsequent flow routing through the drainage network.
In the foregoing discussion and context this study was intended to address the problem of predictions of runoff characteristics in ungauged catchments using a gauged catchment by relating the conceptual modelling of instantaneous unit hydrograph (IUH) given by Nash (1957) with the geomorphological characteristics of the catchment.

2.0 MATERIALS AND METHODS

2.1. Study Area

The Kothuwatari watershed lies between 24^{0}12'18"- 24^{0}16'49"N latitude and 85^{0}24'18" - 85^{0}28'08"E longitude and it has an area of 29.67 km^2 with relief varying from 289 to 479 m above the mean sea level. It has a heterogeneous land physiography as it is composed of hill rocks, rolling uplands, depressional lands and ravines occurring side by side. The climate of this watershed varies from sub-tropical to sub-temperate. Soil textures are coarse or coarse loamy in upper surfaces, becoming finer with depth, which indicates well drained conditions and maturity of the soils. Rain starts from middle of June and continue till October as a result of South-West monsoon. Rain in abundance occurs during the months of July and August. About 90 percent of rain occurs from mid-June to September; about 4 percent from October to February, and about 6 percent from March to May. The humidity is very high from June to September. Nearly 53.7 percent of the total watershed area consists of agricultural land, 26.38 percent as forest land, 18.6 percent as waste land and the remaining 1.32 percent may be categorized under miscellaneous uses. The drainage network map of the watershed is shown in Figure 1.

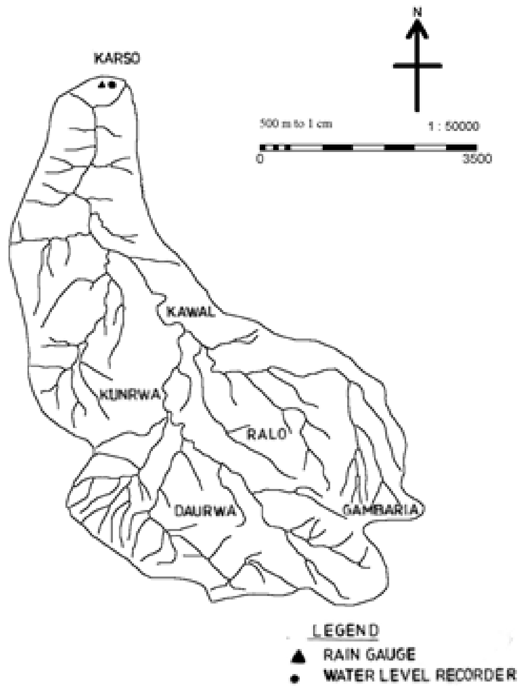

Figure 1. Drainage network map of Kothuwatari watershed

The required rainfall and runoff data for the study area were collected from Damodar Valley Corporation (DVC), Hazaribagh, Jharkhand, while the geomorphological data were generated with the help of toposheets procured from Survey of India, Dehradun. In this study, nine storm events for the years of 1992-1996 recorded at Karso gauging station that resulted in single peaked runoff hydrographs were selected.

2.2. Preparation of Geomorphologic Database

Geomorphological database of the study area was developed with the help of freely available GIS software, ILWIS. The boundary of the watershed and all the streams have been traced at a scale of 1:50,000 from Survey of India toposheets 72H/7 and 72H/8. Three maps, i.e., boundary map, drainage map and contour map of the same scale were prepared. Then these three maps were scanned and converted into appropriate file formats and were opened in ILWIS environment for the on screen digitization. The area and perimeter of the basin can be computed after converting raster map to polygon map. After converting the contour map into digital form, it was rasterised. Then interpolation from isolines was carried out on this map. This interpolated map gives the elevation at each point (pixel) in the basin. For ordering of streams of the drainage network Strahler's method (Strahler, 1964) of stream ordering was followed. In the system, the length of each stream was stored in a table. The various geomorphologic characteristics such as bifurcation ratio, length ratio, area ratio, length of main stream etc. were determined by using the Horton's law of stream number, stream length and stream area (Horton 1945).

2.3. Preparation of Time-Area Diagram Using GIS

The time-area diagram illustrates the spatial distribution of travel time of overland flow in a catchment. The time-area methods were developed in recognition of the importance of the time distribution of rainfall on runoff in the hydrologic design of storage and regulation of water works. Application of GIS makes preparation of the time-area diagram of a catchment less time consuming and quite easier. The distance from the most upstream point in the basin upto the gauging site, along the main stream was measured from the line attributes of digitized drainage map. It was assumed that the time of travel between two points is proportional to the distance and inversely proportional to square root of the slope between these points, and given by:

$$t = CL/\sqrt{S} \tag{1}$$

where, t is time of travel, L is the length of stream, S is the slope of the stream between two points and C is a proportionality constant. An initial estimate of time of concentration may be made by the Kirpich's formula as:

$$T_c = 0.06628\ L^{0.77}\ H^{-0.385} \tag{2}$$

where, T_C is the time of concentration in h, L is the length of stream in km and H is the average slope of the stream.

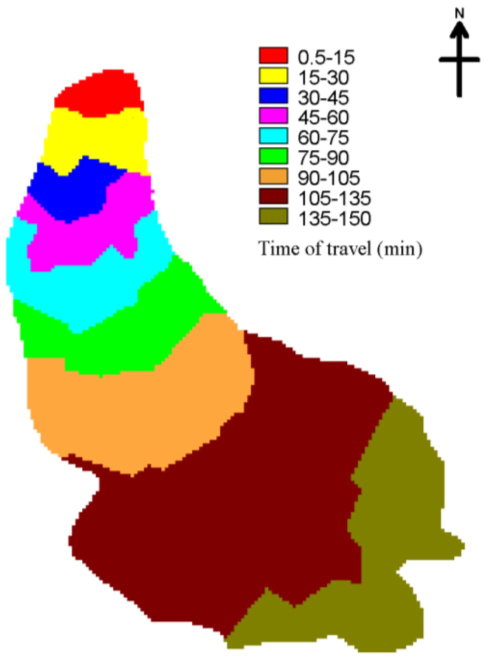

Figure 2. Time-area diagram of Kothuwatari watershed

Substituting the values of L and H in equation (3), the value of t_c can be calculated. This value of t_c may be substituted in the equation (2) and then the final formula for C obtained as:

$$C = t_c \sqrt{S_A / L} \tag{3}$$

where, S_A is mean slope of the main stream. Now the computed values of constant of proportionality C may be used in the equation (1) for computing the time of travel between the two points of the catchment. The time of travel between various locations over the catchment is progressively computed, beginning from the gauging site of the catchment. All the values of the time of travels for each stream were then marked on the map of the catchment. Then, these points are transferred in the digital form. Using interpolation technique a map of time distribution is drawn through these points, from the time distribution map values, a map of isochrones at a desired interval, e. g. 0.25 h is prepared. The inter-isochronal areas were estimated in the ILWIS environment to prepare the time-area diagram of the catchment as shown in Figure 2.

2.4. Model Development

Rodriguez-Iturbe et al. (1979) first introduced the concept of geomorphologic instantaneous unit hydrograph (GIUH), which led to the renewal of research in hydrogeomorphology. The expressions for peak discharge and time to peak of IUH were determined by the following formulae as given by (Rodriguez-Iturbe and Valdes, 1979):

$$q_p = 1.31 R_L^{0.43} \left(\frac{V}{L_\Omega} \right) \tag{4}$$

$$t_p = 0.44 \left(\frac{L_\Omega}{V} \right) \left(\frac{R_B}{R_A} \right)^{0.55} (R_L)^{-0.38} \tag{5}$$

where, L_Ω is the length of the stream of order Ω in km, V is the expected peak velocity in m/s, q_p is the peak flow in h-1, t_p is the time to peak in h and R_B, R_L and R_A are the bifurcation ratio, length ratio and area ratio given by the Horton's laws of stream numbers, lengths and areas, respectively.

Empirical results indicated that for natural basins the values for R_B normally range from 3 to 5, for R_L from 1.5 to 3.5 and for R_A from 3 to 6 (Smart, 1968).

On multiplying Eq. (5) and (6), we get a non-dimensional term $q_p * t_p$ as given below:

$$IR = q_p * t_p = 0.5764 \left(\frac{R_B}{R_A} \right)^{0.55} (R_L)^{0.05} \tag{6}$$

This dimensionless ratio IR is not dependent upon the flow velocity and thereby, on the storm characteristics and hence is only a function of the catchment characteristics.

2.5. Derivation of Direct Surface Runoff Hydrograph Using the GIUH Based Nash Model Approach

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:

$$u(t) = \frac{1}{k\Gamma(n)} (t/k)^{n-1} e^{-t/k} \tag{7}$$

Where u (t) is the ordinates of IUH (hour^{-1}), t is the sampling 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).

A unit hydrograph (UH) of desired duration (D) may be derived by using the following expression:

$$U(D,\ t)=\frac{1}{T}\left[I\left(n,\ t/k\right)-I\left(n,\left(t-D\right)/k\right)\right] \tag{8}$$

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. (7) to zero, t becomes the time to peak discharge. Thus, taking the natural logarithm of both sides of eq. (7), differentiating with respect to t and by simplification eq. (9) is derived.

$$\frac{\partial}{\partial t}\ln[u(t)] = \left[-\frac{1}{k} + \frac{(n-1)}{t}\right] \tag{9}$$

Equating eq. (9) to zero results in by replacing t with t_p,

$$T = t_p = k\ (n\text{-}1) \tag{10}$$

Simplifying the value of t_p from eq. (10) in eq. (7) and simplifying yields

$$q_p = \frac{1}{k\Gamma\ (n)}\exp[-(n-)].\,(n-1)^{(n-1)} \tag{11}$$

Combining eqs. (10) and (11) results:

$$q_p.\,t_p = \frac{(n-1)}{\Gamma(n)}\exp[-(n-1)].\,(n-1)^{(n-1)} \tag{12}$$

Equating eq. (12) with eq. (6) results in:

$$\frac{(n-1)}{\Gamma(n)}\exp[-(n-1)].\,(n-1)^{(n-1)}\ = 0.5764[R_B/R_B]^{0.55} \times {R_L}^{0.05} \tag{13}$$

The Nash parameter n, can be obtained by solving eq. (13) using the Newton-Rapson method. The Nash's parameter k for the given velocity V is obtained using eqs. (5) and (10) and the known value of the parameter n as follows:

$$k = \frac{0.44L_\Omega}{v}\ .\left[\frac{R_B}{R_A}\right]^{0.55}.\,{R_L}^{-0.38}.\frac{1}{(n-1)} \tag{14}$$

The derived values of n and k are used to determine the complete shape of the Nash based GIUH using eq. (7). Subsequently, the D-hour UH can be derived from eq. (8). The direct runoff hydrograph (DRH) is estimated by convoluting the excess rainfall hyetograph with the UH.
The various statistical indices were employed in the present study for evaluation of the direct surface runoff (DSRO) hydrographs derived by the developed GIUH based Nash model with respect to the observed DSRO hydrographs were: (i) absolute relative error, (ii) percentage absolute deviation in peak flow rates, (iii) coefficient of efficiency, (iv) absolute average error, (v) root mean square error and (vi) average error in volume.

3.0 RESULTS AND DISCUSSION

3.1. Geomorphological Characteristics

In the present study, the length of the highest order, i.e., the fourth order stream (L_Ω) was estimated as 6.37 km. The length of main stream of Kothuwatari river basin upto Karso gauging site, L was measured as 11.89 km. The time of concentration (T_c) was estimated by using values of the length of main stream (L) and mean slope of the main stream (S) of the Kothuwatari catchment, was found to be equal to 2.25 hours. Using the computed value of T_c time-area diagram of the catchment was prepared as shown in figure 2. The various geomorphologic details for the study area are presented in the Table 1.

Table 1. Geomorphologic detail of different stream orders for Kothuwatari watershed

Stream order	Total number of streams	Total length of streams (km)	Mean stream length (km)	Mean stream area (km^2)	Other computed geomorphologic characteristics
1	87	50.1403	0.5763	0.1649	Bifurcation ratio (R_B) = 4.547
2	23	18.1349	0.7885	1.1352	Length ratio (R_L) = 2.337
3	4	11.3489	2.8372	6.0627	
4	1	6.3697	6.3697	29.676	Area ratio (R_A) = 5.614

3.2. Determination of Parameters for the GIUH Based Nash Model

The Nash model parameters of the watershed, viz., number of linear reservoirs (n) and storage coefficient (k) have been computed for the development of the GIUH based Nash model as per the procedure elaborated under section 2.5. The computed values of Nash parameters are also presented in Table 2. It is clear from the table that the value of first Nash model parameter, n remains constant, i.e., 2.961 irrespective of the events, whereas the second parameter, k varies from 0.238 to 0.639 hours. The value of n remains constant for a particular basin as it is only dependent on the geomorphological parameters of catchments and independent of the flow velocity; but k is inversely proportional to velocity and also dependent on the geomorphological parameters of the catchment (Bhaskar et al., 1997). The ordinates of the Nash IUH model were computed by substituting the final values of Nash parameters and the ordinates of unit hydrographs were worked out with the help of equations (7) and (8) and the estimated values also given in Table 2.

Table 2. Parameters of GIUH based Nash models for different storm events

Event	Date	Nash Model Parameters		Peak discharge Q_p (m^3/s)	
		N	k (h)	Observed	GIUH-Nash
E1	June 24-25,1992	2.961	0.345	12.417	12.900
E2	October 12-13,1993	2.961	0.639	30.552	29.700
E3	November 2-3,1993	2.961	0.387	7.183	7.100
E4	June 14,1994	2.961	0.559	2.893	2.800
E5	June 18,1994	2.961	0.238	4.500	4.100
E6	July 4,1994	2.961	0.372	2.985	3.100
E7	August 13,1996	2.961	0.304	6.621	6.800
E8	September 15,1996	2.961	0.259	18.582	20.190
E9	October 15-16,1996	2.961	0.458	7.297	7.940

3.3. Comparison of Observed and Computed DSRO Hydrographs

The direct surface runoff (DSRO) hydrographs computed by GIUH based Nash model were compared with the observed DSRO hydrographs. The accuracy of models was also tested by comparison of computed and observed DSRO hydrographs shown in Figure 3 through Figure 5 for events E2, E4 and E4. The values of peak discharge of the DSRO hydrographs for the various storm events are given in Table 2.

3.4. Performance Evaluation of GIUH Based Nash Model

The statistical indices employed in the present study for evaluation of the direct surface runoff (DSRO) hydrographs derived by the GIUH based Nash model with respect to the observed DSRO hydrographs are described below and the results are summarized in Table 3:

3.4.1 Coefficient of efficiency (CE)

The goodness of fit between observed and predicted values of DSRO ordinates was examined using following equation of coefficient of efficiency (Yu *et al*., 1994),

$$CE = \frac{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q}\right)^2 - \sum_{i=1}^{n}\left(Q_{oi} - Q_{ci}\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q}\right)^2} * 100 \tag{15}$$

where, Q_{oi} is the i^{th} ordinate of the observed discharge, $\overline{Q}$ is the average of the ordinates of observed discharge, Q_{ci} is the computed discharge and n is the number of ordinates.

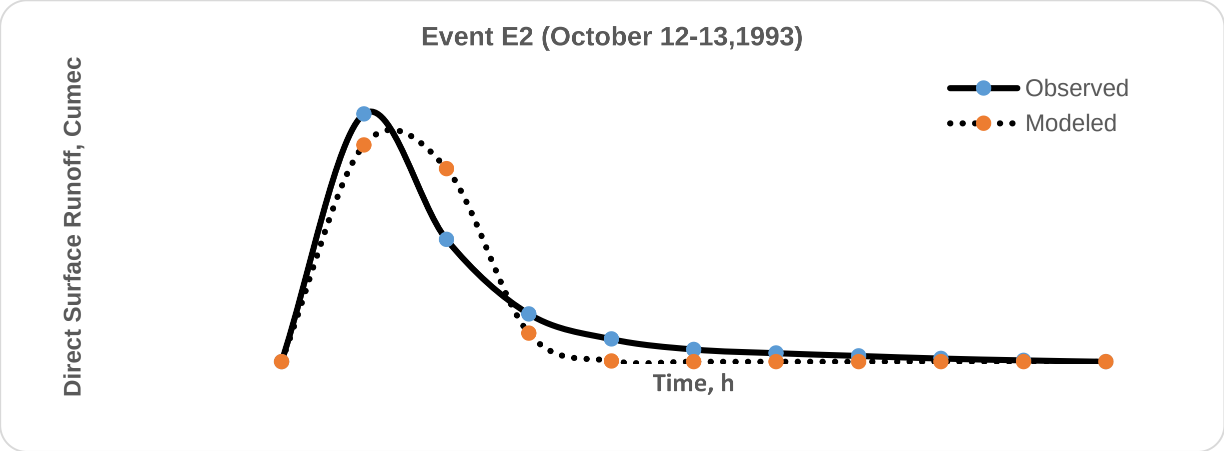

Figure 3. Comparison of observed and predicted direct surface runoff hydrographs of event E2

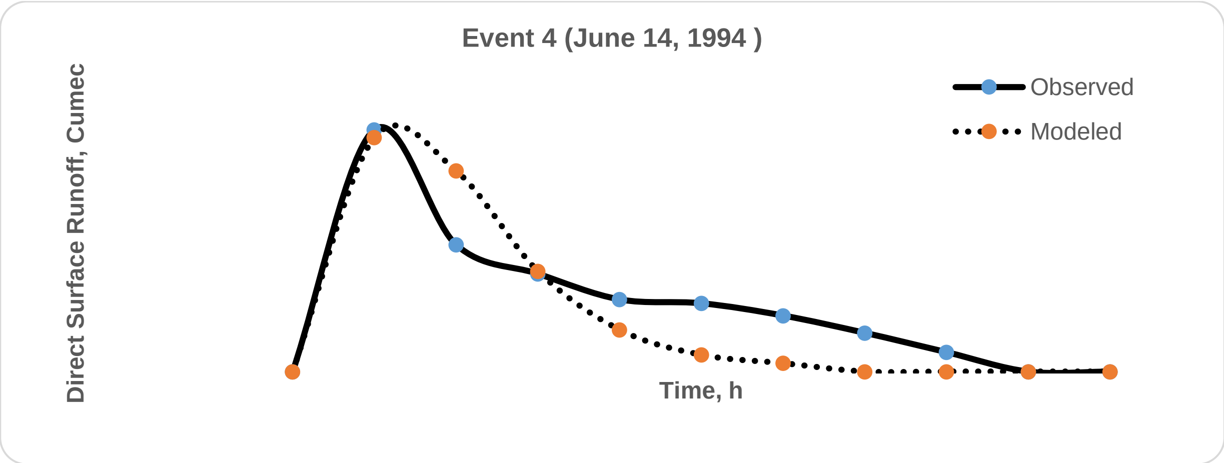

Figure 4. Comparison of observed and predicted direct surface runoff hydrographs of event E4

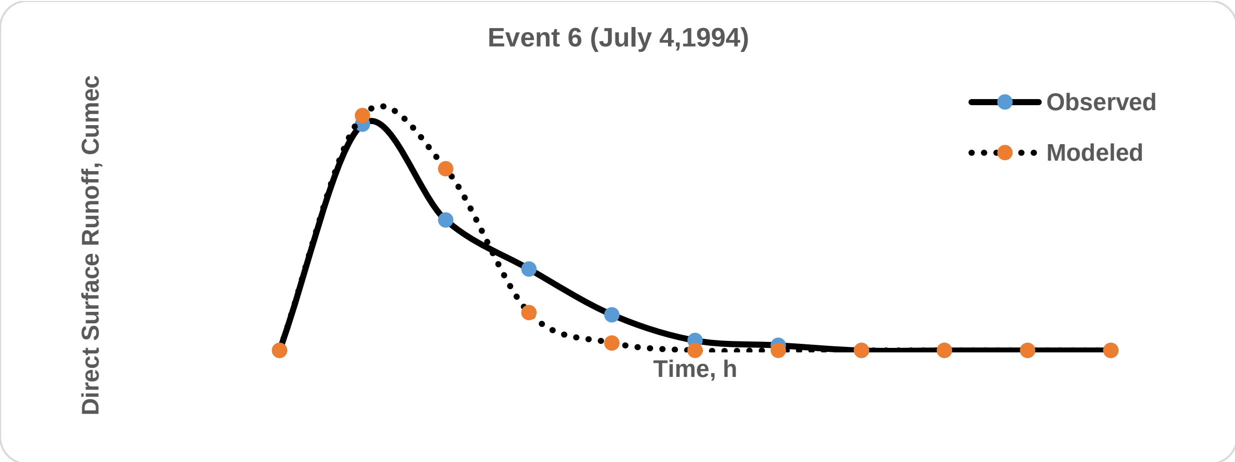

Figure 5. Comparison of observed and predicted direct surface runoff hydrographs of event E6

It can be observed from the Table 3 that the values of CE vary from 46.37 % to 94.71 % for GIUH based Nash Model. In the present study the model, yielding coefficient of efficiency (CE) values 60 % or more, is considered as applicable for the study area.

3.4.2 Absolute average error (AAE)

Sarma *et al*. (1973) gave the equation of absolute average error (AAE) between observed and predicted values as follows,

$$AAE = \frac{\sum_{i=1}^{n} \left|\left(Q_{oi} - Q_{ci}\right)\right|}{n} \tag{16}$$

The AAE values lie in the range of 0.185 to 3.528 for GIUH based Nash model, which are well within the acceptable limits of less than five, the criteria adopted in the study.

Table 3. Estimated values of performance evaluation indices for GIUH based Nash model for different events

Event	Date	Performance evaluation indices				
		CE (%)	AAE	RMSE	AEV	PEP (%)
E1	June 24-25,1992	92.35	0.636	1.21	0.164	4.000
E2	October 12-13,1993	48.57	3.528	3.282	0.394	13.080
E3	November 2-3,1993	77.04	0.612	1.165	0.324	1.148
E4	June 14,1994	82.5	0.416	0.685	0.018	3.110
E5	June 18,1994	92.17	0.231	0.367	0.014	8.926
E6	July 4,1994	88.14	0.185	0.296	0.035	3.606
E7	August 13,1996	57.47	0.738	1.357	0.097	2.676
E8	September 15,1996	94.71	0.927	2.11	0.394	8.025
E9	October 15-16,1996	46.37	1.037	1.698	0.02	8.260

3.4.3 Root mean square error (RMSE)

The root mean square error (RMSE) between the observed and the predicted values are determined by following equation (Yu *et al*., 1994),

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Q_{oi} - Q_{ci}\right)^2}{n}} \tag{17}$$

It is found that the values of RMSE ranges from 0.296 to 3.282for the GIUH based Nash model.

3.4.4 Average error in volume (AEV)

The average error in volume (AEV) for the prediction models can be estimated by using the following equation (Sarma *et al*., 1973)

$$AEV = \frac{\left(Vol_o - Vol_c\right)}{n} \tag{18}$$

where, Vol_o is the observed runoff volume and Vol_c is the computed runoff volume. The values of AEV vary from 0.014 to 0.394 for GIUH based Nash model.

3.4.5 Percentage absolute deviation in peak flow rates (PEP)

As suggested by Wang *et al*., (1992) the percentage absolute deviations between observed and predicted values are determined by the following equation,

$$PEP = \frac{(Q_{OP} - Q_{PP})}{Q_{OP}} \tag{19}$$

where, PEP is percentage absolute deviation in peak flow rates, Q_{OP} is the observed peak flow rate and Q_{PP} is the predicted peak flow rate. The values of PEP vary from 1.148 % to 13.080 % for GIUH based Nash model.

4.0 CONCLUSIONS

The results of the present study reveal that the Kothuwatari watershed was found to be fourth ordered hydrologic unit. The various geomorphological parameters like bifurcation ratio (R_B), length ratio (R_L), area ratio (R_A), length of main stream (L_Ω) and length of highest order stream (L) of Kothuwatari watershed were determined as 4.548, 2.337, 5.614, 11.893 km and 6.36 km, respectively. Based on the percentage absolute deviation in peak flow rates, coefficient of efficiency and average error in volume values, the GIUH based Nash model estimate direct surface runoff hydrographs in agreement with the observed hydrographs for the study watershed. Comparison of direct surface runoff hydrographs estimated using GIUH based Nash model with the observed surface runoff hydrograph indicates that the geomorphologic instantaneous unit hydrograph (GIUH) can be used as a transfer function in ungauged watersheds for modeling the transformation of excess rainfall into surface runoff.

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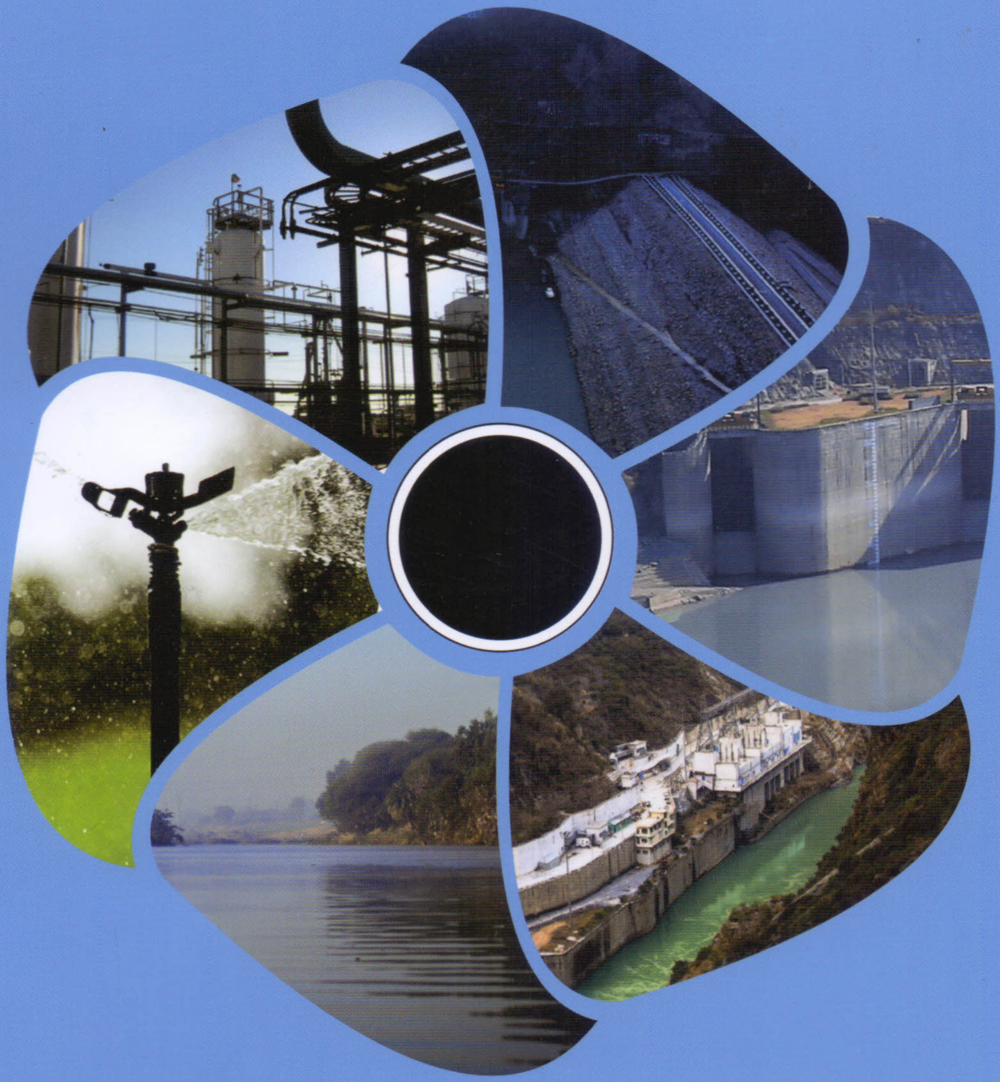

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