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A Study on Geomorphological Response for Runoff Prediction in Small Watershed

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Abstract: *Hydrological data of Arki sub-watershed comprising an area of 2460 hectares of a hilly catchment of Upper River Gambhar, located in mid hills of Solan district of Himachal Pradesh were analyzed to study the geomorphological response for estimation of direct runoff by using GIUH model. GIUH model was based on storm basis incorporating geomorphological parameters with the hydrological characteristics of the watershed. Geomorphological parameters were derived from topographic maps of the watershed satisfying Horton's[1] (1945) law when ordered according to Strahler[2] (1957) ordering procedure. The GIUH of the watershed was calibrated using the observed direct runoff hydrograph data. Direct runoff hydrographs were obtained from GIUH and these were compared with the observed DRHs to judge the performance of the model. The model performed well for all the test data sets with high coefficient of efficiency, lower relative squared error and absolute relative error in computed peak flow rates values and near zero Coefficients of Residual Mass values. The percentage absolute error in time to peak between computed and observed direct runoff hydrograph was found to be zero percent. The performance of the model showed that it simulates components of direct runoff of hydrographs well.*
Key words: *Watershed, Runoff, Instaneous, Unit Hydrograph and Rainfall*

I. Introduction

Development of rainfall-runoff models for accurate estimation of runoff is very important for proper planning, design and management of water resources projects. As a result of continuous research in the field of hydrological modelling many models have been developed to define the rainfall-runoff relationship of ungauged watersheds. There has been a gap in the coupling of quantitative geomorphological analysis with the most important hydrologic variables namely, the stream flow response to the surface runoff of geomorphological unit. An improvement over some of the models is the geomorphology-based models e.g., Gupta and Waymire[3] (1983), which represent the watershed structure and the stream network well. The watershed geomorphology plays a major role in the transformation of rainfall into runoff. By using the quantitative geomorphological parameters of a watershed, its hydrological response can be modeled. In the present study this concept has been successfully used for the development of geomorphological parameters and geomorphological instantaneous unit hydrograph (GIUH) for Arki watershed (2460 ha) of hilly catchment of river Gambhar, located in Himachal Pradesh.

II. Materials and Method

Study Area

The Arki watershed, a hilly catchment of river Gambhar lies in mid hills in Solan district of Himachal Pradesh as shown in Fig. 1. The watershed is located between 31^0 8'58" to 31^0 12'58" N latitude and 76^0 56'50" to 76^0 59'50" E longitudes. The watershed has an area of 24.60 sq km (2460 ha) and the shape of the watershed is more or less rectangular with mean length of 7 km and width 3.5 km. The maximum elevation of the watershed at its upstream is 1828 m whereas it is 1060 m above mean sea level at the gauging station near the Arki town. The watershed has a hilly terrain with extremely undulating and irregular slopes varying from relatively flat in the valleys to quite steep towards ridges. On the basis of prevailing slopes, the land may be classified under three categories, i.e. valley, moderate and steep hills. The average slope of the watershed is about 9 per cent. Agriculture is practiced on narrow width terraces constructed on slopes ranging from 10 per cent to 45 per cent.

Geomorphological Data

The drainage map and the contour map of the Arki watershed were obtained from the Divisional Forest office (Hydrology Investigation Division), Shimla, Himachal Pradesh and used to determine the geomorphological parameters. Fig. 2 and 3 shows the stream ordering for the watershed and the area contributing to different order streams, respectively. Geomorphological parameters for the watershed were determined with the

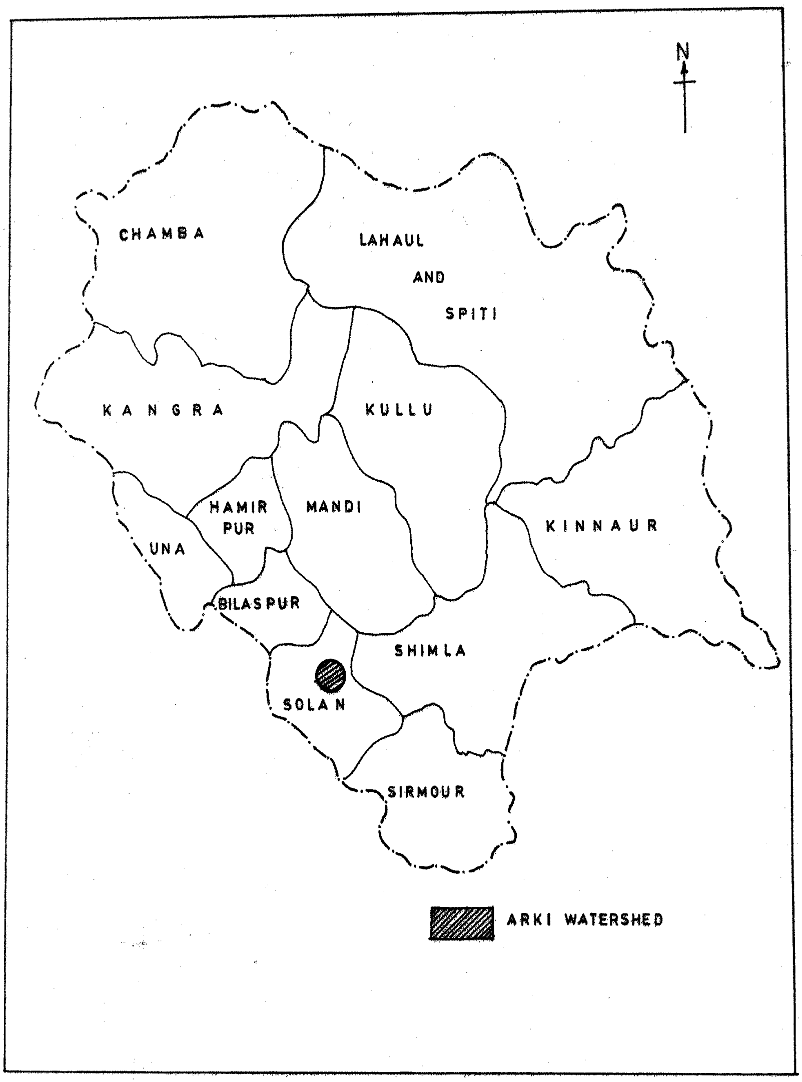

FIG.1 LOCATION OF ARKI WATERSHED IN HIMANCHAL PRADESH

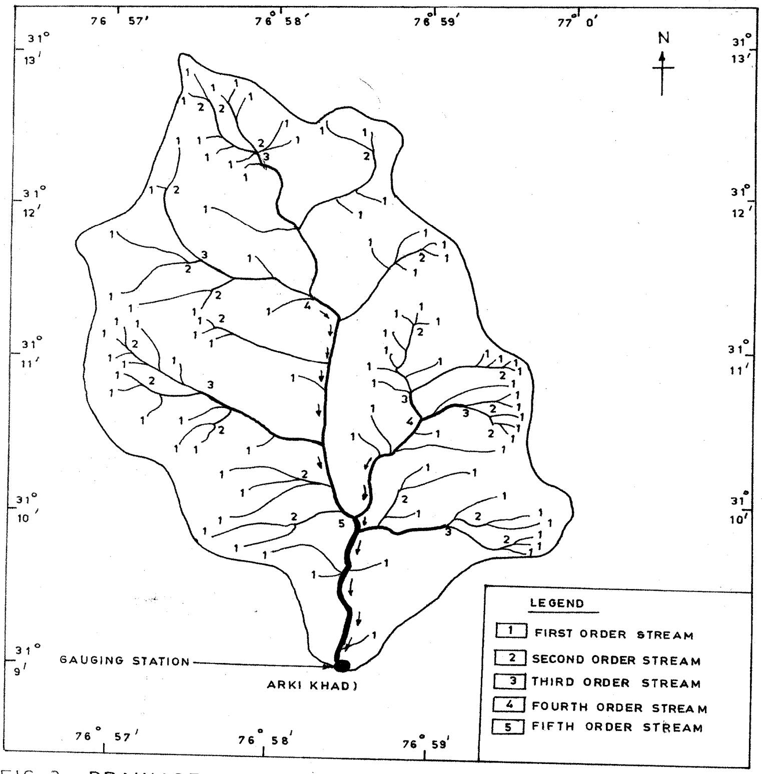

FIG. 2 DRAINAGE NETWORK MAP OF ARKI WATERSHED DEPICTING DESIGNATION OF STREAM ORDERS

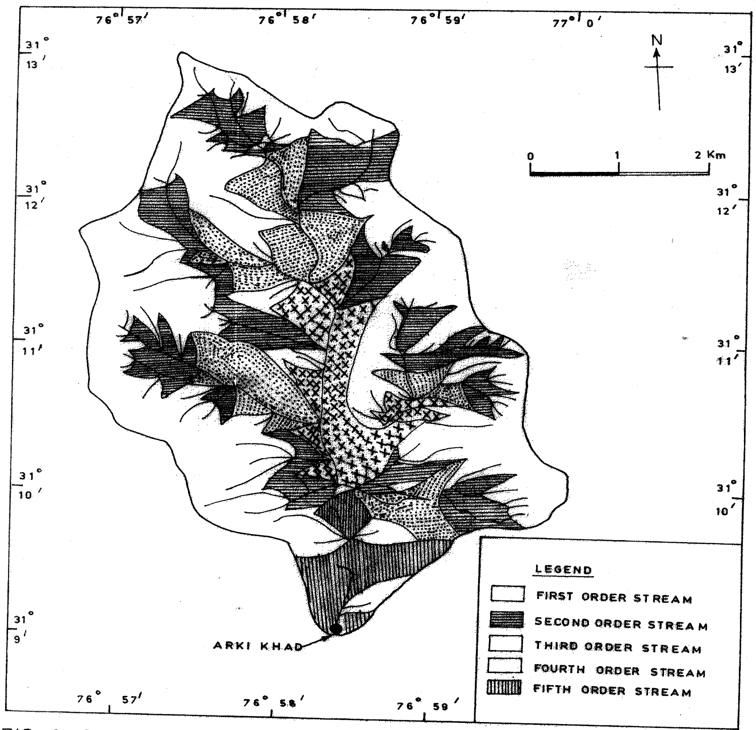

FIG. 3 DRAINAGE AREA CONTRIBUTION MAP OF ARKI WATERSHED

help of different maps of the study area (Table 1). The geomorphological ratios, i.e. bifurcation ratio, R_B, area ratio, R_A, and length ratio, R_L, were estimated using Horton's (1945) graphical procedure and their values were found as 3.0767, 3.6753 and 1.5774, respectively.

Rainfall and Runoff data

The rainfall and runoff data were obtained from Divisional Forest office (Hydrology Investigation Division), Shimala, Himachal Pradesh. The rainfall data were collected with the computerized automatic rain gauge (Tipping bucket type automatic rain gauge) and runoff in the form of stage hydrograph is being measured by data logger connected to the automatic water level recorder installed at the gauging station in the watershed. The collected rainfall and runoff data were used for determining the Geomorphological Instantaneous Unit Hydrographs for the study area.

Geomorphological Instantaneous Unit Hydrograph (GIUH) Model

The Geomorphological Instantaneous Unit Hydrograph (GIUH) Model used in the present study is based on the theory proposed by Rodriguez-Iturbe & Valdes[4] (1979) and its subsequent generalization by Gupta[5] *et al.* (1980). According to the theory, the unit input (unit depth of rainfall) is considered to be composed of an infinite number of small, non-interacting drops of uniform size, falling instantaneously over the entire region. The travel time of a randomly chosen drop of water, from its starting point to the outlet, represents the instantaneous unit hydrograph (IUH) of the basin. The Instantaneous Unit Hydrograph for the Arki watershed was developed by the convolution of the probability density function of travel time with the help of geomorphological characteristics of the watershed, and is finally expressed as:

$$h(t) = \sum_{s \in S} \sum_{j=1}^{k} C_{jk} \ \exp\left(-\lambda_{x_j} t\right) p\,(s) \qquad \ldots (1)$$

Where, p (s) is the probability that a drop follows a particular path S_K from a finite set of possible paths to reach the outlet and is given by:

$$p(s) = \pi_{r_1} \ p_{x_1 x_2} \ \ldots\ldots\ldots\ldots \ p_{x_{k-1} x_k} \qquad \ldots (2)$$

where, is the initial state probability, defined as the ratio of the total area of the overland segment draining directly to stream of order *i* to the total watersheds area; and P_{ij} is the transition probability, defined as the ratio of the number of streams of order *i* draining to stream of order *j* to total number of streams of order *j*. The possible path space for the study area, i.e., for 5th order watershed, is given as:

$$S = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}\} \qquad \ldots (3)$$

These paths are the combination of overland (r_j) and channel flow (c_j) states and are expressed as follows:

$S_1 = r_1\text{-}c_1\text{-}c_2\text{-}c_3\text{-}c_4\text{-}c_5\text{-}o$
$S_2 = r_1\text{-}c_1\text{-}c_2\text{-}c_3\text{-}c_5\text{-}o$
$S_3 = r_1\text{-}c_1\text{-}c_2\text{-}c_4\text{-}c_5\text{-}o$
$S_4 = r_1\text{-}c_1\text{-}c_2\text{-}c_5\text{-}o$
$S_5 = r_1\text{-}c_1\text{-}c_3\text{-}c_4\text{-}c_5\text{-}o$
$S_6 = r_1\text{-}c_1\text{-}c_3\text{-}c_5\text{-}o$
$S_7 = r_1\text{-}c_1\text{-}c_4\text{-}c_5\text{-}o$
$S_8 = r_1\text{-}c_1\text{-}c_5\text{-}o$
$S_9 = r_2\text{-}c_2\text{-}c_3\text{-}c_4\text{-}c_5\text{-}o$
$S_{10} = r_2\text{-}c_2\text{-}c_3\text{-}c_5\text{-}o$
$S_{11} = r_2\text{-}c_2\text{-}c_4\text{-}c_5\text{-}o$
$S_{12} = r_2\text{-}c_2\text{-}c_5\text{-}o$
$S_{13} = r_3\text{-}c_3\text{-}c_4\text{-}c_5\text{-}o$
$S_{14} = r_3\text{-}c_3\text{-}c_5\text{-}o$
$S_{15} = r_4\text{-}c_4\text{-}c_5\text{-}o$
$S_{16} = r_5\text{-}c_5\text{-}o$

C_{jk} in equation (3) is expressed as:

$$C_{jk} = \frac{\lambda_{x1} \cdot \lambda_{x2} \cdot \cdots \lambda_{xk}}{(\lambda_{x1} - \lambda_{xj}) \cdot (\lambda_{x2} - \lambda_{xj}) \cdot \ldots (\lambda_{xj-1} - \lambda_{xj}) \cdot (\lambda_{xj+1} - \lambda_{xj}) \cdot \ldots (\lambda_{xk} - \lambda_{xj})} \qquad \ldots (5)$$

Where, λ_{x_j} is the parameter termed as mean holding time of a drop.

The values of parameter λ_{x_j} are not directly obtainable. However, for overland and channel flow states, these can be determined as:

$$\frac{1}{\lambda_{r_i}} = \gamma \left[\frac{\pi_{r_i} A_\Omega}{2 \; N_i \; \overline{\overline{L_i}}} \right]^{1/3} \qquad 1 \le i \le \Omega \qquad \ldots (6)$$

and

$$\frac{1}{\lambda_{c_i}} = \gamma \; \overline{L_i}^{1/3} \qquad 1 \le i \le \Omega \qquad \ldots (7)$$

Table 1. Geomorphological parameters of the Arki Watershed

Order of the basin						5
Stream order, i	Total number of streams, Ni	Total length of streams, Li (km)	Mean stream length, $\overline{Li}$ (km)	Total area of streams, Ai (km2)	Mean stream area, $\overline{Ai}$ (km2)	Area of draining directly to streams, A'i (km2)
1	85	42.9250	0.5050	11.3050	0.1330	11.3050
2	21	17.6610	0.8410	18.5640	0.8840	7.2590
3	6	9.5400	1.5900	21.4200	3.5700	2.8560
4	2	7.1600	3.5800	23.2400	11.6200	1.8200
5	1	2.3900	2.3900	24.6000	24.6000	1.3600

No. of streams draining directly to streams of higher order				
Order	2	3	4	5
1	68	7	6	4
2	-	17	4	-
3	-	-	5	1
4	-	-	-	2
Bifurcation ratio (RB)				3.0767
Length ratio (RL)				1.5774
Area ratio (RA)				3.6753

where, Ω is the order of the watershed; N_j, number of stream of order j; $\overline{L_j}$, mean length of stream of order j; and γ is the empirical constant, ie, the mean holding time of a give state. λ_{r_i}, λ_{c_i} are the parameters for overland and channel flow state.

The mean holding time is obtained from the direct runoff hydrograph of the watershed by equating the first moment of the IUH with that of the DRH. C_{jk} is calculated using equation (5) whereas, λ_{x_j} ($x_j \in \{r_j, c_j\}$) is calculated using equations (6) and (7) for overland and channel flow states, respectively. By substituting the values of λ_{x_j} in equation (5), the values of C_{jk} can be obtained. After substituting the values of C_{jk}, λ_{x_j} and p(s) in equation (1), the GIUH ordinates for the watershed were obtained. Which are illustrated in Fig. 4.

Estimation of parameters of GIUH model

The required parameters, initial state probabilities, transitional probabilities and path probabilities were estimated by using appropriate method as described by Singh[6] *et al*. (2000). By using the observed DRH and the estimated net effective rainfall intensity, the mean holding time of the watershed was estimated. From these parameters the coefficients of the final equation (1) were estimated (Table 2).

Computation of Direct Runoff Hydrograph

The ordinates of direct runoff hydrograph for the watershed were obtained using the derived GIUH by convoluting the effective rainfall hyetograph with the GIUH. The ordinates of direct runoff hydrograph, Q(t) at any time t may be given as:

$$Q(t) = \int_0^{t'} u\,(t - \tau)\, I\,(\tau)\, d\,\tau \qquad \dots (8)$$

Where, u(t) is IUH ordinate; and $I(\tau)$ = effective rainfall of duration t_0
$t' = t$ when $t < t_0$
$t' = t_0$ when $t \geq t_0$

Table 2. Estimated values of model parameters for GIUH of the Arki Watershed

Initial state probability matrix* (π_i)	
Order (i)	(π_i)
1	0.4595
2	0.2951
3	0.1161
4	0.0740
5	0.0553
TOTAL	1.0000

Transitional probability matrix\$ (P_{ij})					
i	j = 2	j = 3	j = 4	j = 5	TOTAL
1	0.8000	0.8230	0.0706	0.0471	1.0000
2	0.0000	0.8095	0.1905	0.0000	1.0000
3	0.0000	0.0000	0.8333	0.1667	1.0000
5	0.0000	0.0000	0.0000	0.0000	1.0000

Path probabilities#		
Path No.	Path (S)!	Probability {P(S)}
1	r_1-c_1-c_2-c_3-c_4-c_5-o	0.2480
2	r_1-c_1-c_2-c_3-c_5-o	0.0496
3	r_1-c_1-c_2-c_4-c_5-o	0.0700
4	r_1-c_1-c_2-c_5-o	0.0000
5	r_1-c_1-c_3-c_4-c_5-o	0.0315
6	r_1-c_1-c_3-c_5-o	0.0063
7	r_1-c_1-c_4-c_5-o	0.0324
8	r_1-c_1-c_5-o	0.0216
9	r_2-c_2-c_3-c_4-c_5-o	0.1991
10	r_2-c_2-c_3-c_5-o	0.0398
11	r_2-c_2-c_4-c_5-o	0.0562
12	r_2-c_2-c_5-o	0.0000
13	r_3-c_3-c_4-c_5-o	0.0968
14	r_3-c_3-c_5-o	0.0194
15	r_4-c_4-c_5-o	0.0740
16	r_5-c_5-o	0.0553
	TOTAL	**1.0000**

Table 2. Contd….

K_B=1.9043 and Gamma = 0.3876		
Lambda valuses		
…… $\boldsymbol{\lambda_{ri}}$ and $\boldsymbol{\lambda_{ci}}$ values		
i	λ_{ri}	λ_{ci}
1	5.0717	3.2402
2	4.3724	2.7336
3	4.8596	2.2107
4	5.1320	1.6867
5	3.9231	1.9299
C_{ij} values for different patahs@		

Path No.(i)	j = 0	j = 1	j = 2	j = 3	j = 4	j = 5
1	-2.4809	166.2694	-620.3647	1426.4389	460.7851	-1430.6478
2	4.9789	-153.1364	385.0443	-443.1602	206.2734	
3	3.2107	-77.4261	146.7273	109.2221	-181.7340	
4	-6.4434	71.3105	-91.0698	26.2027		
5	2.1220	-30.8127	272.8454	176.4681	-420.6228	
6	-4.2586	28.3789	-84.7665	60.6462		
7	-2.7462	14.3485	41.8291	-53.4314		
8	5.5113	-13.2151	7.7038			
9	3.7011	-119.2976	517.1094	240.0498	-641.5627	
10	-5.8932	74.0449	-160.6534	92.5017		
11	-3.6190	28.2160	56.9002	-81.4972		
12	5.7625	-17.5129	11.7504			
13	-1.4202	89.7126	86.4867	-174.7791		
14	2.6716	-27.8716	25.2000			
15	1.5142	19.9379	-21.4521			
16	-3.7985	3.7985				

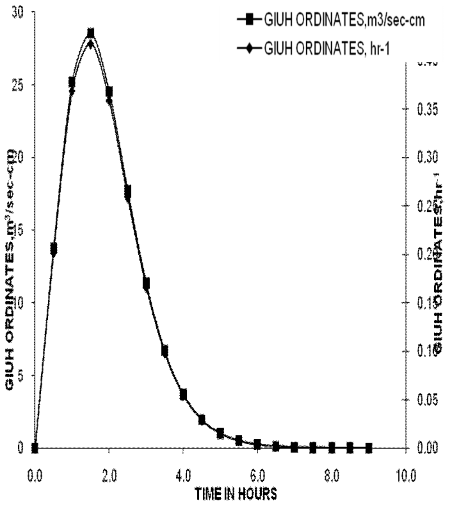

Fig. 4. Geomorphological Instantaneous Unit Hydrograph for Arki Watershed by using GIUH Model.

Above integral is known as convolution integral and is difficult to solve, so an approximate numerical method is adopted to solve the integral as follows.

$$Q(\mathrm{t}) = \sum_{\mathrm{i}=1}^{\mathrm{M}} Q_i = \sum_{\mathrm{i}=1}^{\mathrm{M}} I_i(t)\, \mathrm{u}\,(\mathrm{t} - (\mathrm{i}-1)\mathrm{D}) \qquad \ldots (9)$$

Where, I_i (t) is the rainfall excess value at i^{th} part, when total time t is divided into M equal parts of D duration.

By utilizing equation (9), the direct runoff hydrographs were estimated for Arki watershed.

III. Results And Discussion

The primary goal of the developing geomorphological instantaneous unit hydrographs of the watershed was to apply these for hydrograph generation and prediction which may be used in water resources planning. The ordinates of GIUH for Arki watershed were computed by the equations (1) which are shown in Fig. 4. As a test, to verify and validate the equivalence between computed and observed direct runoff hydrographs, the qualitative relative performance of the model developed in the study was examined by visual comparisons of various components of the regenerated and predicted direct runoff hydrographs with respect to the observed direct runoff hydrographs of the corresponding storm events. The quantitatively performance of the model as regards to regeneration and prediction of storm runoff hydrographs was compared with one another by determining statistical measures, namely, coefficient of efficiency, relative squared error, absolute relative error in computed peak flow rates and coefficient of residual mass (Table 3).

The regenerated direct runoff hydrograph for the representative storm event of July 8, 1994 and the predicted direct run off hydrograph for the representative storm event of July 20, 1994 are illustrated in Fig. 5 and Fig. 6, respectively for comparison with the observed direct runoff hydrographs of the corresponding storm event. On the basis of the qualitative and quantitative performance of the GIUH model with regards to regenerating and predicting of the direct runoff hydrographs, it is

Table 3. Estimated values of coefficient of efficiency, relative squared error, absolute relative error in computed peak flow rates and coefficient of residual mass on storm basis for Arki watershed

Date of storm event	Coefficient of efficiency, E	Relative squared error, RSE	Absolute relative error in computed peak flow rates (%), E_p	coefficient of residual mass, CRM
August 6, 1993	0.8392	0.0746	0.0000	+0.0131
July 8, 1994	0.9949	0.0031	4.0284	+0.0086
August 2-3, 1994	0.9376	0.0334	0.4598	+0.0081
August 23, 1994	0.9446	0.0363	2.7273	+0.0311
September 5, 1994	0.9736	0.0149	0.1653	+0.0052
September 8, 1994	0.9781	0.0129	2.9126	+0.0099
June 30, 1996	0.9622	0.0195	7.5652	+0.0079
August 2-3, 1996	0.9772	0.0126	4.3290	+0.0107
September 2, 1996	0.9442	0.0310	2.4000	+0.0056
August 12, 1997	0.9459	0.0298	3.9370	+0.0055
Average value	0.9498	0.0268	2.8525	+0.0106
February 2,1994 *	0.9498	0.0286	7.6158	+0.0082
February 20,1994 *	0.9546	0.0245	0.3384	+0.0057
July 19,1994 *	0.9446	0.0255	3.6427	+0.0079
July 20,1994 *	0.9712	0.0151	1.5957	+0.0078
Average value	0.9550	0.0234	3.2982	+0.0074
Overall Average value	0.9513	0.0258	2.9798	+0.0097

*Predicted storm events.

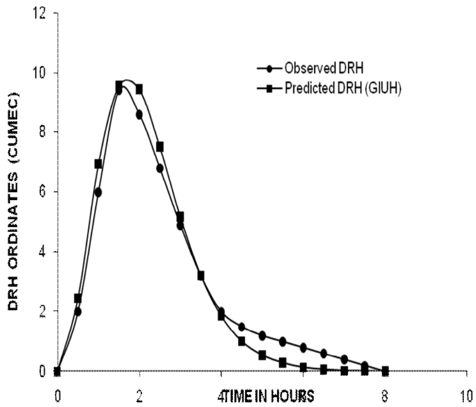

Fig. 5. Comparison of Observed and Regenerated Direct Runoff Hydrographs for the Storm Event of July 8, 1994 for Arki Watershed

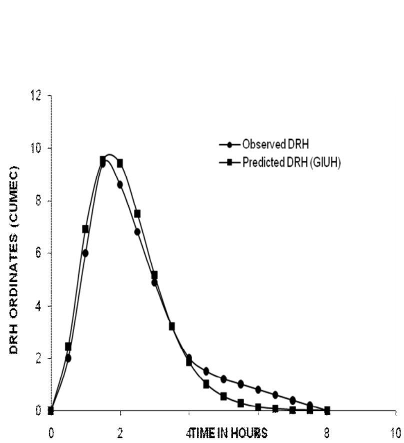

Fig. 6 Comparison of Observed and Predicted Direct Runoff Hydrographs for the Storm Event of July 20, 1994 for Arki Watershed

Concluded that GIUH model simulates well with closer agreement with the observed direct runoff hydrographs.

IV. Conclusion

Based on the overall qualitative, quantitative performance of the model, the GIUH model can very well be used for regeneration and prediction of direct runoff hydrographs with sufficient degree of accuracy.

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