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Research Paper :

Prediction of runoff for small watershed using GIUH_CAL model and GIS approach in Chhattisgarh

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ABSTRACT

A Geomorphological Instantaneous Unit Hydrograph Calculator (GIUH_CAL) model was applied for estimating the direct runoff from a small watershed (Arang) in Chhattisgarh (India). Various maps including Digital Elevation Model (DEM), watershed and sub-watershed boundaries, drainage network and soil texture were generated using topographic and soil resource data in the environment of a Geographical Information System (GIS). Several geomorphological parameters of the watershed were determined using various maps generated through GIS and given as input to the model. The GIUH_CAL model was tested for the monsoon season of years 2003 and 2004 using daily rainfall data of selected events. Performance of model was evaluated by comparing runoff values predicted by the model with the observed values using graphical, statistical and mathematical criteria. The results revealed that the observed runoff values were having good agreement with the runoff values predicted by the GIUH_CAL model. Student's t-test resulted that the means of observed and predicted runoff were found to be similar at 95 per cent confidence level. Value of coefficient of determination (r^2) was found to be 0.88 and it was indicated that the predicted runoff values for each selected rainfall events were close to the observed values. Overall deviation indicated that the model over predicted the daily runoff by 18 per cent. On the basis of the study it can be concluded that the GIUH_CAL model is capable of predicting direct runoff from the Arang watershed for various storm events satisfactorily.

Key words : GIUH_CAL model, GIS, Runoff, Validation and watershed

In India most of the watersheds are still ungauged or having very limited data due to economic and social constraints. Several hydrological models including physically based models and models incorporating geomorphological parameters are available to study the rainfall-runoff transformation process. The physically based models, though technically sound are too expensive, probably beyond the economic reach of the developing countries like India, whereas geomorphological parameters based models are comparatively less expensive and uses a simplistic approach (Tiwari *et al*., 1997).

The compilation of input data, which are required by the geomorphological parameter based models are often cumbersome. The time-consuming nature of extraction of watershed parameters can be eliminated by means of Geographical Information System (GIS) in addition to obtaining high accuracy. Jain *et al*. (2001) found that the input data for the hydrological models can be extracted with the use of GIS mainly from the map layers including DEM, soil, slope, drainage and watershed and sub-watershed boundaries.

Among the several hydrological simulation models which are in use to study the rainfall-runoff transformation process, the Geomorphological Instantaneous Unit Hydrograph Calculator (GIUH_CAL) model is the most recent one and used successfully for generating Instantaneous Unit Hydrograph (IUH) and Direct Runoff Hydrograph (DRH) of various watersheds. A physically based model GIUIH_CAL was developed by Panigrahy (2002) at Indian Institute of Technology (IIT), Kharagpur, West Bengal, India to estimate the surface runoff from ungauged watersheds. Looking to the importance of hydrological models and GIS technique the current study was under taken with the use of a physically based model (GIUH_CAL) and GIS technique to estimate the surface runoff from a small watershed in Chhattisgarh state of India.

The Geomorphological Instantaneous Unit Hydrograph (GIUH) model is based on the theory proposed by Valdes *et al*. (1979). 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. Several research workers (Rodriguez-Iturbe *et al*., 1982a;

Rodriguez-Iturbe *et al.*, 1982b; Sinha, 2004) were found that the travel time of a drop of water to the outlet is dependent on the geomorphological features of the basin.

METHODOLOGY

Study area and data collection:

The selected watershed (Arang) is a part of eastern plateau Mahanadi basin located between $81^0 90'$ to $82^0 0'$ E longitude and $21^0 20'$ to $21^0 26'$ N latitude and covers an area of 54.50 km^2. Arang is 3rd order watershed according to Strahler's stream ordering scheme (Strahler, 1957). The elevation of the watershed ranges from 270 to 290 m above Mean Sea Level (MSL). The average slope of the watershed is 1.5 per cent. Predominant soil of the watershed is clay loam. Sandy loam, loam, sandy clay are also found in the watershed. The watershed receives an average annual rainfall of 1420 mm, out of which the monsoon season (June to October) contributes more than 80 per cent rainfall.

The topographic maps of the study watershed were collected for use from the Department of Soil and Water Engineering, Faculty of Agricultural Engineering, I.G.A.U., Raipur. Soil texture map and soil resources data of the study area were collected from the Department of Soil and Water Engineering, I.G.A.U., Raipur.

Description of GIUH_CAL model:

The GIUH_CAL model requires geomorphological data of the watershed for estimation of initial and transitional probabilities. This model has two major modules, *viz.*, MAIN and INFILTRA.MAIN module uses geomorphological parameters of the watershed to define path space, {S}, and to estimate the initial state probability and transitional probabilities. The path probabilities p(s) are subsequently estimated. The INFILTRA module is then executed to estimate the Net Effective Hyetograph (NEH). Using the observed Direct Runoff Hydrograph (DRH) and the estimated NEH, the mean holding time, KB, of the basin is estimated, and subsequently used to estimate IUH ordinate, h(t) using geomorphological features. The INFILTRA module estimates the NEH for the supplied set of input (rainfall data) and subsequently, MAIN module evaluates the convolution integral of h(t) and NEH using numerical integration to estimate DRH. The numerical values of derived DRH for each event were added and daily values of direct runoff were obtained.

The Instantaneous Unit Hydrograph (IUH), h(t) with an exponential time distribution is expressed as follows:

$$h(t) = \sum_{s \in S} \sum_{j=1}^{k} C_{jk} \exp\{-\lambda_{x_j} t\} \, p(s) \quad s = < x_1 \ldots x_k > \quad (1)$$

where, C_{jk} = Coefficients; P(s) = transitional probability; λ_{xj} = exponential parameter

The mean holding time of the basin, K_B, is equal to the distance between the centre of gravity of the hydrograph and the centre of gravity of the hyetograph. It can be mathematically expressed as follows:

$$K_B = \frac{\int_0^{\infty} t\, Q_B(t)\, dt}{\int_0^{\infty} Q_B(t)\, dt} - \frac{\int_0^{t'} t\, I(t)\, dt}{\int_0^{t'} I(t)\, dt} \quad (2)$$

where, $Q_B(t)$ = discharge at time t, I(t) = net effective rainfall intensity at time t

Extraction of watershed parameters for the model:

The GIS (Arc/INFO) software was used to process and extract data to prepare input files for the GIUH_CAL model. Topographic map in the scale of 1:50,000 having 10m contour intervals were carefully digitized after registration. Then digitized contours were girded and Digital Elevation Model (DEM) was generated. The drainage map was generated with the help of GIS by digitizing the drainage network as given in the topographic map for determining the various watershed parameters including drainage order, area under each stream, drainage density and channel length as shown in Fig. 1 (Tripathi *et al.*, 2002).

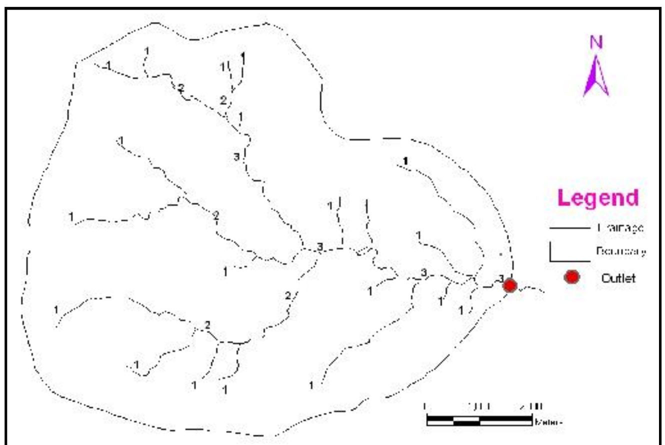

Fig. 1 : Drainage network of the Arang watershed

The GIUH_CAL model requires geomorphological parameters of the watershed for estimation of initial and transitional probabilities. One of the most important parameter of the model, the mean holding time (KB) of the basin is estimated and subsequently used to estimate IUH ordinate. Various others morphological parameters of the watershed such as length of stream, drainage area under each stream, number of drainage orders, bifurcation ratio, length ratio, area ratio given as input to the model are given in Table 1. Other than morphological parameters, areas covered under each soil texture were also given to the model. Infiltration parameters including sorptivity and a parameter depend upon soil properties were also considered as input of the model. Model works on event basis therefore, rainfall occurs during each events of a day were given to the model.

Table 1 : Geomorphological parameters of the Arang watershed

Order of the basin				Individual area
Order (i)	N_i	L_i	A_i	A'_i
1	20	26.14	32.35	32.35
2	4	9.37	43.94	11.59
3	1	8.5668	54.50	10.59
No. of streams draining directly to streams of higher order				
Order		2		3
1		11		9
2		-		4
Bifurcation ratio (R_B)				4.6415
Length ratio (R_L)				1.7579
Area ratio (R_A)				3.5481

N_i : Number of streams of order 'i'
L_i : Length of all streams of order 'i' (km)
A_i : Area of all sub-basins of order 'i' (km^2)
A'_i : Area draining directly to streams of order 'i' (km^2)

Soil texture map:

Soil texture map was generated using soil resource data of the study watershed, which was collected by personal visits as shown in Fig. 2. Sub-watershed wise areas covered by each soil texture were also extracted. Soil texture were found to be about 174.6, 520.2, 711.8 and 4043.4 ha for sandy loam (*Bhata*), sandy clay loam (*Matasi*), loam (*Dorsa*), and clay (*Kanhar*), respectively.

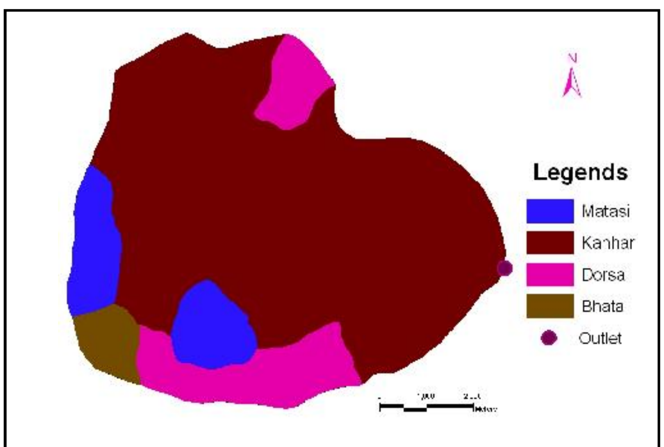

Fig. 2 : Soil texture map of the Arang watershed

Calibration and validation of GIUH_CAL model:

The successful application of a physically based model for ungauged watershed depends on how well the model is calibrated. Singh *et al.* (2004) have calibrated the GIUH_CAL model satisfactorily for Guptamani watershed of West Bengal in India. They used various sets of rainfall-runoff data and calibrated several parameters including mean holding time (KB) and initial degree of saturation (S_r). The value of S_r at which the model performed the best was taken as the calibrated value and the corresponding K_B values were treated as the average mean holding time for the watershed. Bhadra, (2003) has validated the GIUH_CAL model for the Chhokranala watershed of Raipur, Chhattisgarh in India.

RESULTS AND DISCUSSION

The results obtained from the present investigation are presented below :

Verification of GIUH_CAL model:

Since GIUH_CAL is a morphological parameter based model and used for simulating the runoff hydrographs for the ungauged watershed, therefore, it should be verified at least for that watershed using available data. Since, daily values of rainfall and surface runoff recorded at the outlet of the Arang watershed during monsoon season of the years 2003 and 2004 were available hence; model was verified for that period only.

Previously the GIUH_CAL model was tested for simulating the daily runoff from the small watershed, "Chhokranala" which is located nearby the study watershed (Bhadra, 2003). This small watershed is more or less similar in all respects therefore, calibrated values for most of the parameters including both overland and channel flow, sorptivity (S) and infiltration rate were considered in this study as used by Bhadra (2003). Philip Two Term model was chosen for computation of infiltration since it gave better results (Philip, 1957). All the input data for study watershed entered into the respective files and simulated direct runoff were compared with their observed counterparts for model verification. Model performance was evaluated using various criterion including graphical, mathematical, linear regression method and statistical tests of significance.

The observed and simulated daily runoff values of the study watershed for the verification period (1st June to 31st October) were compared graphically as shown in Fig. 3. During the initial events, model was slightly over

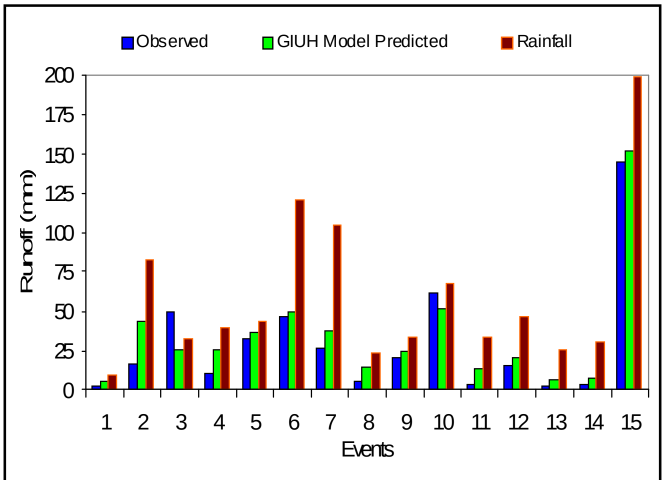

Fig. 3 : Comparison between observed and GIUH_CAL predicted runoff

predicting and there after model was predicting runoff very close to observed runoff. Overall model was predicted runoff more than that of the observed runoff for the selected events. Event-wise predicted runoff values were plotted against the observed values and their distribution along the 1:1 line is shown in Fig. 4. It can be seen that the simulated runoff values were distributed uniformly along the 1:1 line for lower values of observed runoff. A high value (0.88) of the coefficient of

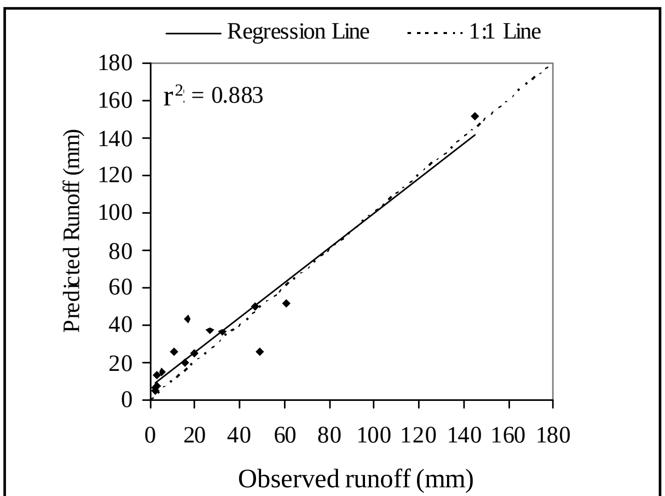

Fig. 4 : Comparison between observed and GIUH_CAL model predicted runoff

determination (r^2) indicated a close relationship between observed and GIUH_CAL model simulated runoff.

The statistical results showing comparison between the observed and simulated daily runoff for GIUH_CAL model are given in Table 2. The total simulated event-wise runoff for GIUH_CAL model was found to be more

Table 2 : Statistical analysis of the observed and GIUH_CAL model predicted runoff

Statistical parameters	Event based runoff (mm) Observed	Event based runoff (mm) GIUH_CAL Model Predicted
Mean	29.098	34.345
Standard Deviation	37.202	35.839
Total	436.47	515.18
Count	15	15
t-cal	-1.848	
t-critical (two tailed)	2.145	
r^2	0.883	
% Deviation (Dv)	18.03	

than the total of observed runoff because the model slightly over predicted for a few events. This over prediction of the runoff rates resulted in more Standard deviation and mean for simulated runoff. However, Student's t-test showed that the means of observed and GIUH_CAL model simulated runoff were not significantly different at 95 per cent confidence level (t-cal = -1.84 and t-crit = 2.14).

The overall deviation indicated that the model was over predicting runoff by about 18 per cent for the selected rainfall events. These simulation results revealed that model could simulate the event-wise runoff for the watershed satisfactorily because the average values (34.35 mm) of runoff was found to be similar with the observed values (29.10 mm) recorded at the outlet of the Arang watershed. Overall prediction of event-wise surface runoff was found to be satisfactory for Arang watershed. Developer and users of the GIUH_CAL model (Panigrahy, 2002; Bhadra, 2003; Singh *et al.*, 2004) have reported similar results.

Conclusion:

Various watershed parameters such as area, channel length, drainage density, slope and area under different soil textures can be derived accurately using various maps including DEM, drainage map, watershed and sub-watershed boundaries and soil texture map in the environment of GIS. The study concluded that the Geomorphological Instantaneous Unit Hydrograph Calculator (GIUH_CAL) model is capable of predicting direct runoff from the Arang watershed for various storm events satisfactorily.

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