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Mathematical Development Model for Estimating Direct Runoff for Kothuwatari Watershed

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Abstract:
Water resources planning, development and operation of various schemes requires accurate estimation of hydrologic response of the basin. Quantification of direct runoff is an essential input for planning and design. Direct runoff Hydrological investigations were carried out to develop mathematical model for estimation of direct runoff for Kothuwatari watershed of an area of 27.93 km^2 on storm basis. 15 single peaked isolated storm events were considered for determination of geo-morphological parameters of the watershed. The computed direct-runoff hydrographs ordinates by developed model were compared with the observed direct runoff hydrographs of the corresponding storm events. Coefficient of efficiency and percentage absolute deviation in time to peak were employed for quantitative comparisons. Average values of the shape factor, n and catchment storage coefficient, K, were determined to be 2.446 and 0.695 hour, respectively. The model resulted in closer agreement of rising segment and crest segment to the observed storm runoff hydrographs of the corresponding storm events. The peak runoff rates and recession segment of storm runoff hydrographs computed by the model was found to be in better agreement with the observed peak runoff rates. Percentage absolute deviation in peak flow rate between computed and observed storm runoff hydrographs of the model varies from 17.60-50.92 and the coefficient of efficiency between computed and observed storm runoff hydrograph of its model varies from 0.690 – 0.960. The overall qualitative and quantitative performance of the model for computed of direct runoff hydrograph was adjudged to be better and used for prediction of storm runoff for watershed with sufficient degree of accuracy with acceptable limits.

Keywords: *Geomorphological instantaneous unit hydrograph (giuh) model*

1. Introduction

The Geomorphometry-hydrology relationship provides the geomorphological control on basin hydrology. The role of basin geomorphology in controlling the hydrological response of a river basin is known for long time. Water resources planning, development and operation of various schemes requires accurate estimation of hydrologic response of the basin. In surface hydrology, rainfall-runoff and soil erosion process are very important and needs good understanding. These hydrological processes are nonlinear and involve various climatic, topographic, soils, land use information. To develop a good understanding and hydrological model for these processes, a reliable and wide variety geophysical and hydro-meteorological data are required.

Geomorphology of a river basin describes the status of topographic features of the surfaces and streams, and its relationship with hydrology provides the geo-morphological control on basin hydrology. 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.

The geo-morphological parameters are mostly time-invariant in nature and therefore, geomorphology based approach could be the most suitable technique for modeling the rainfall-runoff process for ungauged catchments. The rainfall pattern, in general is undergoing a change due to global changes in atmospheric conditions. Further, because of different activities in the watershed, its land use is also having a gradual changes and this has an impact on the characteristics of the runoff produced from the watersheds.

Thus, the geo-morphological instantaneous unit hydrograph (GIUH) (Iturbi and Valdes, 1979) and further simplified by Gupta et al. (1980) is a hydrological model that relates the geo-morphological features of a basin to its response to rainfall. They can be applied to ungauged basins having scarce hydrologic data.

GIUH uses the assumption that a stream of a certain order has a nonlinear response function of the familiar or complex probability distributions. Thus, the GIUH based transfer function approach is applicable in such a situation where rainfall data is available but runoff data are not, and it is a more powerful technique for the flood estimation. The GIUH technique is applicable for the estimation of the direct runoff component of the stream flow and hence, can be used to generate the direct runoff hydrograph (DRH). The DRH is computed, the flood hydrograph can be simply obtained by adding the base flow component.

A synthesis of the hydrologic response of a watershed to surface runoff is derived by linking it instantaneous unit hydrograph (IUH) or its geo-morphological parameters. Geo-morphological parameter is desired from different makes of its watershed satisfying Horton's law. In present study, the GIUH is derived from watershed geomorphological characteristics i.e. Bifurcation ratio (R_B), length ratio (R_L) and area ratio (R_A). The performance of developed model by qualitative and quantitative comparisons between the computed and observed direct runoff hydrographs were also done.

2. Materials & Methods

2.1. Description of Watershed

Kothuwatari watershed was selected for present hydrological studies which is one of the sub-watersheds of the Tilaiya catchment of upper Damoder Valley. The Kothuwatari watershed is situated at the south eastern part of the Tilaiya dam catchment between $24^0$12' 27" and $24^0$16' 54" North latitudes and 85^0 24' 18" and 85^0 28' 10"longitude. The Kothuwatari River originates from the south eastern part of the Kothuwatari watershed. The Tilaiya dam has been constructed on the Barakar River near Tilaiya in Hazaribagh District of Jharkhand State. The Tilaiya dam is one of the five drainage basins of Damodar-Barakar catchment of upper Damodar valley.

2.2. Climatic and Topographic Characteristics

The climate of the watershed varies from sub-tropical to sub temperate. The sub-humid tropical type climate is characterized by a very hot and dry period from March to May, a moist and hot period from June to September and a cool dry period from October to February. Mean air temperature is maximum in the month of May and minimum in January with an annual average temperature of about 25^0C. Rain starts from middle of June and continue till October as a result of south –west monsoon. The Kothuwatari watershed comprising of an area 27.93 Km^2 (2793 hectare) is irregular in shape with a mean length and width of 7.5 km and 3.6 km respectively. The general slope of the land in the watershed ranges from 1 to 5%. The land physiography is heterogeneous in nature as it is composed of hillocks, rolling uplands and ravines accruing side by side.

2.3. Geological Features; Soil Characteristics and Drainage

Geological formation found in the Kothuwatari watershed consists of granite, time stone and granite-genesis. The soils seem to have been derived mostly from coarse textured quartzites. Generally, the soils are immature due to washing away of top soils. The soil pH is mostly on acidic side ranging from 5.5 to 6.5 excluding same deep paddy soils which so slight alkalinity with pH ranging from 6.5 to7.5. Organic matter in the soil is poor due to high temperature, low moisture contents, excess runoff and less addition of natural vegetative residue.

The maximum water holding capacity of the soil is about 42%. The water holding capacity increases with increases in soil depth in all of the soils. The watershed is well drained owing to coarse textured soil and high slopes.

2.4. Land Used Pattern

Land is the, main resource in the watershed which contributes to agricultural and Horticultural production nearly62% of the, total area of the watershed consists of cultivable lands 26.38% under forest land, 53.7% under agricultural land, 18.6% under waste land and remaining 1.32% as miscellaneous. One of the total area of the watershed, about 10.3% area is under paddy land, 20.94% area is under gullied land 16% area hillock.

2.5. Hydrological Instrumentation and Collection of Data

The soil conservation measures were initiated in Kothuwatari watershed by the soil conservation department of Damodar Valley Corporation. Automatic and non recording rain gauges were setup at Karso-gauging station at the outlet of the Kothuwatari river which flows through the Kothuwatari watershed. The data related to the characteristics of Kothuwatari watershed pertaining the topography features, geological characteristics, soil characteristics, land used pattern total depth of rainfall, were collected from soil conservation department Damodar valley Hazaribagh District.

2.6. Analysis of Hydrologic Data

In order to determine to hydrologic response of the watershed, the analysis of rainfall and runoff data is essential. Fifteen storm events which produced single peaked runoff hydrographs were considered in this study. These events include the rainfall runoff date of August 20, 1991; September 21-22, 1991; July 24-25 1992; August 12-13, 1993; October 02-03, 1994; November 05-06, 1994; June 18, 1995; July 06, 1996; September 15, 1996; August 20-21, 1997; Sept. 15-16, 1997; Oct. 13,1997; June. 28,1998; July. 30-31, 1998; Aug.15-16, 1998.

2.7. Analysis of (Direct Runoff) Storm Runoff Data

Fifteen single peaked storm events as outlined in subsection were analyzed for separation of total runoff into base flow and storm runoff. These storm events satisfied the requisite criteria for the selection of hydrologic data. The ordinates to total runoff hydrograph for the 15 storm events were calculated.

2.8. Base Runoff Separation

The base runoff separation method suggested by Chow (1964) to separate quick responses flown from the slow responses flow was used in the study. Base runoff or base flow is composed of ground water runoff and delayed sub-surface runoff water.

2.9. Derivation of Storm Runoff Hydrographs

Storm runoff is the sum of surface runoff, sub-surface runoff and channel precipitation. The storm runoff hydrograph ordinates were computed for all fifteen storm event by subtracting the base flow ordinates from the total runoff hydrograph ordinates using the following equation.

$$Q_{Di} = Q_{Ti} - Q_{Bi} \qquad (1)$$

Where,

Q_{Di} = is the storm runoff (Direct runoff, m^3/sec)

$Q_{Ti} =$ total runoff in m^3/sec

Q_{Bi} = Base runoff in m^3/sec

The subscript, i refer to the time of runoff occurrence.

2.10. The Model

Geo-morphological instantaneous unit Hydrograph (GIUH) model was developed herein for watershed geo-morphological characteristics and later related to the parameters of the Nash Instantaneous Unit Hydrograph Model for deriving its complete shape. The model parameters of GIUH and the Nash IUH model parameters were derived by using the approach that rainfall intensity is averaged over the entire storm period. The storm wise geo-morphological instantaneous unit hydrograph model was developed by using conceptual model, in which catchment impulse response can be represented as the out flow obtained from routing the unit volume of instantaneous excess rainfall input through a series of successive linear reservoirs having equal delay time. The conceptual model proposed by Nash (1957) can be expressed by equation.

$$U(o,t) = \frac{1}{k}\frac{1}{n!}e^{(-\frac{t}{k})}\left[\frac{t}{k}\right]^{n-1} \qquad (1)$$

Where,

U (0, t) = Ordinate of IUH in cm/hr

K = Catchment storage coefficient (scale parameter)

n = Number of linear reservoirs (shape factor)

t = time interval in hr.

On taking logarithms of both sides of equation and differentiating with respect to time the resulting equation becomes.

$$\frac{d}{dt}\left[U\,(o,t)\right] = U\,(o,t)\left[-\frac{1}{k} + \frac{(n-1)}{t}\frac{1}{k}\right] + \frac{(n-1)}{t} \qquad (2)$$

Equating the preceding equation to zero and solving for t, the resulting equation expressed as.

$$T = t_P = (n-1)\,k \qquad (3)$$

On substituting the value of tP for t from equation (3) into equation (1), the peak discharge q_p of the IUH is obtained in the form of equation.

$$q_p = \frac{1}{k\,n!} e^{-(n-1)} (n-1) \qquad (4)$$

The product of peak discharge and time to peak is expressed as.

$$q_p . t_p = \frac{(n-1)}{n!} e^{-(n-1)} . (n-1)^{m-1} \qquad (5)$$

2.11. Quantitative properties of hydrographs:

- Percentage absolute deviation
- Coefficient of efficiency

→ Percentage Evaluation peak (PEP): the percentage evaluation peak with the help following formula.

$$PEP = \frac{|Q_{po} - Q_{pc}|}{Q_{po}} \times 100 \qquad (6)$$

In which
Q_{PO} = Observed Peak flow rate
Q_{PC} = Computed Peak flow rate

→ Coefficient efficiency (E): Coefficient efficiency is computed with the help of following formula.

$$E = \frac{\sum_{i=1}^{m} (Q_{Doi} - \overline{Q_{Doi}})^2}{m-1} \qquad (7)$$

Where,
E = Coefficient of efficiency
Q_{DOi} = Observed storm runoff hydrograph ordinates
Q_{DCi} = Computed storm runoff hydrograph ordinates
$\overline{Q}_{DOi}$ = mean observed storm runoff hydrograph ordinates

3. Results & Discussion

3.1. Model Development

Equation (5) is a function of the Nash IUH model parameter, n. Relationship between peak discharge, q_p and time to peak t_p, in terms of geo-morphological characteristics (Table 1) is given as below.

$$q_p t_p = 0.5764 \; R_B^{0.55} \; R_A^{-0.55} \; R_L^{0.05} \qquad (8)$$

or

$$\frac{(n-1)}{n!} e^{-(n-1)} . (n-1)^{n-1} = 0.5764 \; R_B^{0.55} \; R_A^{-0.55} \; R_L^{0.05} \qquad (9)$$

In which, R_B is the bifurcation ratio, R_A is the stream area ratio and RL is the stream length ratio. The value of Nash IUH parameter, n, can be determined by using equation (9) by iterative process and scale parameter, K, and can be computed by using equation.

$$K = \frac{t_p}{n-1} = \frac{0.44}{V} L_w . R_B^{0.55} \; R_A^{-0.55} \; R_L^{-0.38} (\frac{1}{n-1}) \qquad (10)$$

The resulting geo-morphological instantaneous unit hydrograph model (GIUH) for Kothuwatari watershed is expressed as.

$$U(o,t) = \left(\frac{e^{(-\frac{t}{0.695})}}{0.695 \; (2.466)!} \right) \left(\frac{t}{0.695} \right)^{2.446 - 1} \qquad (11)$$

In which U (o,t) is the ordinates of IUH in hr^{-1} from zero to t hour, and t, is the time interval in hour from the beginning of IUH.

3.2. Computation of Storm Runoff Hydrograph Ordinates for Kothuwatari Watershed

The ordinates of geo-morphological instantaneous unit hydrograph in m^3/sec were multiplied by a conversion factor of 2.78 to the area of water is equal to 27.93 km^2 to get the IUH ordinates in m^3 /sec. A sample observed ordinates of total runoff hydrograph, base flow ordinates and computed storm runoff ordinates are presented in Table 2 for August 20, 1991. Direct Runoff Hydrograph for this event is presented in Table 3 and Figure 1.

The model developed by using Nash's model parameters have been used form estimation of storm runoff on storm basis. The results containing to the storm runoff hydrographs were developed in the study, Coefficient of efficiency, percentage absolute deviation (PEP) to judge the adequacy of the models for estimating storm runoff hydrographs. Qualitative and quantitative comparisons of observed and computed storm runoff hydrographs are presented and discussed in this chapter.

3.3. Two Parameters Model

The mathematical model based on Nash-model was developed with the help of shape and scale parameter, n and K, equal to 2.446 and 0.695 respectively, estimated from the characteristics the watershed. The ordinates of direct runoff hydrographs for the Kothuwatari watershed was computed by the equation developed in the study expressed as-

$$U(o,t) = \left(\frac{e^{(-\frac{t}{0.695})}}{0.695\ (2.466)!} \right) \left(\frac{t}{0.695} \right)^{2.446-1} \qquad (12)$$

3.4. Qualitative Performance of Model

As a test, to verify and validate the equivalence between computed and observed storm runoff hydrographs, the qualitative performance of the model developed in the study was examine by visual comparison of various component with respect to the observed storm runoff hydrographs of the corresponding storm events.

As mention the storm runoff hydrograph ordinates for the fifteen single peaked storm events considered in the estimation of model parameters. The visual comparison of hydrographs features viz. concentration segment, crest segment, recession segment, time to peak between the computed storm runoff hydrographs and the observed storm hydrograph for the corresponding storm event were employed for assessing the performance of the model. The model results in closer agreement to rising segment and crest segment with the observed storm runoff. The peak flow rate is of more importance as compare to the characteristics of the other component of the storm runoff hydrograph in the design of hydraulic structure. The peak flow rate computed by model was also found to be a better agreement with the observed storm runoff hydrographs of the corresponding storm events. At the lower end of recession segment, closer agreement between computed and observed storm runoff hydrograph for the model was observed as compare to lower end of recession curve of storm runoff hydrograph computed by developed model using Nash's parameters. On the basis of above discussion, the qualitative performance of developed model in computing the storm runoff hydrographs has been found satisfactory.

3.5. Quantitative Performance of the Model for Computation of Storm Runoff Hydrographs

The quantitatively performance of the model as regards to regeneration of storm runoff hydrographs was compared with one another by determining several statistical measures such as coefficient of efficiency and percentage absolute deviation.

3.6. Coefficient of Efficiency of the Model

The term, the coefficient of efficiency was introduced by Nash, and Suteliffic (1970) for assessing the fitting of models simulated responses to that of recorded catchment responses. The coefficient of efficiency is defined the criteria of goodness of fit to described the degree of association between the observed and estimated flows. The coefficient of efficiency of the model developed in the study was evaluated by the equation proposed by Nash and Suteliffic (1970).

$$E = \frac{\sum_{i=1}^{m} (Q_{Doi} - \overline{Q_{Doi}})^2}{m-1} \qquad (13)$$

In which E is Coefficient of efficiency, Q_{Doi} and QDcoare the observed and computed storm runoff hydrographs ordinates respectively. Q_{Doi} is the mean observed storm runoff hydrograph ordinates. i is the time at which storm runoff hydrograph ordinates are computed or measured, and m is the number or ordinates. The values of coefficient of efficiency is presented in Table 3 which varied from 0.838 to 0.995 which shows fair degree of goodness of fit between the observed and computed storm runoff hydrographs.

3.7. Percentage Absolute Deviation

Percentage absolute deviation inflow peak was determined for judging the quantitative performance as a test of verification of the equivalence between the computed and observed runoff hydrographs. The percentage absolute deviation between the computed and observed peak runoff rate where determined by the equation as reported by Wang et al. (1992).

$$PEP = \frac{|Q_{po} - Q_{pc}|}{Q_{po}} \times 100 \qquad (14)$$

In which PEP is the percentage absolute deviation in estimated Peak flow rate and Q_{po} and Q_{pc} are the observed and computed peak flow rate. The quantitative comparisons of computed and observed values with regard to peak runoff rate along with percentage absolute deviation in peak flow rate for the storm event were computed which varied from 2.05 to 30.0 (Table 4). The overall average percentage absolute deviation in Peak flow rate for the model reveal that the peak flow rate computed by this model is in better agreement with the observed peak flow rate.

Stream order (u)	Total no. of streams (Nu)	Total length stream (Lu)(m)	Total area of stream (Au) (Km^2)	Mean stream length (Lu) (m)	Mean stream area(Au), (km^2)	Bifurcation Ratio (R_B)	Stream length ratio(R_L)	Stream area ratio (R_A)
1	65	30000	12.15	461.53	0.186	4.089	2.423	2.574
2	18	19804	03.99	1100.2	0.221			
3	4	11020	6.577	2755.5	1.644			
4	1	6570	5.215	6570	5.215			

Table 1: Measured and computed geomorphologic characteristic of Kothuwatari Watershed for different stream orders

ER-0.645 mm

Time in (h)	Total runoff hydrograph ordinate Q Ti (m^3/s)	Base flow ordinate Q Bi (m^3/s)	Storm runoff hydrograph ordinates Q Di (m^3/s)
04.15	0.000	0.000	0.000
05.15	8.085	0.000	8.025
06.15	4.520	0.180	4.340
07.15	3.150	0.265	2.885
08.15	2.750	0.370	2.380
09.15	2.500	0.560	1.940
10.15	1.980	0.455	1.525
11.15	1.150	0.420	1.080
12.15	0.750	0.280	0.470
13.15	0.525	0.135	0.390
14.15	0.154	0.069	0.085
15.15	0.000	0.000	0.000

Table 2: Observed total runoff hydrographs, base flow and storm runoff hydrograph ordinates for the storm event of Aug.20, 1991

Time(h)	Observed DRH (m^3/s)	Computed DRH ordinates (m^3/s)
04.15	0.000	0.000
05.15	8.025	10.520
06.15	4.340	7.250
07.15	2.885	5.155
08.15	2.380	3.550
09.15	1.940	2.975
10.15	1.525	2.150
11.15	1.080	1.755
12.15	0.470	0.950
13.15	0.390	0.520
14.15	0.085	0.066
15.15	0.000	0.002

Table 3: Observed and Computed direct runoff hydrograph ordinates for the storm event of August 20, 1991

S No	Storm events	Percentage absolute deviation	Coefficient of efficiency
1	Aug 20., 1991	50.92	0.69
2	Sept. 21,1991	17.60	0.96
3	July 24-25,1992	46.01	0.75
4	Aug. 12-13, 1993	34.95	0.85
5	Oct. 02-03, 1994	50.52	0.69
6	Nov. 05-06,1994	31.88	0.87
7	June. 18,1995	37.00	0.82
8	July. 06,1996	26.20	0.91
9	Sept. 15, 1996	31.90	0.93
10	Aug. 20-21 , 1997	23.26	0.87
11	Sept.15-16,1997	22.38	0.94
12	Oct 13,1997	38.29	0.82
13	June.28 ,1998	35.28	0.84
14	July. 30-31, 1998	28.07	0.92
15	Aug. 15-16,1998	45.87	0.74

Table 4: Computed percentage, absolute deviation and coefficient of efficiency of storm events of August 20, 1991 to August 15-16, 1998

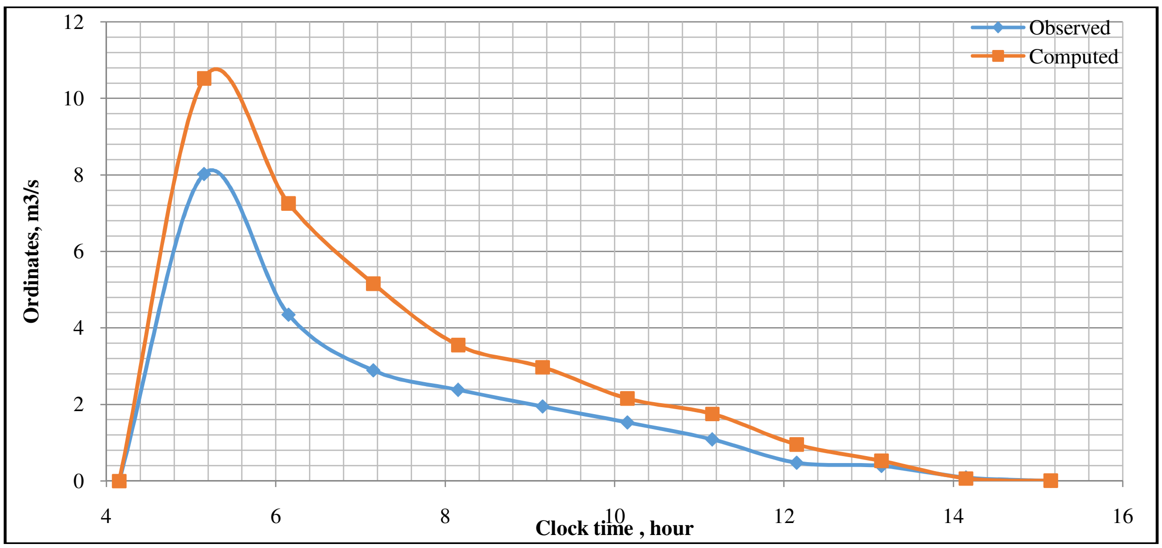

Figure 1: Observed and computed Direct Runoff Hydrograph (DRH) for August 20, 1991

4. Summary and Conclusion

Hydrological investigations were carried out to develop mathematical model for estimation of direct runoff for Kothuwatari watershed on storm basis. Kothuwatari watershed comprising an area of 27.93 km^2 lies in upper Damodar Valley catchment in district Hazaribagh, Jharkhand State. Hydrologic sequences data regarding investigation were collected from the soil conservation Department, Damodar Valley Corporation, Hazaribagh for the years 1991 through 1998. Fifteen single peaked isolated storm events were considered for determination of Geo-morphological parameters of the watershed. A Mathematical model for determination of direct runoff from Kothuwatari watershed is developed during the study. The computed direct-runoff hydrographs ordinate by developed model was compared with the observed direct runoff hydrographs of the corresponding storm events. Qualitative comparisons of Computed storm runoff hydrographs of the storm events with regards to concentration segment, crest segment, recession segment and time to peak were made to assess the performance of the model, Quantitative comparison between the computed storm runoff hydrographs and observed storm runoff hydrographs of the same storm events were made to judge the performance of the model in estimating the storm runoff on storm basis. Coefficient of efficiency and percentage absolute deviation in time to peak were employed for quantitative comparisons. Average values of the shape factor, n and catchment storage coefficient, K, were determined to be 2.446 and 0.695 hour, respectively, on the basis of computed first and second moment of direct runoff hydrographs.

The developed model for determination of direct runoff hydrographs ordinates for Kothuwatari watershed with computed parameters is expressed as,

$$U(o,t) = \left(\frac{e^{\left(-\frac{t}{0.695}\right)}}{0.695\ (2.466)!} \right) \left(\frac{t}{0.695} \right)^{2.446-1}$$

The model yielded in closer agreement of rising segment and crest segment to the observed storm runoff hydrographs of the corresponding storm events. The peak runoff rates and recession segment of storm runoff hydrographs computed by the model was found to be in better agreement with the observed peak runoff rates. Percentage absolute deviation in peak flow rate between computed and observed storm runoff hydrographs of the model varies from 17.60-50.92. The coefficient of efficiency between computed and observed storm runoff hydrograph of its model varies from 0.690 – 0.960. The overall qualitative and quantitative performance of the model for computed of direct runoff hydrograph was adjudged to be better and used for predication of storm runoff for Kothuwatari watershed with sufficient degree of accuracy with acceptable limits.

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