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Application of HEC-HMS for simulation of peak runoff rates from a small watershed

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ABSTRACT

Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS), a versatile hydrological model, was applied to a small watershed situated in Chotanagpur plateau region of India for simulation of peak runoff rates. Initial and constant loss method and Snyder unit hydrograph were chosen for computing the precipitation losses and transforming the estimated runoff into direct surface runoff, respectively. Seven sets of observed hyetographs and corresponding flood hydrographs were used for calibration of model parameters *viz.,* initial loss, constant loss rate, Snyder peaking coefficient and standard time lag. The model output was validated with other set of flood hydrographs (five in number) of the same watershed. A simple linear relationship between predicted and observed peak flow rates was also developed. The HEC-HMS simulated depths of runoff and peak runoff rates matched reasonably well with the observed data. The average value of absolute relative error in estimated peak, a measure of goodness of fit between the peak runoff rates of predicted and observed hydrographs was found to be 6.94 %. It was concluded from the study that the HEC-HMS model with the calibrated parameters can be safely used for the determination of the depth of runoff and peak runoff rates from ungauged watersheds with similar hydrological conditions (**Keywords:** HEC-HMS, runoff, runoff peak rate, Snyder unit hydrograph).

INTRODUCTION

Estimation of peak runoff rate for the desired return period is an important aspect of hydrological design of any soil and water conservation engineering structure in a given watershed (Mishra, 2007). Further, an accurate and timely forecast of flood peak discharge is required for the design of flood control projects as it affects both safety and cost of any structure (Gupta and Rastogi, 2005). Several hydrological models (empirical, physical based and mixed) are available for prediction of runoff including peak flow rates, which vary in complexity of inputs and number of parameters to be determined (Mishra *et al.,* 2009).

Hydrologic Engineering Centre - Hydrologic Modelling System (HEC-HMS) version 3.4 of United States Army Corps of Engineers (USACE) is a versatile hydrological model for simulation of rainfall - runoff processes of dendritic watersheds. HEC - HMS has an extensive array of capabilities for conducting hydrologic simulation. The physical representation of watershed is accomplished with a basin model. Hydrologic elements are connected in a dendritic network to simulate runoff processes. An assortment of different methods namely deficit constant, initial and constant, exponential, Green and Ampt, SCS (Soil Conservation Service) Curve Number, Soil Moisture Accounting and Smith Parlange are available for simulation of infiltration losses. Seven methods namely Clark unit hydrograph, Kinematic wave, modified Clark, SCS unit hydrograph, Snyder unit hydrograph, user specified S-graph and unit hydrograph are included for transforming excess precipitation into surface runoff (USACE, 2006). In Indian conditions, gauging of runoff in relation to rainfall was not carried out in general in majority of the watersheds. However, for the designing of soil and water conservation engineering structures like check dams, weirs of earthen dams and other gully control structures in agricultural watersheds, the peak flow rates should be estimated. Suitable hydrologic models can be developed by calibration using the rainfall-runoff data of gauged watersheds which can be used for predicting peak flow rates from the ungauged watersheds with similar agro-climatic and land use practices. With this objective, in the present study, HEC-HMS was calibrated and applied to a small watershed in Chotangapur plateau of India for simulation of peak runoff rates.

MATERIALS AND METHODS

The Karakara watershed located at 24° 17'45" and 24° 17'45" North latitude and 85° 12'2" and 85° 16'5" East longitude (Figure 1) with geographical area of 17.51 km^2, a sub-watershed of catchment of Tilaiya dam in upper Damodar valley, Chotangapur plateau, Jharakand state of India was chosen for the study. The maximum elevation of the watershed at the upstream end was 445 m above mean sea level, whereas the elevation of the watershed at the gauging site was 402 m above the mean sea level. Sub-tropical and humid climatic conditions were observed at the watershed with an average rainfall of 1100 mm and an average annual maximum and minimum temperature of 43.4 °C and 5 °C, respectively. The texture of the soil varied from sandy loam to clay. Data on rainfall depth (mm), runoff rate ($m^3 s^{-1}$) and sediment loss (g L^{-1}) were recorded and maintained by the Damodar Valley Corporation Authority, Jharkhand.

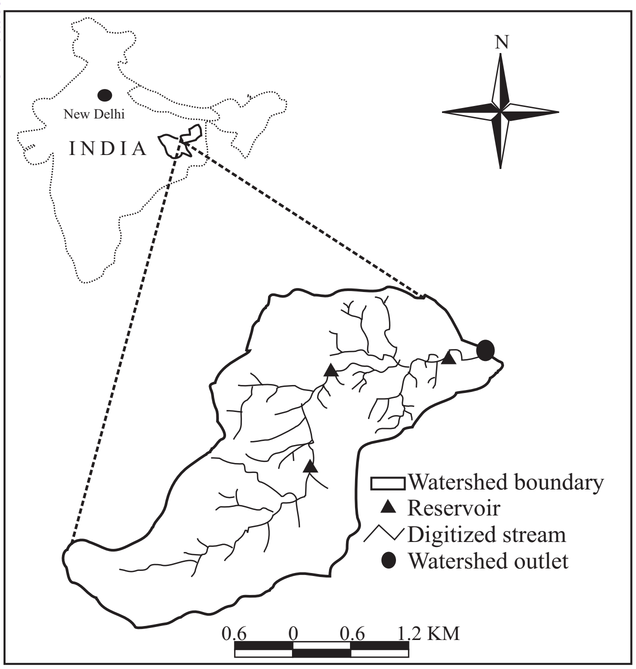

Figure 1. Map of Karkara watershed (Source: Mishra *et al.,* 2010)

HEC-HMS of USACE was designed to simulate the precipitation-runoff processes of dendritic watersheds. This model represented a significant advancement in terms of both hydrologic engineering and computer science with a variety of options, with a capacity to carry out both event based and continuous simulation of rainfall-runoff process. In this study, event based simulation was attempted with the available data. Though the model was considered to be versatile for simulation of rainfall - runoff processes, the main constraint in application of this model was the generalization of complex hydrologic system, hence calibration and validation of the model becomes necessary before its use for a desired purpose. The present study was carried out to verify the applicability of using the same HEC-HMS model for estimation of peak runoff rates from agricultural watersheds for designing suitable soil and water conservation engineering structures, by using the available rainfall-runoff data of Karakara watershed, Jharkhand state of India.

Initial and constant loss method and Snyder unit hydrograph were chosen for computing the precipitation losses and transforming the estimated runoff into direct surface runoff, respectively. Seven sets of observed hyetographs and corresponding flood hydrographs were used for calibration of model parameters *viz.,* initial loss, constant loss rate, Snyder peaking coefficient and standard time lag. The details of storm events used for calibration were given in Table 1. To compare computed hydrograph to an observed hydrograph, HEC-HMS computes an index of goodness of fit. Hourly time step was chosen for calibration and validation of the model in the present study. In HEC - HMS, four different objective functions *viz.,* sum of absolute squares (Stephenson, 1979), sum of squared residuals (Diskin and Simon, 1977), per cent error in peak (Wang *et al.,* 1991) and peak weighted root mean square error (USACE, 1998) can be used to estimate the goodness of fit between computed results and observed discharge. In the present study, peak weighted root mean square error was chosen as objective function. It can compare all ordinates, squaring differences and it weights the squared differences. The weight assigned to each ordinate was proportional to the magnitude of the ordinate. Ordinates greater than the mean of the observed hydrograph were assigned a weight greater than 1 and those smaller, a weight less than 1. The peak observed ordinate was assigned the maximum weight. The sum of the weighted, squared differences was divided by the number of computed hydrograph ordinates, thus yielding the mean squared error. Root mean squared error was obtained by calculating the square roots for the mean squared error. This function was an implicit measure of comparison of the magnitudes of the peaks, volumes and times of peak of the two hydrographs.

In HEC-HMS, two search methods namely, Univariate gradient algorithm and Nelder and Mead algorithm can be used to minimize the objective function. In the present study, for the optimization of four parameters through calibration, Univariate gradient search algorithm was applied. Calibration was done to identify reasonable parameters that yield the best fit of computed to observed hydrograph, as measured by one of the objective functions. This mathematically corresponded to searching of parameters that minimized the value of the objective function. The search was a trial and error process. The input data to the model included, watershed physical characteristics (area), selected loss method, selected transformation, observed rainfall hyetograph and corresponding hydrograph and control specifications including starting date and time, ending date and time, a time interval, etc. As mentioned earlier, seven sets of observed hyetographs and corresponding flood hydrographs were used for calibration of model parameters *viz.,* initial loss, constant loss rate, Snyder peaking coefficient and standard time lag. First initial estimates within the specified range given in the HEC - HMS user's manual were selected. Then the model was exercised and the error was computed. If the error was found to be unacceptable, then the program changed the trial parameters and the process was repeated. The decision about the changes was dependent on the Univariate gradient search algorithm. Thus, the model parameters (event wise) were calibrated and the average values were worked out. Later, the model output was validated with other set of flood hydrographs (five in number) of the same watershed. The statistical indices such as average absolute deviation between estimated and computed runoff depth and absolute relative error in estimated peak (Wang *et al.,* 1991) were computed for evaluating the closeness between predicted and observed series of data. A simple linear relationship between predicted and observed peak flow rates was also developed.

RESULTS AND DISCUSSION

The HEC-HMS parameters *viz.,* initial loss, constant loss rate, Snyder peaking coefficient and standard time lag were calibrated with the help of seven sets of observed hyetographs and corresponding hydrographs pertaining to study watershed. The details of the calibrated storms (Table 1) revealed that the depth of rainfall of storm events used for calibration of parameters of HEC-HMS varied from 6.9 to 48.6 mm and the corresponding observed runoff varied from 0.4 to 35 mm. The values of calibrated parameters of the model i.e., initial loss, constant loss rate, Snyder peaking coefficient and standard time lag were in the ranges of 2 - 11 mm, 1.5 - 2.33 mm h^{-1}, 0.96 - 0.98 and 2.5 - 3.5 h, respectively. The average values of calibrated parameters of the model i.e., initial loss, constant loss rate, Snyder peaking coefficient and standard time lag for the watershed were 5.63 mm, 2.05 mm h^{-1}, 0.97 and 2.75 h, respectively.

The performance of the model was tested by comparing the predicted and observed hydrographs for other set of five events using the above average values of calibrated parameters of model. The summary of HEC - HMS predicted depths of runoff peak flow rates in relation to observed data with respect to the five events considered in the study for validation of HEC-HMS was

Table 1. Details of calibrated storms

S. No.	Date	Rainfall (mm)	Runoff (mm)	Storm duration (h)
1	20.08.1993	41.0	24.5	6
2	21.08.1993	16.9	09.7	4
3	22.08.1993	18.0	08.5	4
4	04.09.1993	14.8	04.8	3
5	05.09.1993	6.90	00.4	4
6	07.09.1993	10.6	02.2	4
7	14.09.1993	48.6	35.0	4

Table 2. HEC-HMS predicted depth of runoff and peak flow rates vs. observed data

S. No.	Date of storm event	Depth of runoff (mm)			Peak rate of runoff (cumec)			
		Predicted	Observed	Absolute deviation	Predicted	Observed	Absolute deviation	Absolute relative error in peak
1	25.08.1993	01.03	01.17	0.14	01.7	01.7	0.00	00.0
2	24.06.1994	13.50	11.30	2.20	17.1	19.7	2.60	13.2
3	22.08.1994	40.30	47.82	7.52	47.4	47.3	0.10	00.2
4	16.09.1994	36.19	31.89	4.30	43.7	39.5	4.20	10.6
5	16.08.1995	01.88	02.39	0.51	03.1	02.8	0.30	10.7
	Average	-	-	2.934	-	-	1.44	6.94

furnished in Table 2. The statistical indices such as average absolute deviation and absolute relative error in estimate peak were evaluated for testing the goodness of fit between observed and computed values. The average absolute deviation between predicted and observed depths and peak runoff rates were 2.93 and 1.44 cumec, respectively (Table 2). The average absolute relative error in predicted peak runoff rates was found to be 6.94 %, which indicated that HEC-HMS could generate closely comparable peak flow rates to those of observed hydrographs. The comparison of HEC-HMS predicted and observed hydrographs for two events, for example, one on 25.08.1993 and the other on 24.06.1994 (Figures 2 and 3), apparently revealed that the predicted and observed hydrographs to be in close agreement with each other. Further, the peak flow rates predicted by HEC-HMS were related to the observed peak flow rates (Figure 4) by a simple linear regression equation as given below:

$$y = 1.043\,x - 0.572\ (r^2 = 0.989)$$

Where,

y = Predicted peak runoff rate, $m^3 sec^{-1}$

x = Observed peak runoff rate, $m^3 sec^{-1}$

The high value of correlation coefficient indicated that the estimated peak runoff rates were very close to those of observed hydrographs.

CONCLUSION

The hydrographs and peak runoff rates generated by calibrated HEC-HMS were in close agreement with the observed hydrographs. The results reported in the present study indicated that HEC-HMS with the calibrated parameters can be utilized for regeneration of

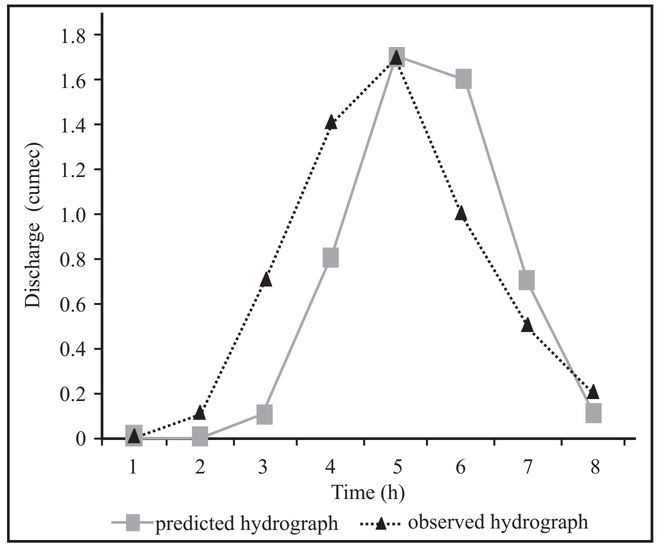

Figure 2. Comparision of HEC-HMS predicted and observed hydrographs (25.08.1993)

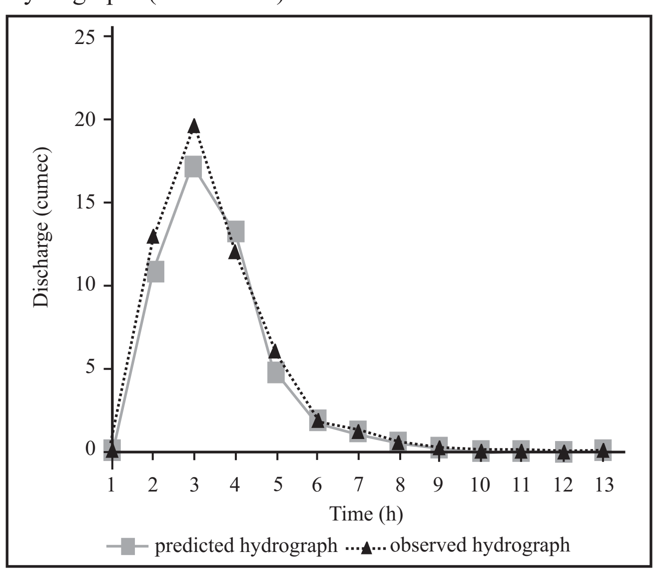

Figure 3. Comparision of HEC-HMS predicted and observed hydrographs (24.06.1994)

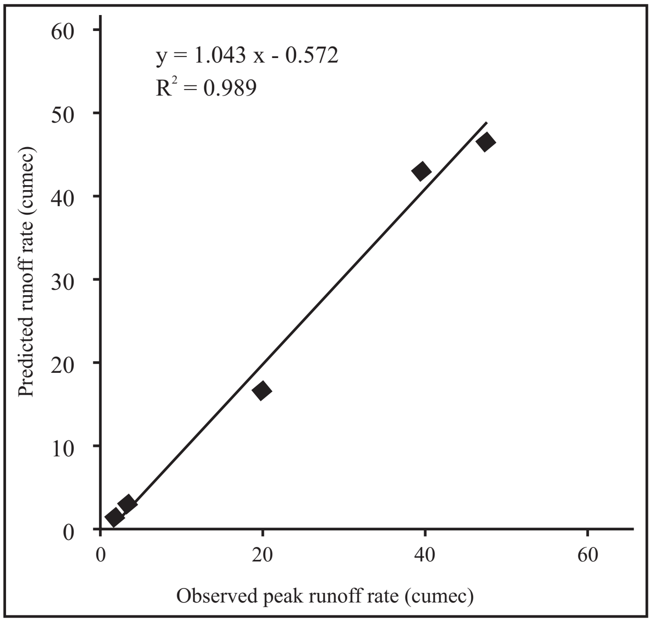

Figure 4. Relationship between predicted and observed peak runoff rates

hydrographs and predicting peak flow rates from Karakara watershed. This model with the calibrated parameters can also be used for regeneration of hydrographs and predicting the depth and peak runoff rates from ungauged watersheds having similar hydrological conditions. The predicted peak runoff rates for the rainfall of desired returned period would be helpful in designing soil and water conservation engineering measures in agricultural watersheds with similar hydrologic conditions.

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