Development of Distribution Hydrograph for Simulation of Design Flood Hydrographs from Bino Watershed

B. L. Sinha, Assistant Professor (Soil and Water Engineering), BRSM College of Agricultural Engineering and Technology & Research Station, Indira Gandhi Krishi Visheda Vidyalay, Chhattisgarh, India
Love Kumar, M.Tech. Students, Indira Gandhi Krishi Visheda Vidyalay, Raipur, India
Lalit Kumar, M.Tech. Students, Indira Gandhi Krishi Visheda Vidyalay, Raipur, India
R. Kanwar, M.Tech. Students, Indira Gandhi Krishi Visheda Vidyalay, Raipur, India

ABSTRACT

A study was carried out to develop a distribution hydrograph for simulation of peak runoff rate and temporal distribution of direct runoff on storm basis for Bino watershed (304.76 km²) of Ramganga River at BRSM College of Agricultural Engineering and Technology, Indira Gandhi Krishi Visheda Vidyalay, Mungeli, Chhattisgarh, India under B. Tech. (Agricultural Engineering) project work in 2013. The distribution hydrograph was calibrated for five storm events and verified for one storm event. The peak runoff rates as well as direct runoff hydrographs computed by distribution hydrograph were in close agreement with the observed direct runoff hydrographs. The relationships of computed and observed peak runoff rates with effective rainfall were also established. The average value of the absolute relative error in estimated peak and coefficient of efficiency of the model was found to be 2.82, and 0.99 per cent, respectively.

Key words:
Distribution hydrograph, Bino watershed, direct runoff

INTRODUCTION

Accurate and easy estimation of runoff from catchments is a primary requirement for water resource planning for controlling the adverse impacts of floods and droughts in an area. The traditional techniques for the design-flood estimation not only require lengthy and reliable rainfall-runoff records, but also a sustainable procedure for updating the model parameters from time to time. Because of the high cost involved in setting up and maintenance of gauging stations, it is not possible to set up and maintain the stations over many locations for a long period of time. Thus, although many large catchments are gauged, a lot of small catchments still remain ungauged. Since long, scientists and engineers have been trying to synthesize stream flow from ungauged catchments. In this direction, the most popular approach has been the use of empirical relationships for determination of the parameters of conceptual models, like the synthetic unit hydrographs. Some relationships have also been developed by researchers for estimation of some of the important characteristics of stream flow hydrographs, such as, lag time, peak discharge, time to peak and hydrograph duration. However, such relationships do not appear to be very accurate, since variations in global atmosphere may bring about changes in the rainfall patterns. Unit hydrograph (UH) was first introduced by Sherman (1932). Mala and Kumar (2008) developed unit hydrograph for estimation of runoff hydrograph for the Kothuwatari watershed by least square method. Rana (2009) analyzed hydrologic data of Gangas sub-catchment of Ramganga reservoir catchment, in Uttarakhand with an area of 506 km² to develop unit hydrographs. Tonde (2011) developed unit hydrograph for simulation of designed flood hydrograph for Bino watershed. A dimensionless unit hydrograph for Bino watershed of Ramganga River was developed to estimate the peak runoff rate and temporal distribution of direct runoff on storm basis by Sinha et al. (2012). The distribution hydrograph based on linear theory represents the percentage of the direct runoff occurring in successive time intervals (Bernard 1935). For development of the distribution hydrograph, a unit hydrograph of the same duration is required (Subramanya 2011). Once as distribution hydrograph has been developed for a basin, it can be used for converting any expected effective rainfall depth into a hydrograph of river discharge. Distribution hydrograph is free from the limitations of size of watershed. The distribution hydrograph becomes more appropriate when the periodic distribution of runoff volume is to be analysed with respect to time, especially peak runoff rate and total runoff volume which are used for design and maintenance of soil conservation, water storage and distribution structures. With this view, the hydrological investigations were carried out in the year 2013 at BRSM College of Agricultural Engineering and Technology, Indira Gandhi Krishi Visheda Vidyalay, Mungeli, Chhattisgarh, India under B. Tech. (Agricultural Engineering) project work to develop distribution hydrograph for Bino watershed (304.76 km²) of Ramganga River catchment treating it as a linear, time invariant fluvial system.
MATERIALS AND METHODS

In the present study, Bino watershed has been taken as the study area for carrying out hydrological and geomorphologic analysis. The Bino watershed is a hilly catchment of the river Bino and is located between 29°47' N and 30°2'15" N latitude and 79°6'15" E and 79°17'15" E longitude in the Ranikhet forest subdivision of Ramganga catchment, Uttarakhand, India. The location of Bino watershed is shown in Fig. 1 (dark boundary line). The Bino watershed comprises of an area of 304.76 km² with its mean length as 30 km and the mean width as 12 km. It has a shallow soil depth and an inadequate vegetal cover with varying surface slopes, ranging from gentle to steep. The watershed is thus susceptible to soil erosion. Most of the area of the watershed is under cultivation even at steep slopes. Forests are confined mostly to hilltops, and grass lands of degraded type are found in patches spread over the entire area. Natural vegetation varies from place to place. Rainfall data of the watershed indicated that about 73.5% of rainfall occurs in the rainy season (June-September).

The hydrological data such as topographic features, land use pattern and stage hydrograph rating curves for the study were obtained from the Department of Soil and Water Conservation Engineering, College of Technology, Govind Vallabh Pant University of Agriculture and Technology, Pantnagar (Uttarakhand) India. Single peaked storm events, which occurred simultaneously at Bino watershed, were considered for the study.

DEVELOPMENT OF DISTRIBUTION HYDROGRAPH (DTH)

The ordinates of unit hydrograph of Bino watershed for all storm events were determined by dividing the direct runoff ordinates by the effective rainfall. The average distribution graph for the watershed was obtained using the following mathematical expression:

\[
D_{ai} = \frac{100}{N} \sum_{j=1}^{N} \sum_{i=0}^{m} \frac{U_{ij}}{ \sum_{i=0}^{m} U_{ij}} \quad \ldots (1)
\]

Where, \(D_{ai}\) = Average distribution hydrograph ordinate (percent)
\(N\) = Number of storm events
\(U_{ij}\) = Unit hydrograph ordinate of event \(j\) at time \(i\)
\(m\) = Time of last observation

The average distribution hydrograph ordinates in percent for Bino watershed were determined by using equation (1) and given in Table-1. The average distribution hydrograph for Bino watershed is shown in Figure-2.

ESTIMATION OF DIRECT RUNOFF HYDROGRAPH

The average distribution hydrograph developed for Bino watershed was utilized for prediction of direct runoff hydrographs for storm events of known effective rainfall. The ordinates of direct runoff hydrographs were estimated by using the relationship:

\[
Q = \frac{A}{2 \times 36} \times D_{ai} \times R_{e} \quad \ldots (2)
\]

Where, \(Q\) = Estimated direct runoff hydrograph ordinate (m³/s⁻¹)
\(A\) = Area of watershed (km²)
\(R_{e}\) = Effective rainfall of particular storm event (cm)

On substitution of the value of area of Bino watershed equal to 304.76 km², the equation (2) becomes:

\[
Q = 4.23 \times D_{ai} \times R_{e} \quad \ldots (3)
\]

RESULTS AND DISCUSSION

To assess the adequacy of distribution hydrograph developed for simulating runoff hydrographs, six storm events of the watershed were selected. The data were divided into two sets: a calibration set, and a prediction set. The data in the calibration set consisted of five events which were used for parameter estimation. The data in the prediction set consisted of one event which was used for model verification to test its validity both qualitatively and quantitatively. The qualitative comparison is based on visual observation and peak reproduction, whereas certain statistical parameters were employed for quantitative comparison of the observed and the computed of direct runoff hydrographs.

1. Qualitative Performance of DTH

Comparisons of regenerated and predicted runoff hydrographs with observed runoff hydrographs

The performance of DTH was tested by comparing regenerated and predicted direct hydrographs with the observed direct runoff hydrographs (Table 1). Comparisons of observed and computed (regenerated and predicted) direct runoff hydrographs for the storm events of July 23-24, 1979 and July 31- August 1, 1980 were shown in Fig. 3 and Fig. 4. The direct runoff hydrographs for the entire storm events were computed by convolving distribution hydrograph developed in this study with effective rainfall of corresponding events. The performance of distribution hydrograph was evaluated on the basis of visual observations of rising, crest and recession segments, time to peak (Table 2) and peak runoff rate (Table 2) of both computed and observed direct runoff hydrographs. Fig. 3 and Fig. 4 clearly depicts that
the base length, time to peak, peak runoff rates and rising, crest and recession segments of the computed direct runoff hydrographs are in close agreement with those of observed direct runoff hydrographs. The slight variations noticed in the computed and observed direct runoff hydrographs should not be attributed to defects of the dimensionless hydrograph model. It may be due to inadequacy of assumptions.

2. Quantitative Performance of DTH

Absolute Relative Error in Estimated Peak
Wang et al. (1991) suggested evaluating the difference between the observed and estimated peak discharges. The absolute relative error in estimated peak in percent was calculated by the following equation:

$$E_p = \frac{|Q_{op} - Q_{cp}|}{Q_{op}} \times 100$$  

In which, $E_p$ is the absolute relative error in estimated peak, $Q_{op}$ is the observed peak runoff rate and $Q_{cp}$ is the computed peak runoff rate. The absolute relative error in estimated peak is a measure of goodness of fit between the peak runoff rates of the observed and computed runoff hydrographs. The values of $E_p$ varied from 0.12 percent to 10.82 percent and the average value was found to be 1.65 percent (Table 2). The low values of $E_p$ indicate that the peak runoff rates estimated by DTH almost coincide with the peak runoff rates of the observed runoff hydrographs.

Coefficient of Efficiency
The term coefficient of efficiency was introduced by Nash and Sutcliffe (1970) to describe the degree of association between observed and estimated flows. The coefficient of efficiency measures directly the ability of the model to reproduce the recorded flows (Chiew et al., 1993). The coefficient of efficiency of the model developed in the study was determined by the following equation:

$$E = 1 - \frac{\sum_{t=1}^{k} [Q_o(t) - Q_c(t)]^2}{\sum_{t=1}^{k} [Q_o(t) - Q_{om}(t)]^2}$$  

Where $E$ is the coefficient of efficiency of the model and $Q_{om}(t)$ is the mean of observed runoff ordinates. The coefficient of efficiency measures the regeneration and prediction performance of the DUH, and if $E = 1.0$, all simulated flows are the same as the recorded flows. Table 4.3 gives the values of coefficient of efficiency for the calibration and verification events. The maximum value of coefficient of efficiency the storm is event 0.99 of for 24-25 July, 1979 and the minimum value is 0.98 for the storm event of 30 July-1 Aug., 1980. The average value of coefficient of efficiency was found to be 0.9904. Chew et al. (1993) classified flow estimates as perfectly acceptable simulation resulting in coefficient of efficiency greater than 0.9 (with mean simulated flow always within 10% of mean recorded flow). The estimation of runoff hydrographs by the DTH is under the category of perfectly acceptable simulation because the minimum value of coefficient of efficiency of the DTH is 0.98.

Relationships of Observed and Computed Runoff Rates with Effective Rainfall

The mathematical relationships of computed and observed peak runoff rate with effective rainfall obtained from regression analysis were expressed by the following equation:

$$Q_{op} = 167.5 \text{ (Re)}^{0.92} \quad \ldots (6)$$
$$Q_{cp} = 178.6 \text{ (Re)}^{0.99} \quad \ldots (7)$$

Where, $Q_{op}$ is the observed peak runoff rate in m$^3$s$^{-1}$, $Q_{cp}$ is the computed peak runoff rate in m$^3$s$^{-1}$ and $R_e$ is the effective rainfall in cm. Fig. 5 shows plot of peak runoff rates with effective rainfall in log-log paper. The slopes of regression lines are almost equal to one for both the relationships shown in Fig. 5 and 6 which indicate that the computed and observed peak runoff rates are highly correlated with effective rainfall.

CONCLUSION

Based on this study, it can be concluded that the peak runoff rates and runoff hydrographs computed by distribution hydrograph compared satisfactorily with the observed direct runoff hydrographs of Bino watershed. The distribution hydrograph is also good for simulation of flood hydrographs for a particular watershed and accordingly adoption of water harvesting structure, regulation of soil and water erosion, watershed development programme, development of water resources for agricultural and other uses can be planned in a very efficient and effective way and support their adaptability to real time forecasting.

REFERENCES


![Fig 1: Location of Bino watershed in Ramganga reservoir catchment](image1.png)

![Fig. 2: Distribution hydrograph for Bino watershed](image2.png)
Fig. 3: Comparison of observed and regenerated direct runoff hydrographs for the storm event of July 23-24, 1979.

Fig. 4: Comparison of observed and predicted direct runoff hydrographs for the storm event of July 31- August 1, 1980.

Fig. 5: Relationship of observed peak runoff rates with effective rainfall.
Fig. 6: Relationship of computed peak runoff rates with effective rainfall

Table 1: Ordinates of dimensionless unit hydrograph and computed and observed runoff hydrograph for calibration and verification events

<table>
<thead>
<tr>
<th>Date of storm</th>
<th>Effective rainfall (cm)</th>
<th>( Q_{OP} ) (m³/s)</th>
<th>( Q_{CP} ) (m³/s)</th>
<th>EP (%)</th>
<th>E</th>
<th>Time to peak (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 27, 1973</td>
<td>0.344</td>
<td>62.00</td>
<td>61.50</td>
<td>0.8442</td>
<td>0.9923</td>
<td>6.0</td>
</tr>
<tr>
<td>July 26-27, 1973</td>
<td>0.384</td>
<td>68.50</td>
<td>68.60</td>
<td>0.1296</td>
<td>0.9871</td>
<td>6.0</td>
</tr>
<tr>
<td>June 24-25, 1979</td>
<td>0.438</td>
<td>80.00</td>
<td>78.30</td>
<td>2.1292</td>
<td>0.9944</td>
<td>6.0</td>
</tr>
<tr>
<td>July 23-24, 1979</td>
<td>0.843</td>
<td>147.00</td>
<td>150.70</td>
<td>2.5063</td>
<td>0.9943</td>
<td>6.0</td>
</tr>
<tr>
<td>Aug. 28-29, 1980</td>
<td>0.398</td>
<td>71.50</td>
<td>71.10</td>
<td>0.5296</td>
<td>0.9888</td>
<td>6.0</td>
</tr>
<tr>
<td>July 31 - Aug. 1, 1980</td>
<td>1.259</td>
<td>203.00</td>
<td>225.00</td>
<td>10.8232</td>
<td>0.9855</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*UHO - Unit hydrograph ordinates  **DTHO - Distribution unit hydrograph ordinates

Q_{OP} - Observed peak runoff rate,  \( Q_{CP} \) - Computed peak runoff rate
EP - Absolute relative error in estimated peak, RSE - Relative squared error, E - Coefficient of efficiency
\( T_{OP} \) - Time to peak (observed),  \( T_{CP} \) - Time to peak (Computed)