EVENT BASED DISTRIBUTED RAINFALL-RUNOFF MODEL

INTRODUCTION

Rainfall-runoff modelling plays an important role in many hydrological studies. There are scores of types of mathematical models available for this purpose. Black box models to completely physically based models cover the range of deterministic type of models. Black-box models are usually emperical and do not consider the nature of the hydrological system. On the other hand, physically based model structures require extensive database and good computational facilities for their calibration. However, for the Indian conditions at present, the scope of applications of the physically based models is somewhat limited. In between the two types are the conceptual models and are best suited for the task and may provide solutions for a number of hydrological problems with the desired accuracy. There are many conceptual mathematical models available, all of which have there own characteristics. The models can also be classified as the event based type and the continuous simulation type of models.

The continuous models are developed based on the continuous hydrological water balance at each time step for a longer period of time and are used for extending the runoff records, water availability studies, reservoir inflow forecasting, study of the effects of land use changes on the hydrological regimes, consumptive use of surface and ground water and water quality modelling studies etc.. The event based models, as the name suggests simulate discrete flood events and can be applied for filling the short-term gaps in the runoff records, the real time flood forecasting, design flood estimation and estimating the flood hydrographs for ungauged catchments etc..

Generally, the event based models consider uniform rainfall throughout the catchment area and thus are not able to include the spatial variability of rainfall which is normally present in medium sized or bigger catchments. Event based model such as Clark Model (Clark, 1945), Laurenson Model (Laurenson, 1964) fall in this category. The distributed modelling approach is better suited for this purpose and also for reflecting the combined effects of translation and attenuation. Based on this approach, Mein et al (1974), Boyd et al (1979) and others developed distributed models which consider the rainfall excess direct runoff processes occurring within the boundaries of the catchment divided into sub-catchments.

An event based distributed rainfall-runoff model has been presented here which takes into account the spatial variability in the rainfall over the catchment. The structure of the model is very simple, wherein the whole catchment is divided into a number of isochronal zones. The average rainfall excess over each such zone is suitably translated to the outlet using linear channel concept and the resulting flow is then routed through a single linear reservoir (SLR). The model consists of two parameters viz. the time of concentration and the storage coefficient of the SLR. These parameters are calibrated using trial and error method together with Rosenbrock optimisation technique. The application of the model is shown by calibrating and validating it for Kolar subbasin of river Narmada in Central India. This validated model may be used for the simulation of flood events or estimation of design flood for this subbasin.

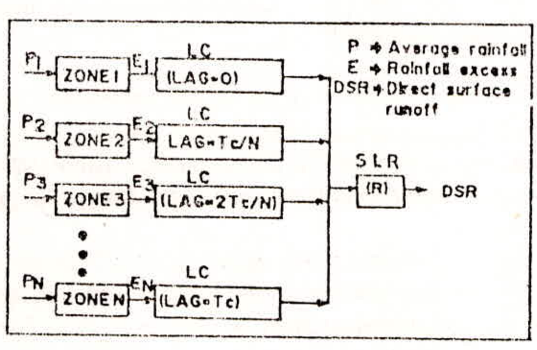

FIG. 1 SCHEMATIC REPRESENTATION OF THE MODEL

MODEL STRUCTURE

The schematic representation of this model considering the catchment to be divided into various isochronal zones is given in Fig. 1. An isochronal zone, here, means that the contribution from this zone reaches outlet within certain lower and upper limits of time. These time limits corresponds to the values of the two isochrones bounding that zone.

The average rainfall over each isochronal zone is estimated by Thiessen polygon method considering all the rainfall stations for each time step. A uniform loss rate (ϕ-index) or SCS curve number method is applied on this average rainfall to result in the rainfall excess. For the calibration period, the value of ϕ-index may be so adjusted as to give the total rainfall excess equal to the observed direct surface runoff.

A map is prepared showing demarcations of zones which are considered to contribute to the outlet at within a certain time interval. Preparation of this time-area diagram is done by assuming that the time of travel between any two points is proportional to the distance and inversely proportional to the square root of the slope between them. Starting from the basin outlet the time of travel for various points over the catchment is thus progressively calculated in terms of the proportionality constant. All the values of the time of travels for different points are then denoted on the map at their respective locations. Curves of specified time of concentration called the "Isochrones" are then drawn through these points by linear interpolation and considering the stream layout. The non-dimensional curve between percent cumulative isochronal area and the percent time of travel is plotted. The time of concentration (T_c), denoting the upper time limit of the farthest isochronal zone is one of the parameters of the model.

The rainfall excess from each of the isochronal zone is suitably lagged and translated to the oultlet. At the outlet the accummulated flow is routed through a single linear reservoir having storage coefficient (R) which is the second parameter of the model.

These parameters, Tc and R, have to be established from the historical records of different events before the model may be used to simulate the catchment's response to a given rainfall excess. The value of R is obtained by Rosenbrock optimization technique for different trial values of T_c. The set of values of R and T_c which gives maximum efficiency is selected for that particular event. Similar sets of values of R and T_c are obtained for each event. An average value of Tc and R may be obtained by averaging the individual values derived from the historical records of different flood events keeping the ratio $\{R/(T_c+R)\}$ as constant.

This final set of values of parameters T_c and R is then used for the simulation of other events to validate the model. In case the validation is found satisfactory then these parameters may be recommended for use for transforming rainfall excess into runoff.

METHODOLOGY

Model Calibration

The steps involved in the model calibration from historical rainfall-runoff records are as follows:

(a) Compute the direct surface runoff after separating the baseflow from observed discharge hydrograph using straight line technique for base flow separation.

(b) Assuming that the travel time between two points in the catchment is proportional to distance and inversely proportional to the square root of the difference in elevation between them the isochronal map is prepared. The time contours are in the terms of the proportionality constant.

(c) If A_t is the area contributing to the flow at the outlet within time t and A the total area of the catchment then plot the percent cumulative area of consecutive isochronal zone ($100A_t/A$) against percent time of travel ($100t/T_c$).

(d) Compute the average rainfall for each time step for every isochronal area based on the Thiessen polygon method.

(e) Compute the average rainfall for each time step for cumulative areas based on the averages obtained in step (d) for individual areas.

(f) Plot the average rainfall obtained for cumulative area against the percent cumulative area.

(g) For the trial value of time of concentration find out the number of isochrones by dividing it by the time interval. Then for each zone enclosed between two consecutive isochrones, estimate: (i) the area enclosed using the plot developed at step(c) and (ii) the average hourly rainfall using the plot developed at step (f)

(h) Compute the rainfall excess hyetograph for each isochronal zone using an uniform loss rate or SCS curve number procedure to the average hourly rainfall values obtained from step (f).

The uniform loss rate (ϕ-index) is found by trial and error method. The total excess rainfall volume at the catchment outlet is obtained by adding the rainfall excess volume contributed by different isochronal zones. The required uniform loss rate is the one which makes total excess rainfall volume equal to the volume of direct surface runoff hydrograph.

(i) Compute the simulated direct surface runoff hydrograph by routing the total excess rainfall hyetograph obtained at step (h) through a single linear reservoir with storage coefficient (R).

(j) Evaluate the objective function, F, as:

$$F = \sum_{1}^{n} (y_i - \hat{y}_i)^2 \qquad (1)$$

Where y_i is the i^{th} ordinate of observed direct surface runoff and $\hat{y}_i$ is the i^{th} ordinate of simulated direct surface runoff at step (i) and n is the total number of ordinates. F is also a measure of model variance.

(k) Minimise the objective function F using Rosenbrock optimisation technique (Rosenbrock, 1960) for estimating an optimum value of the storage coefficient (R).

(l) Select another trial value of time of concentration (T_c) and repeat step (g) to (k) to find out another optimum value of the storage coefficient (R).

(m) Based on the above procedure estimate the optimum values of T_c and R so that the objective function, F is minimum or the efficiency is maximum.

Model Validation

The calibrated model may be used to reproduce the direct surface runoff hydrographs of some of the independent flood event not used for calibration. The reproduction may be judged based on the following error functions.

(a) Percentage Error in Peak :

It is the percentage ratio of the absolute difference between observed and computed peak flow and observed peak flow.

(b) Percentage Error in Time to Peak :

It is the percentage ratio of the absolute difference between observed and computed time to peak and observed time to peak.

(c) Average Percentage Absolute Error :

It is defined as the average of absolute value of percentage difference between computed and observed hydrograph ordinates.

(d) Efficiency :

Efficiency of the model in reproducing an event is defined mathematically as:

$$\eta = \frac{F_0 - F}{F_0} \times 100 \qquad (2)$$

where F_0 is the measure of the initial variance, given as:

$$F_0 = \sum_{1}^{n} (y_i - \bar{y}_i)^2 \qquad (3)$$

$\eta \Rightarrow$ the efficiency of the model

$\bar{y} \Rightarrow$ mean of the observed hydrograph ordinates

MODEL APPLICATION

STUDY AREA AND DATA AVAILABILITY

The flood events of the Kolar sub-basin of Narmada river system in Central India are simulated using the proposed model structure. Kolar river originates in the Vindhayachal mountain range at an elevation of 550 m above mean sea level (msl). It is a tributary from northern side of the Narmada river which flows from east to west and drains in the Arabian sea. The catchment area of this sub-basin lies between the latitudes 22° 40′ and 23° 08′ and longitudes 77° 01′ and 77° 29′. The catchment has an elongated shape which is oriented in east-west direction in its upper part and north-south direction in the lower part. The river also, during its 100 km. course, first flows towards east and then towards south before joining the main river Narmada. The Kolar river has an elaborate drainage network which drains a total area of 1350 sq. km.. However, this case study is done only for an area of 875 sq. km. which drains through a gauge-discharge measurement site near Satrana. A map showing the catchment boundary and the locations of various rainfall stations and the stage-discharge gauging site is given in Fig. 2.

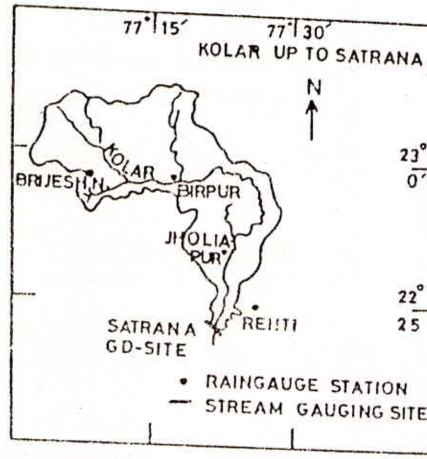

Figure 2. KOLAR BASIN UP TO SATRANA G-D SITE

The map of Kolar sub-basin alongwith the contours and drainage network was prepared using the Survey of India toposheets on 1:50,000 scale. In the present study the rainfall and runoff data for the period 1983 to 1986 has been used. Six storm events have been selected from this data. Hourly rainfall values at four rainfall stations namely Rehti, Jholiapur, Birpur and Brijeshnagar were obtained from the recording type rainfall stations at these places.

ANALYSIS AND DISCUSSION OF RESULTS

The methodology presented above is applied for the six events of dates 28.3.83, 10.8.84, 31.7.85, 13.8.85, 15.8.86 and 27.8.87. These events would be called event no. 1, 2, 3, ...6 respectively, here-in-after in this text.

The volume of the rainfall excess for a given storm event is assumed to be known. It is computed as the volume of direct surface runoff hydrograph for a given event. The direct surface runoff hydrograph is computed by separating the baseflow from the observed hydrograph ordinates using the straight line technique.

The values of the time of travels in terms of proportionality constant for different points are denoted on the map at their respective locations and the isochrones are drawn considering the layout of the streams and linearly interpolating between the values at various points. The non-dimensionalised plot between the cumulative isochronal area and the travel time is shown in Fig. 3.

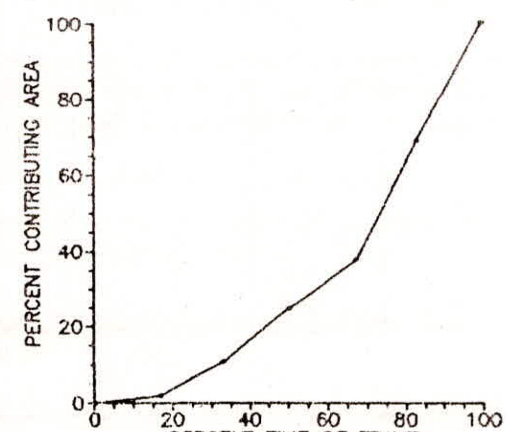

Figure 3: NON-DIMENSIONAL PLOT BETWEEN TIME OF TRAVFI AND CONTRIBUTING ARFA.

Thiessen weights of each rainfall station are found considering the catchment divided into six isochronal zones. These weights are given in Table 1 for different isochronal zones.

Table 1 : Thiessen Weights on the basis of 60 minutes isochrones

Isochronal Zones	Thiessen Weights for Rainfall Station			
	Rehti	Jholiapur	Birpur	Brijeshnagar
I (Nearest to Outlet)	1.00	0.00	0.00	0.00
II	0.22	0.78	0.00	0.00
III	0.00	1.00	0.00	0.00
IV	0.00	0.15	0.85	0.00
V	0.00	0.00	0.65	0.35
VI (Farthest from Outlet)	0.00	0.00	0.25	0.75

From the six events the first four are chosen for calibrating the model parameters. The data of the last two events are used for the validation of the model.

The value of R is obtained by Rosenbrock optimization technique to minimize the objective function computed as the sum of the squares of differences between the observed and the computed hydrograph ordinates for each trial value of T_c. In order to arrive at optimum values of the parameters T_c and R the model is run for a few trials of T_c. The plots of observed and simulated discharge values for the event 1 for various trial values of T_c are given in Fig. 4. Those values of R and T_c are chosen for each of the four events which give the minimum objective function or the maximum efficiency. The set of values of T_c and R which gives the maximum efficiency are given in Table 2. The final calibrated values of R and T_c are 2.48 hours and 6.0 hours respectively.

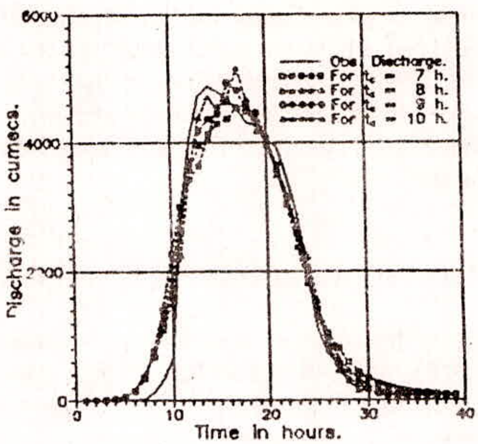

Figure 4: OBSERVED & COMPUTED HYDROGRAPHS FOR EVENT 1.

Table 2 : Set of parameters for maximum efficiency during calibration with events 1,2,3 & 4

Event	T_c	R	% error in peak flow	% error in time to peak	Average % absolute error	Efficiency η
1	9.0	1.45	1.3	15.4	132.7	97.25
2	5.0	2.44	8.6	0.0	65.3	93.33
3	6.0	3.59	35.3	0.0	506.7	70.31
4	3.0	3.13	0.4	20.0	34.1	93.81

While calibrating the model the value of ϕ-index is found by trial and error procedure by equating the excess rainfall to the direct surface runoff volume. The same cannot be done for simulation or validation runs since the direct surface runoff is not known. Therefore, the value of ϕ-index is either chosen based upon the experience and judgement or otherwise the losses are found by some direct method such as SCS curve number method (SCS, 1972).

The validation of the model parameters is done by comparing the simulated runoff with the observed runoff for the later two events, i.e. events 5 and 6. The summary of the results of the validation process is given in Table 3.

Table 3. Summary of results of validation runs for events 5 & 6

Event	T_c	R	% error in peak flow	% error in time to peak	Average % absolute error	Efficiency η
5	6.0	2.48	32.5	21.4	111.0	81.72
6	6.0	2.48	10.3	23.1	48.6	72.70

Base flow is added to the simulated direct surface runoff to obtain the computed total surface runoff. From the data of the six events it could be seen that the base flows are 0.96%, 3.45%, 1.75, 6.08, 5.58 and 4.71% of the peak flow respectively. Hence, 3.75% of the peak of the simulated direct surface flow is taken as the average to be added to the simulated direct surface runoff to get the simulated total runoff. The plots between observed and simulated discharges for these events are given in Fig. 5 & 6.

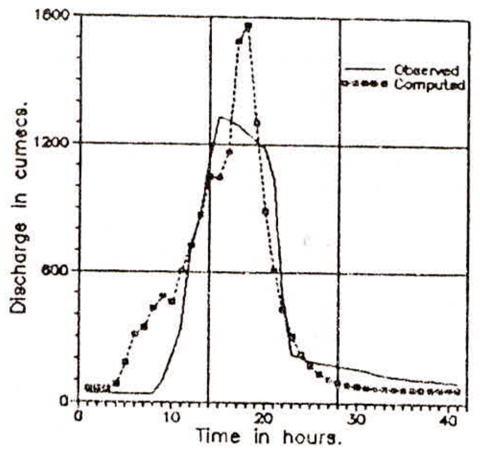

Figure 5: OBSERVED & COMPUTED HYDROGRAPHS FOR EVENT 5.

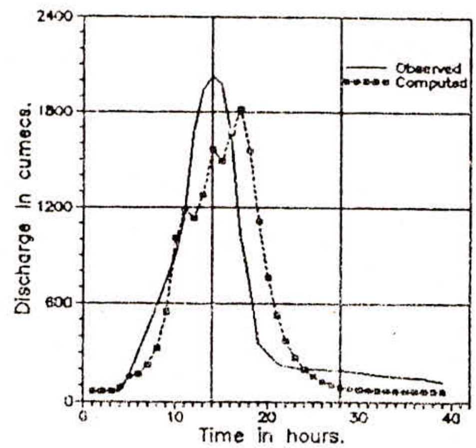

Figure 6: OBSERVED & COMPUTED HYDROGRAPHS FOR EVENT 6.

CONCLUSION

Application of this Event Based Distributed Rainfall-Runoff Model comes as very handy tool for the transformation of rainfall into runoff for discrete events. The data required for this model is not difficult to prepare. Much emphasis is put on the preparation of time-area diagram called the isochronal map in which contours of equal time of travel are plotted over the catchment area. The importance of using the time-area diagram is in having a distribution of the catchment area into isochronal zones of varying magnitudes depending on the topography of the region and the layout of the streams. This is the most important aspect of this model that it takes the topography of the catchment into consideration while simulating the rainfall-runoff process.

The structure of the model is based on the concept of linear channels draining simultaneously from different isochronal areas and lagging differently according to the placement of these areas. This flow at the outlet is then routed through a linear reservoir to get the final response from the catchment. Thus, the model is extremely simple to understand and operate.

Performance of this model for the presented case study is found to be good. This model may very conveniently be put to use while carrying out design flood studies, filling of short term runoff records, reservoir inflow studies, extension of runoff records and real time flow forecasting etc.. It is proposed that more such applications for catchments of different hydro-meteorological regions would give a complete picture of the applicability of the model under such conditions.

REFERENCES

Boyd, M.J., D.H.Pilgrim and I. Cordery, 1979. *A Storage Routing Model Based on Catchment Geomorphology.* J.Hydrology, Vol.42, pp.209-230.

Mein, R.G., E.M.Laurenson, and R.A.McMohan, 1974. *Simple Non-Linear Model for Flood Estimation.* ASCE, HY-11, pp.1507-1518.

Rosenbrock, H.N., 1960. *An Automatic Method for finding the greatest of least value of a function.* Computer Jour. Vol.3.

Singh, V.P., 1988. *Hydrologic Systems Vol.I, Rainfall-Runoff Modelling.* Prentice Hall, Englewood Cliffs, New Jersey.

Soil Conservation Service, *National Engineering Handbook section 4, Hydrology.* US Department of Agriculture, available from US Govt Priding Office, Washington, D C ,1972.

National 'Institute of Hydrology, 1993-94. *Flood Hydrograph Simulation in Kolar Sub-basin Using Event Based Distributed Rainfall-Runoff Model.* CS(AR)-130.

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