FLOOD HYDROGRAPH ESTIMATION USING WATERSHED BOUNDED NETWORK MODEL

D. NAGESH KUMAR[1], K.C. SWAIN[2] and P. ANAND RAJ[3]
Department of Civil Engineering, Indian Institute of Technology,
Kharagpur - 721 302. West Bengal, INDIA.

ABSTRACT

Storage routing models are becoming more widely accepted for flood hydrograph synthesis. The network models represent a considerable advance in this direction even though these models are based on many assumptions and empirical relationships. Watershed Bounded Network Model (WBNM) is one such model. This model maintains a good relationship between the hydrological and geomorphological properties of a watershed and is capable of accurate flood hydrograph synthesis. The model can account for the non-uniform distribution of rainfall over the watershed. Lag is a dominant factor to be known for the successful application of WBNM. In this paper the theoretical basis of WBNM and its application to Pageru watershed in southern India is presented. The watershed contains three well spread rain gauges. Isolated flood events from a four years record were considered for the calibration of the model. Validation of the model revealed that the predicted hydrographs are compared well with observed hydrographs for the given rainfall excess hyetographs. Therefore, with its sound geomorphological basis, Watershed Bounded Network Model has a valid and versatile application over a wide range of conditions.

KEY WORDS

Watershed modelling, flood hydrograph, hydrograph synthesis, network models, flood estimation, Watershed bounded network model.

1. INTRODUCTION

The search for the physically based rainfall-runoff models over the last few decades has resulted in a much better understanding of the hydrological processes today. Though these models have a general physical basis and attempt to reproduce the overall process of transforming rainfall excess into stream flow, it should be kept in mind that they have many simplifying assumptions, empirical relationships and have certain limitations. If the models are not simpler in some sense than the real world processes, they may not be of much use and for this reason certain aspects which are considered unimportant are neglected. The simpler models are therefore more general and involve few parameters and are considered to be superior from the application point of view.

The regression model (Keith et al., 1985) requires rainfall and stream flow records only. The parameters of three separate regressions were estimated using six summary variables. Output of the model does not provide a full hydrograph but a simpler triangular representation can be produced. Unit Hydrograph Model (UHM) (Keith et. al., 1985), on the other hand, is a predictive model. The ordinates of UH are derived with the help of the coefficients of a set of linear equations using unity constrained least square matrix approach. In the quasi-physically based model, the hydrologic response of the catchment is described by coupled partial differential equations (i.e., physical basis) and uses analytical solutions of these equations (i.e., quasi) as operating algorithm rather than a direct numerical solutions for some of the components.

Digital Evaluation Models (DEM) (Garg, 1995) assess the runoff within and at the mouth of the watershed. DEM takes slope and catchment areas computed from topographical maps which were subsequently used to generate the flow direction, flow pattern and drainage network. This information along with infiltration and rainfall data were used for rainfall-runoff modelling employing Horton's equation. Allen et al. (1994) used Artificial Neural Networks (ANN) for rainfall-runoff modelling and it has the same structure as that of unit hydrograph model. The advantages of ANN based models is their ability to learn non-linear situations and alleviate some of the problems of other methods because they provide a method which includes a fitting, or a training scheme as a fundamental part of the model. Water tank model (Muzumura, 1995) is computationally simple and the associated parameter values are physically based. The results of the tank model were in good agreement with the observed data and the model may be used for runoff prediction. Modified Bartlett - Lewis Rectangular Pulse Model is a six parameter stochastic point process model and was applied to fairly long hourly rainfall data by Khaliq and Cunnane (1995). Statistics of rainfall data of each month are used to estimate the parameters and to simulate the model output. Results compare favourably with the historic data. A search for physically based runoff models using recession curves was presented by Woolhiser (1996).

Storage routing models are increasingly becoming more acceptable for flood hydrograph synthesis. The network model represents a considerable advance in flood estimation methods, particularly for situations where the flood hydrograph is required. In the following section the theoritical basis for the Watershed Bounded Network Model (WBNM) (Boyed et al., 1979) is presented. In section 3, the application of WBNM to model rainfall-runoff process of a catchment in southern India is presented. Section 4 contains results and discussions followed by conclusions in section 5.

2. WATERSHED BOUNDED NETWORK MODEL

WBNM is a development over Monash (1977) model and is based on a detailed consideration of geomorphological properties of the catchment. The aim of the model is to realistically represent the detailed catchment structure and the flow within the watershed. Lag is a dominant factor in the model and can be applied to any range of watershed areas. Advantage of this model over the others is that it requires less number of parameters to be known. It can handle even the spatially varying rainfall excess and hence the model has more practical importance.

Geomorphology and hydrology of a watershed are so intensely related that the catchment transforms rainfall excess (i.e., input) into a runoff hydrograph (i.e., output), while the catchment itself gets modified by rainfall - induced erosion so as to approach a steady state. Therefore, geomorphological relationships together with hydrological data were utilized to define the model structure. This enables the direct evaluation of several model parameters. Parameters to be evaluated by optimization, are very small in number. This avoids the problems of parameter inter dependence. In this paper the basic structure of the model and the general form of the relationships were formulated using linear form, but can be extended to non-linear version which is more versatile for practical applications.

2.1 Model Structure

The watershed is divided into two types of storage elements (sub-areas) depending on how storage and runoff are created. These storage elements are ordered basin and inter basin areas. Ordered basins are geomorphologically similar to an independent sub catchments where there is no flow across the boundaries of the catchment. The rainfall excess within these sub basins is transformed into direct runoff at the outlet. Inter basin areas consists of a main stream segment flowing from upstream sub areas (can be either ordered or inter basin areas) and overland flow. Over land flow eventually joins main stream through the tributary channels. Therefore, outflow from the inter basins consists of upstream inflow routed through the main stream coming from the upper reaches and runoff resulting from the rainfall excess which is routed through overland and tributary channels within it. Number of sub areas selected for the application of the model to a given catchment is subjective. But studies revealed that the fineness of sub division was not critical provided, the number of sub areas exceed some minimum value. Five sub divisions for a catchment area of 20 sq. km., and upto ten sub divisions for catchments exceeding 50 sq. km. was recommended.

2.2 Storage Properties

Each sub area of the catchment is represented by concentrated storage. These storages are linked in the same network topology as the streams in the catchment. Storage effects within the catchment are essentially non-linear. But to this day little firm evidence is available on the true form of non-linearity. The relationships in use were partially empirical and their use for discharges beyond observed range incorporates errors. Studies by Pilgrim (1976, 1977) indicate that linear behaviour may be approximated at very high flows.

For both ordered and inter basins, storage relationships transform the rainfall excess into direct runoff at the down stream end. In addition to this, for inter basins, a separate storage relationship routes the upstream inflow hydrograph into down stream outflow hydrograph. These components are added to get the outflow hydrograph for the inter basins.

Each of the storages in the storage routing model is characterized by a time or storage delay (lag) parameter. Lag is the most useful time measure, defined here as the time between the centroids of the rainfall excess hyetograph and the resulting direct runoff hydrograph. It can be readily measured for each of the recorded rainfall - runoff event and represent an average travel time of surface runoff from all points to the outlet of the catchment. Since catchments display non-linear storage effects, the variation of lag with magnitude of flood can be approximated as

(1)

where q is the instantaneous discharge and α & β are the constants. It is found that the coefficient differs by less than 3% for β ranging from 0 to -0.25 but diverge rapidly as β becomes more negative and the coefficient approaches infinity as β approaches -0.5.

There is also strong correlation between stream length and the area of the catchment. A measure of one of these variables will thus contain much of the geomorphological information and one of these variables may be selected as the basis for developing a relationship with lag. In WBNM area, A, was selected as it is already required for calculating runoff and the need for determining the stream lengths is eliminated.

Two independent relationships between lag and area of the sub basins are to be established for application of WBNM. First relationship is the one that transforms rainfall excess into direct runoff for both ordered and inter basins. This relationship is expressed as a linear storage equation with delay time K_B. The second relationship is for routing upstream runoff through main stream segment within the inter basin. This relationship is similar to the one above with delay time K_I. The values of both K_B and K_I are dependent on main stream length. However, channel flow velocities and flood flow velocities tend to increase slightly in the down stream direction and thus these velocities in the main stream are higher than in tributaries. Thus the value of K_I for a given sub area would be expected to be less than K_B. Even though K_I is more closely related to stream length, for consistency, drainage area (A) was used as the geomorphological variable to route the upstream runoff. The ratio of K_I to K_B was found to be equal to 0.6 and the same is adopted in this study. Logerithemic relationships were used in WBNM for both K_B and K_I in the following form.

$$K_B \ or \ K_I \cdot \ \tilde{a}A^{\delta} \qquad \textbf{(2)}$$

For non-linear models K_B and K_I were related to both catchment area and the instantaneous discharge (Askew, 1970) as shown in the following equation.

$$K_B \cdot \ \mu A^{\zeta} q^{\eta} \quad and \quad K_I \cdot \ 0.6\mu A^{\zeta} q^{\eta} \qquad \textbf{(3)}$$

Where μ, z and η are the constants and the units of K, A and q are hours, sq. km. and m^3/sec. respectively.

For studying the applicability of WBNM, the following two points are to be noted. The first point is to evaluate the parameters of the model by establishing the correct relationship between hydrological and geomorphological variables. The second is to establish the validity by comparing the hydrograph predicted from the model with the observed historic data. Therefore, correct modelling of geomorphological and hydrological relationships should enable valid application of the model for rainfall-runoff modelling with suitable parameter values over a wide range of conditions.

3. APPLICATION

WBNM developed in section 2 is applied to Pageru river basin. This river basin is located in Andhra Pradesh state of Southern India. The catchment area of the basin is about 400 sq. km. upto a railway bridge where the runoff data is regularly monitored. There are three rain gauge stations within the basin: one at Indukuru, one at Uppaleru and the other at the mouth of the basin (i.e., at the bridge site). Rainfall data at these rain gauge stations are recorded at hourly intervals while runoff data is collected at two hourly interval. This data is collected by Flood Division of South Central Railway.

The catchment is sub divided into a number of sub-areas of approximately of equal size using watershed lines to establish the boundaries of the sub-areas. Each sub-area is represented by a single non-linear concentrated storage element. In our study the catchment is subdivided into 14 sub-areas. Out of these sub-areas seven are ordered basins and the rest are inter basins. These are connected in a branched network model structure, having the same pattern as that of the stream network in the basin. The catchment sub-areas (and corresponding model storage elements) are numbered consecutively, beginning with the uppermost (N = 1) and progressing down stream through the model. The sub-area at the catchment outlet has the highest number, equal to the total number of the catchment sub-areas. Routing follows this numbering system, i.e., progressing from upper most to the lower most storage element. Pageru river basin, watershed bounded sub-areas and their numbering, location of the gauging stations and a schematic representation of the network of the storage elements is shown in figure 1. Table I gives the details of the sub-basin areas for both spatially uniform and non-uniform rainfall cases.

A computer program was developed for the WBNM for the Pageru river basin which can handle both uniform and non-uniform rainfall data (upto 5 hyetographs). Both K_B and K_I are taken as functions of A and q. The program also calculates Theissen weights for each sub-area for the estimation of total rainfall. Loss rate is estimated using φ-index. If required, the loss rate assumption used in this program can be modified by the user to suit to his requirements. Additional program segments can also be added to calculate the depth of rainfall excess associated with a given loss rate. A code (NCODE) to distinguish between ordered (NCODE = 1) and inter basins (NCODE = 0) was used. For branching from one segment to the other another to arrive at the runoff from various storage elements, a code NOBRCH was used.

4. RESULTS AND DISCUSSIONS

Four years of data was collected for this study from August 1993. Eight storm events were considered from the data and the parameters of the model were calculated and the following relationships were established.

$$K_I = 1.01A^{0.57}q^{-0.23} \tag{5}$$

$$K_B = 1.68A^{0.57}q^{-0.23} \tag{4}$$

The optimum value of μ was calculated to be 1.68. The exponents of A (i.e., ζ) was found to be 0.57 and the exponent of q (i.e., η) was equal to -0.23. The travel time was found to be 5.86 hours. ϕ-index value is subtracted from rainfall values before feeding rainfall data into the program. A routing period of 1 hour is used in the study. The degree of non-linearity may be varied by adjusting the exponent (η) of q. For example, η = 0 results in a linear model. The allocation of storages to sub-areas may be varied by adjusting the exponent (ζ) of A. Having obtained the equations for KB and KI in the form of equations (4) and (5), stream routing was done with the help of the following lumped continuity and storage equations.

$$S = Kq \tag{6}$$

$$\frac{dS}{dT} = (i - q) \tag{7}$$

Combining equations (6) and (7), the following numerical solution is obtained.

$$q_2 = \frac{(i_1 + i_2)dt + q_1(2K_1 - dt)}{(2K_2 + dt)} \tag{8}$$

Where i_1 = inflow hydrograph value at the start of the routing period in m^3/sec.;

i_2 = inflow hydrograph value at the end of the routing period m^3/sec.;

q_1 = outflow hydrograph value at the start of the routing period m^3/sec.;

q_2 = outflow hydrograph value at the end of the routing period m^3/sec.;

K_1 = value of the lag parameter at the start of the routing period in hours;

K_2 = value of the lag parameter at the end of the routing period in hours and

dt = routing period in hours.

After calibration of the model validation was done and the results for a storm event occurred on 18 th. August, 1995 for both uniform and non-uniform rainfall and are presented in table II. Rainfall excess hyetographs and the corresponding observed and expected hydrographs for both uniform and non-uniform rainfall were presented in figures (2) and (3) respectively. It can be seen that the model predicted hydrograph very well fits the observed hydrograph. The peak flow error is well within 5% of the observed peak and the time to peak is same for both predicted and observed hydrographs. This means that the model parameters and the relationships established between geomorphological and hydrological variables are reasonably able to establish the rainfall-runoff process in the Pageru river basin and this WBNM can be extended to other basin studies where rainfall-runoff modelling is required with appropriate parameters.

5. CONCLUSIONS

WBNM is based on the detailed considerations of geomorphological and hydrological properties of a catchment and contains two types of storage elements representing ordered basin and inter basin areas. Application of this model is easier than other network models. WBNM for Pageru river basin in southern India was developed and applied for both uniform and varying rainfall events including non-linear effects on storage. Application of the model has shown that it maintains correct relationships between hydrological and geomorphological properties and that it is capable of synthesising hydrographs with reasonable accuracy. Therefore, with it's sound geomorphological basis, the model should have valid and versatile application over a wider range of conditions.

REFERENCES

Askew, A. J. (1970), "Derivation of Formulae for Variable Lag Time", *Journal of Hydrology*, Vol. 10, pp 225 - 242.

Allen, T., Hjelemfelt and Managua Wang (1995), "Predicting runoff using Artificial Neural Networks", *Proceedings of the International Conference on Hydrology and Water Resources*, Vol. 1, pp 233 - 244.

Boyed, M. J., D. H. Pilgrim and I. Corder (1979), "A Watershed Bounded Network Model for Flood Estimation", *Report No. 154*, University of New South Wales, pp 1 - 34.

Woolhiser, D. A. (1996), "Search for Physically Based Runoff Model using Recession Curves", *Journal of Hydraulic Engineering*, Vol. 121, No. 3, pp 122 - 128.

Garg, P. K. (1995), "Use of Digital Evaluation Model in Runoff Modelling", *Proceedings of the International Conference on Hydrology and Water Resources*, Vol. 1, pp 245 - 256.

Khaliq, M. N., C. Cunnane (1996), "Modelling Point Rainfall Occurrences with the Modified Bartlett - Lewis Rectangular Pulse Model", *Journal of Hydrology*, Vol. 180, pp 109 - 138.

Muzumura, K. (1995), "Runoff Prediction by Simple Tank Model using Recession Curves", *Journal of Hydraulic Engineering*, Vol. 121, No. 11, pp 812 - 818.

Monash (1977), "Australian Rainfall and Runoff", *Journal of Institution of Engineers (Australia)*.

Pilgrim, D. H. (1976), "Travel Times and Non-linearity of Flood Runoff from Tracer Measurements on a Small watershed", *Water Resources Research*, Vol. 12, pp 487 - 496.

Pilgrim, D. H. (1977), "Isochrones of Travel Time and Distribution of Flood Storage from a Tracer Study on a Small Watershed", *Water Resources Research*, Vol. 13, pp 587 - 595.

Table I: Details of sub basin areas for both specially uniform and varying rainfall

Spatially Uniform Rainfall			Spacially Varying Rainfall		
Sub-area No.	Area (ha.)	NCODE	Sub-area No.	Ares (ha.)	NCODE
1.00	2739.21	1.00	1.00	2739.21	1.00
2.00	13578.22	0.00	2.00	2077.80	0.00
3.00	3060.40	1.00	3.00	2216.62	0.00
4.00	3622.00	1.00	4.00	2819.84	0.00
5.00	3463.90	1.00	5.00	2016.76	0.00
6.00	8560.00	0.00	6.00	1778.80	0.00
7.00	2900.00	1.00	7.00	1334.20	0.00
8.00	1936.00	1.00	8.00	1334.20	0.00
			9.00	3060.40	1.00
			10.00	3622.00	1.00
			11.00	3463.90	1.00
			12.00	8560.00	0.00
			13.00	2900.00	1.00
			14.00	1936.00	1.00

Table II: Ordinates of the observed and predicted hydrographs with the corresponding hyetographs

Time (hours)	Specially uniform rainfall			Spacially varying rainfall				
	Ordinates of Hyetograph (mm)	Ordinates of Hydrograph (cum.)		Ordinates of Hyetographs (mm)			Ordinates of Hydrograph (cum.)	
		Observed	Predicted	Uppaleru	Indukuru	Bridge site	Observed	Predicted
1	0.00		0.01	0.00	0.00	0.00		2.37
2	22.00		3.64	0.00	3.00	20.00		3.98
3	103.00		26.72	60.00	25.00	18.50		5.87
4	125.00		59.75	72.00	42.00	10.20		37.87
5	71.00		68.96	4.00	64.00	6.10		65.98
6	19.00		79.64	5.00	7.00	8.00		79.55
7	10.00	88.57	92.74	3.00	6.00	0.00	88.57	93.76
8	5.00		156.92	1.00	2.00	3.00		246.69
9	1.00	443.96	389.74	0.00	1.00	0.00	443.46	457.48
10	0.00		407.25	0.00	0.00	0.00		375.77
11	0.00	341.40	357.37	0.00	0.00	0.00	341.40	342.65
12	0.00		241.44	0.00	0.00	0.00		231.63
13	0.00	196.65	201.75	0.00	0.00	0.00	196.65	214.38
14	0.00		173.83	0.00	0.00	0.00		189.76
15	0.00	118.63	137.65	0.00	0.00	0.00	118.63	130.84
16	3.00		108.94	0.00	0.00	3.20		114.75
17	25.00	65.61	83.74	6.00	0.00	18.20	65.64	91.75
18	0.00		62.37	0.00	0.00	0.20		112.65
19	0.00		43.79	0.00	0.00	0.00		118.75
20	0.00		28.48	0.00	0.00	0.00		123.76
21	0.00		13.47	0.00	0.00	0.00		76.96
22	0.00		7.37	0.00	0.00	0.00		64.95