International Seminar on Hydrology of Extremes

1-3 December, 1988
Roorkee (India)

REAL-TIME FLOOD FORECASTING USING HYDROMETEOROLOGICAL MODEL

Saleh A. Wasimi

Institute of Flood Control and Drainage Research,
Bangladesh University of Engineering & Technology,
Dhaka, Bangladesh

SYNOPSIS

A conceptual hydrometeorological model suitable for use in real-time flood and flash flood forecasting has been developed. The model has three basic components: the rainfall forecasting model, the rainfall-runoff model, and the flood routing model. The rainfall forecasting model uses meteorological variables (temperature, atmospheric pressure, and humidity) and their seasonal characteristics to produce rainfall volume rate in a watershed. In the next step soil moisture accounting is done by a lumped conceptual model which is followed by channel routing by a hydrodynamic model of unsteady flow. The integrated model can be operated in a micro-computer at site and has been tested in the real-world situation in Bangladesh.

INTRODUCTION

By flood forecasting, it is meant the estimation of the degree of inundation or water level rise that is expected in the next few hours or even days. It is differentiated from flood prediction which is concerned with the estimation of probability of floods in greater time spans.

The purpose of flood forecasting is primarily to warn people against the impending danger. Our present knowledge about the mechanism of flood occurrence and propagation does not permit us to learn the precise nature of coming floods very far ahead in time. Thus, flood forecasting is of little use in planning agricultural activities, nor can it help in saving crop lands, houses, roads, farms, and towns from inundation. But, given sufficient lead time, it can be used to evacuate people and moveables, plan timely succour, and hedge against some of the calamities in the wake, like epidemic diseases. These emergency measures are very costly and would result in great financial loss if flood forecasting is inaccurate. Therefore, precision and long lead time are two of the vital considerations in any flood forecasting scheme.

Generally, a flood forecasting scheme has two basic components, namely, a routing model and a rainfall-runoff model. The routing model delineates a flood wave down a water course from known values at an upstream point and the rainfall-runoff model estimates the fraction of rainfall that finds its way directly into channels. On small catchments, the two basic component models together do not provide enough lead time for evacuation and other emergency measures. So, for floods in small catchments, known as flash floods, a third component, a rainfall forecasting model has been added in some very recent forecasting schemes.

The science of flood routing is very well developed. In other words, if we have a gage at an upstream point in a river, we can fairly accurately predict the water levels at downstream locations. By contrast, rainfall-runoff models are less accurate. The physics of the rainfall-runoff relationship is mostly known, but the complex characteristics of a basin imposes boundary restrictions on the use of analytic models; instead conceptual models have been developed. The rainfall forecasting models are even less accurate. The complexity and variability of meteorological factors have always thwarted human efforts to forecast rainfall reliably. With modern sophisticated equipments for meteorological observations, there has been some very recent attempts to obtain reliable rainfall forecasts of a few hours, a process in which the term, *nowcast* is often used instead of *forecast*. The available nowcasting methodologies have not yet been tested adequately.

The flood forecasting model presented in this paper includes all three basic component models. The first two component models have been used in Bangladesh with considerable success. These models are the S11 hydrodynamic system and the NAM model developed by the Danish Hydraulic Institute and described by Refsgaard, Jensen, and Havno (1985). Therefore, these component models are not described here in detail; the bulk of the presentation in the sequel is on the third component - the rainfall forecasting model.

RAINFALL FORECASTING MODEL

General Information:

Meteorologists and engineers have given serious attention to rainfall forecasting only in the past three decades. The early works use probabilistic techniques linked to both space and time. The probabilistic models suggested for rainfall forecasting have evolved from the alternating renewal models (Green, 1964: Grace and Eagleson, 1966), to Poisson models (Duckstein et al., 1972), Markov chains (Smith and Schreiber, 1973; Coe and Stern, 1982; Srikanthan and McMahon, 1982), discrete autoregressive moving average models (Chang et al., 1984), and to point process models (Kavvas and Delleur, 1981; Smith and Karr, 1983, Rodriguez-Iturbe, 1986). These probabilistic and black box models have been of limited success because the rainfall correlation structure is generally quickly decaying. Nevertheless, rainfall is nonlinearly related to a series of meteorological variables, which in turn exhibit slowly decaying correlations and high cross-correlation. Their forecasting, using statistical techniques, is then feasible. Georgakakos and Bras (1984) have proposed a rainfall model based on the conservation of condensed water equivalent mass in a cloud column characterized by the input variables of ground station data on temperature, humidity, and pressure. Cloud microphysics gives expressions for the rainfall rate as a function of the input variables, the model state, and the storm invariant parameters. Pseudo adiabatic condensation gives the input rate in the cloud column. Temperature, humidity, and pressure values are presently well predicted by statistical techniques like the model output statistics method of the Techniques Development Laboratory of the U.S. National Weather Service (Glahn and Lowry, 1972, Lowry and Glahn, 1976). Georgakakos and Bras (1984) have successfully applied their model to storms at Boston (Massachussetts) and Tulsa (Oaklahoma).

In areas where rainfall has a highly seasonal characteristics it is proposed that further improvement to the model developed by Georgakakos and Bras can be achieved by incorporating seasonal information in the causal model. In fact, similar improvement in streamflow forecasting has been reported by Nash and Barsi (1983) and Liang(1986). They developed a hybrid model for the seasonal values and for the departure values of the individual events which is now referred to as the linear perturbation model to distinguish it from other hybrid models.

The Linear Perturbation Model:

The linear perturbation model for rainfall forecasting is a hybrid model wherein seasonal values of atmospheric pressure, temperature, and humidity are assumed to generate seasonal values of rainfall and the deviations of individual events of atmospheric pressure, temperature, and humidity occurrences from their seasonal values are assumed to produce the corresponding deviations of rainfall. The basic philosophy of the model is that for each time period when the actual values of atmospheric pressure (p_t), humidity (h_t), and temperature (T_t) equal the simple seasonal mean values $\bar{p}_t$, $\bar{h}_t$, and $\bar{T}_t$ for that time period, the corresponding rainfall would also agree with its seasonal mean value, $\bar{i}_t$.

Hence, it follows that $(\bar{p}_t, \bar{h}_t, \bar{T}_t) \rightarrow \bar{i}_t$ for each time period t, where the bar indicates an average for that time step estimated over n years of observation which is taken as an estimate of the seasonal value for that time step. Further, the departures of the atmospheric pressure, temperature, and humidity from their respective seasonal values are related by a linear time-invariant relationship, i.e.

the series $(p_t-\bar{p}_t, h_t-\bar{h}_t, T_t-\bar{T}_t) \rightarrow (i_t-\bar{i}_t)$

Intuitively, the population $\bar{p}_t$, $\bar{h}_t$, $\bar{T}_t$, and $\bar{i}_t$ series are smooth, so the estimates obtained by simple time averaging are then smoothed by harmonic analysis to yield more realistic estimates. Thus, Fourier series of a few harmonics is fitted separately to the mean values of each time period of atmospheric pressure, temperature, humidity, and rainfall of the form (for daily values):

$$x_k = \bar{x} + \sum_{j=1}^{\beta}\{a_j \cos(2\pi jk/365) + b_j \sin(2\pi jk/365)\}$$

where x_k is smoothed $\bar{p}_t$, $\bar{h}_t$, $\bar{T}_t$, or $\bar{i}_t$

$$\bar{x} = \frac{1}{365}\sum_{k=1}^{365} x_k$$

$$a_j = \frac{1}{365}\sum_{k=1}^{365} x_k \cos(2\pi jk/365)$$

$$b_j = \frac{2}{365}\sum_{k=1}^{365} x_k \sin(2\pi jk/365)$$

and β = the total number of harmonics required to represent the seasonal values which is adopted in a particular case on the basis of the proportion of total variance $(1/365)* \sum_k (x_k-\bar{x})^2$ accounted for by the variance of the βth harmonic $0.5(a_\beta^2+b_\beta^2)$. Usually, the appropriate value is determined to be a single value for all the variables from a comparative study. In a leap year, February 29th values may be averaged into February 28th values and March 1st values when the time step is taken to be one day.

The new values obtained by Fourier smoothing are designated as seasonal values of atmospheric pressure, temperature, humidity, and rainfall. So far, no interpretation or investigation into the relationship between the smoothed p_t, h_t, T_t, and i_t series have been carried out, or indeed considered necessary as the smoothed $\bar{i}_t$ series is determined independently of the corresponding p_t, h_t, and T_t series' and used as a simple seasonal forecast of rainfall, while the smoothed p_t, h_t, and T_t series' are required only for the purpose of estimating the corresponding series' of departures.

It is proposed here that, in any observed record, the series of departures of atmospheric pressure, temperature, humidity, and rainfall from their respective seasonal means are linearly related by a simple linear regression relationship, as follows:

$$(i_t-\bar{i}_t) = c_1(p_t-\bar{p}_t) + c_2(h_t-\bar{h}_t) + c_3(T_t-\bar{T}_t) + e_d$$

where the vector c represents regression coefficients and e_d is error term. It is reasonable to expect significant cross-correlation among the pressure, humidity, and temperature terms which will introduce instability in the algorithm. This problem may be avoided by principal component regression as is described in Draper and Smith (1981) or by canonical correlation analysis as is described in Wasimi and Kitanidis (1983).

FLOOD FORECASTING IN BANGLADESH

A major setback in developing effective flood forecasting scheme for Bangladesh is that most part of the catchment of major rivers lie outside the country; and data are transmitted to us by an agreement with India, only when the rivers attain warning stages. Eventually, therefore, flood forecasting on major rivers, where contributions from local rainfall is trivial will be primarily from a routing model that will route the flows from the international borderline areas to the desired locations. However, on small catchments, many of which lie entirely in Bangladesh, rainfall forecasting and rainfall-runoff models, in addition, are essential to have useful lead time in flood forecasting.

Currently, flood forecasting in Bangladesh is done by the Flood Forecasting Cell of Bangladesh Water Development Board (BWDB). The prevalent method on large rivers for flood forecasting is basically the Muskingum method of flood routing. On small basins and flashy rivers flood forecasting is done by APIC model of W.M.O. APIC (abbreviation for continuous antecedent precipitation index) is an empirical rainfall-runoff model that correlates storm rainfall, antecedent basin conditions, storm duration, and the resulting storm runoff. The basic principle is that antecedent basin conditions are represented by two variables. The first is an antecedent precipitation index(API) which is essentially the summation of the precipitation amounts occurring prior to the storm, weighted according to time of occurrence. The second variable is the time of the year in which the storm occurs. Time of the year introduces the average interception and evapo-transpiration characteristics of each season, which when combined with the API provides an index of antecedent soil condition. The runoff is the excess moisture after detention and retention by the soil which is routed by the unit hydrograph method. The input to the APIC model, i.e.; rainfall forecasting, is done by the Dhaka Meteorological Office by synoptic procedure. In essence, synoptic rainfall forecasting is an empirical inference procedure from various meteorological data, for example, wind pattern, atmospheric pressure, humidity, temperature, etc. The synoptic rainfall forecasting in Bangladesh is verified against radar observation of clouds before being transmitted to the Flood Forecasting Cell.

Recently, Master Plan Organization (MPO) have tested and applied to the Southeast region of Bangladesh the NAM model and the S11 hydrodynamic model of the Danish Hydraulic Institute (DHI). The performance of the models have been satisfactory. Although the models are yet at the experimental level, they are expected to be made operational in the very near future.

The NAM model is of the lumped conceptual type. The input data to the NAM model are: rainfall, potential evapotranspiration, and temperature. NAM simulates the rainfall-runoff relationship in rural catchments. It operates by continuously accounting for the moisture content in five interrelated storages, namely, snow storage, surface storage, lower zone storage, upper groundwater storage, and lower ground water storage. Precipitation passing through the snow storage is controlled by temperature conditions, and in Bangladesh, temperature is always above freezing point. Moisture intercepted on the vegetation, as well as water trapped in depressions and in the uppermost cultivated part of the ground is represented as surface storage. The soil moisture in the root zone, a soil layer below the surface from which the vegetation can draw water for transpiration, is represented as lower zone storage. The ground water recharge from infiltration is divided into two ground water storages, upper and lower, having different time constants. The capacities of these storages as well as their overland flow, inter flow and base flow coefficients determine about ten model parameters. These parameters are initially estimated from average physical catchment data, but final estimation is performed by calibration applying concurrent input and output time series.

The hydrographs obtained from the NAM model as well as other inflow values if any are routed by the S11 hydrodynamic model. The S11 model operates by solving the Saint Venant equations numerically with a fully centered, implicit, finite difference scheme. The algorithm used is commonly referred to as 'double sweep' algorithm. Double sweep algorithm makes successive use of a set of recursive formulas with coefficients. These coefficients include channel resistance terms which are calibrated with observed data. Again, S11 has structure descriptions covering weirs, narrow cross-sections, flood plains, reservoir operations, etc. These are incorporated by replacing the aforementioned coefficients with modified coefficients. The modified coefficients are calibrated from observed data.

With the scourge of two recent devastating floods of 1987 and 1988 the Government of Bangladesh is seriously considering the implementation of the airborne radar flood monitoring system developed by four institutes of Holland.

MODEL APPLICATIONS

The integrated model for flood forecasting with the conjunctive use of the three component models has not been possible due to lack of availability of meteorologic and hydrologic data on a single catchment in Bangladesh. However, each component model has been tested independently. The S11 model provided excellent correspondence between observed and predicted values for the Southeast region, Central region, and Northwest region of Bangladesh. The NAM model provided satisfactory results for the Southeast region, but its application to the Central region and Northwest region posed some problem due to difficulties in identification of watershed boundaries owing to flatness of the land and criss-cross pattern of the rivers. To provide an idea of the performance of NAM model for the latter regions an example of model output along with the observed values are given in Fig.1. The model parameters used for this particular run are given in Table 1.

The rainfall forecasting model has been tested with daily values of observations at Dhaka. To find seasonal components of rainfall, pressure, temperature, and humidity a series of 30 years of daily data from 1951 to 1980 for each variable was smoothed by Fourier analysis. The number of Fourier coefficients for each series was selected from variance analysis to be 5. The Fourier coefficients used for smoothing are given in Table 2. To verify the performance of the proposed linear perturbation model (LPM), the departures (perturbations) of daily individual observations of 1985 from the seasonal values were calculated. A simple linear regression was performed to forecast rainfall perturbations from those of pressure, temperature, and humidity. The forecasted rainfall perturbations were then added to the seasonal rainfall values to get the total predicted daily rainfalls. The predicted values of rainfall, thus obtained for the Rainy season, are given in Fig. 2 along with the observed values. Evidently, LPM smoothens the peak values, but better maintains the volumetric quantities than the model of Georgakakos and Bras. Similar results were obtained with rainfall observations of the year 1986. To provide a comparative study of the performance of LPM with that of Georgakakos and Bras's model for five storms, their least squares performance measures are given in Table 3. It may be noted here that with principal component regression, instead of simple linear regression, the performance of LPM somewhat decreases. However, it is expected that the performance of the proposed model will improve further if hourly time step is used instead of daily values. Research is underway to verify the performance of the model with hourly data and the results will be reported elsewhere.

REFERENCES

Chang, T.J., M.L. Kavvas, and J.W. Delleur, "Daily Precipitation Modeling by Discrete Autoregressive Moving Average process",Water Resources Research, 20(5), 565-580, 1984.

Coe, R. and R.D. Stern, "Fitting Models to Daily Rainfall Data" Journal of Applied Meteorology, 21(7), 1024-1031, 1982.

Draper, N.R. and H. Smith, "Applied Regression Analysis", Second Ed., John Wiley & Sons, Inc., 1981.

Duckstein, L., M. Fogel, and C.C. Kisiel, "A Stochastic Model of Runoff Producing Rainfall for Summer Type Storms", Water Resources Research, 8(2), 410-421, 1972.

Geogakakos, K.P. and R.L. Bras, "A Hydrologically Useful Station Precipitation Model", 2 papers, Water Resources Research, 20 (11), 1985-1610, 1984.

Glahn, H.R. and D.A. Lowry, "The Use of Model Output Statistics (MOS) in Objective Weather Forecasting", Journal of Applied Meteorology, 11, 1203-1211, 1972.

Grace, R.A. and P.S. Eagleson, "The Synthesis of Short-Time-Increment Rainfall Sequences", Hydrodyn. Lab. Rep. 91, Dept. of Civil Engineerin l, M.I.T., Cambridge, Massachusetts. 1966.

Green, J.R., "A Model for Rainfall Occurrence", J.R. Stat. Soc., Ser. B., 26, 345-353, 1964.

Kavvas, M. L. and J. W. Delleur," Stochastic Cluster Model of Daily Rainfall Sequences", Water Resources Research, 17(4), 1151-1160, 1981.

Liang, G. C.,"Linear Models for Multiple Inflows - Single Outflow Flow Routing in Real Time", Ph.D. Thesis, Engineering Hydrology Dept., University College, Galway, Ireland.

Lowry, D. A. and H. R. Glahn, "An Operational Model for Forecasting Probability of Precipitation - PEATMOS P. P., Monthly Weather Review, 104, 221-232, 1976.

Nash, J. E. and B. I. Barsi,"A Hybrid Model for Flow Forecasting on Large Catchments", Journal of Hydrology, 65, 125-137, 1983.

Rodriguez-Iturbe, I.,"Scale of Fluctuation of Rainfall Models", Water Resources Research, 22(9), 15S-37S,1986.

Smith, R. E. and H. A. Schreiber,"Point Process of Seasonal Thunderstorm Rainfall, I. Distribution of Rainfall Events", Water Resources Research, 9(4), 871-884, 1973.

Smith, J. A. and A.F. Karr,"A Point Process Model of Summer Season Rainfall Occurrences", Water Resources Research, 19(1), 95-103, 1983.

Srikanthan, R. and T. A. McMahon,"Simulation of Annual and Monthly Rainfalls - A Preliminary Study at Five Australian Stations", Journal of Applied Meteorology, 21(10), 1472-1479, 1982.

Wasimi, S. A. and P. K. Kitanidis,"Real-Time Forecasting and Daily Operation of a Multireservoir System During Floods by Linear Quadratic Gaussian Control", Water Resources Research, 19(6), 1511-1522, 1983.

Table 1 : Parameters of NAM simulation on catchment 5 (NW-region).

1979 3 31 09	Start time (YYYY MM DD HH)
1980 3 31 09	End time (YYYY MM DD HH)
24	Time step length (hours)
1	Number of subcathments
1	Print of parameters?
1	Print of init. cond.?
0	Print of results ?
Catchment no: NWS	
0	Snow included ?
0	Groundwater abstraction included?
466	Catchment area (km**2)
50.0	Umax (mm)
200.0	Lmax (mm)
0	Cmelt (mm/centigrade/day)
0.50	Cqof
0.7	Clof
0.001	Cqif
0	Clif
0.60	Clg
1	Carea
3.0	gwbf0 (m below surface)
2.5	gwfl0 (m...)
0.009	Sy
24	ck1
24	ck2
360	ckuz
3160	ckbf
0	Initial conditions: U
0	L
0	Snow
0	OF1
0	OF
0	IF1
0	IF
0	BFU
3.0	gwl

Table 2: Fourier Coefficients of Smoothed Rainfall and Meteorologic Data of Dhaka from 1951 to 1980.

	a_1	a_2	a_3	a_4	a_5	b_1	b_2	b_3	b_4	b_5
Rainfall	-6.17	0.76	-0.26	0.16	0.33	-1.84	0.23	0.83	-0.14	-0.11
Pressure	7.74	0.36	0.33	0.10	0.08	0.28	-0.72	-0.19	0.38	0.05
Humidity	-8.56	2.60	1.38	0.67	-0.32	-8.06	-1.57	1.58	0.41	-0.16
Temperature	-4.74	-2.38	-0.41	0.20	0.14	-0.44	-0.64	-0.25	-0.02	0.04

Table 3: Deterministic Precipitation Model Least Squares Performance Measures.

Description	Determination coefficient	Coefficient of efficiency
Georgakakos and Bras's Model:		
Storm 1	0.19	0.02
Storm 2	0.12	0.10
Storm 3	0.17	0.12
Storm 4	0.13	0.03
Storm 5	0.16	0.15
Proposed Model:		
Seasonal Model	0.21	0.14
Linear Perturbation Model	0.38	0.23

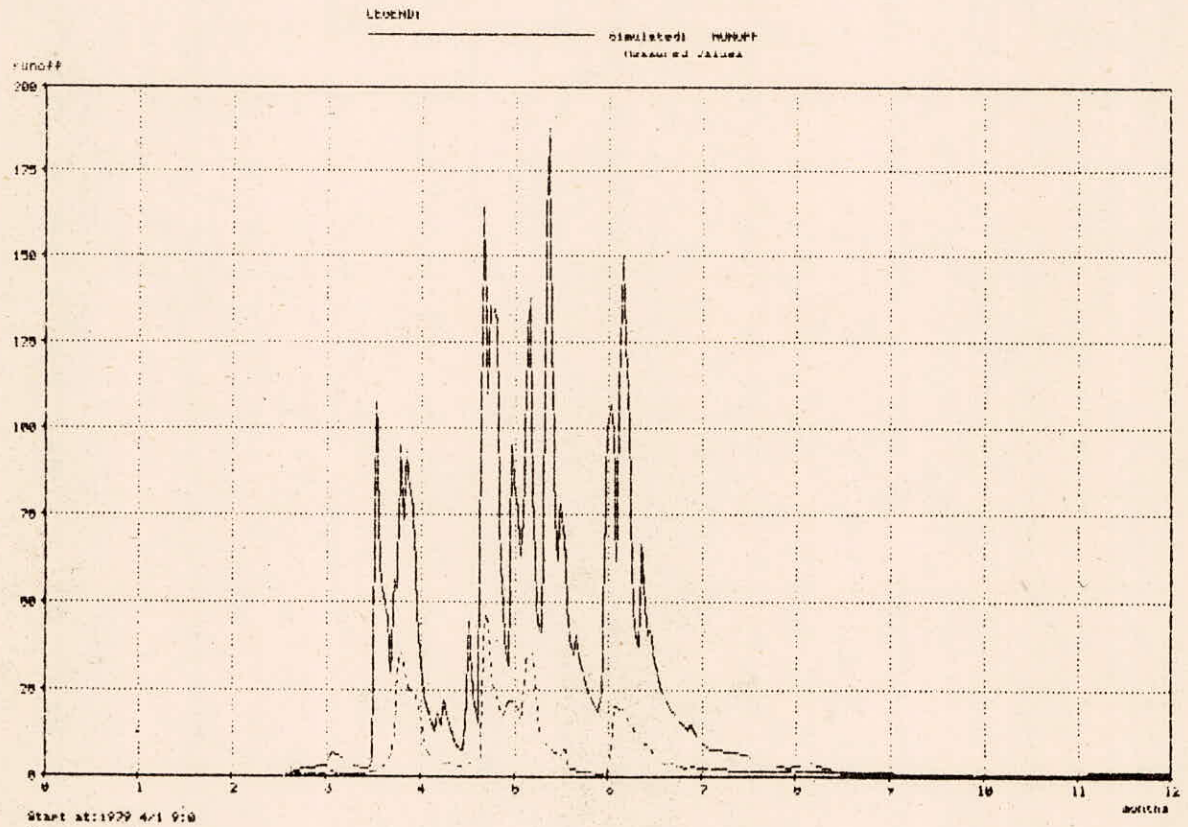

Fig. 1: NAM Simulated and Measured Runoff of Catchment 5 in the Northwest Region of Bangladesh.

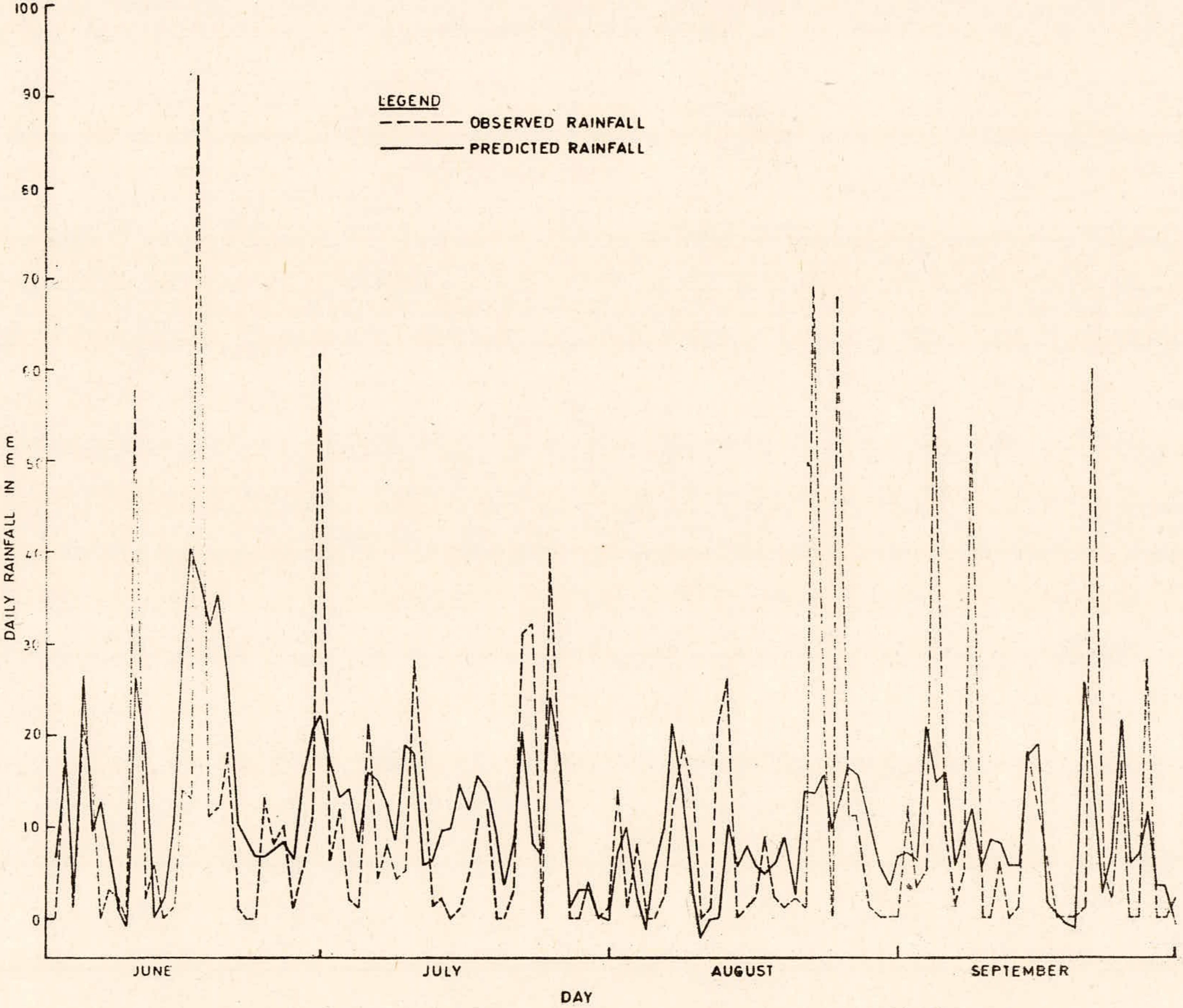

FIG. 2 LPM PREDICTED RAINFALL AND OBSERVED RAINFALL AT DHAKA IN THE RAINY SEASON OF 1985